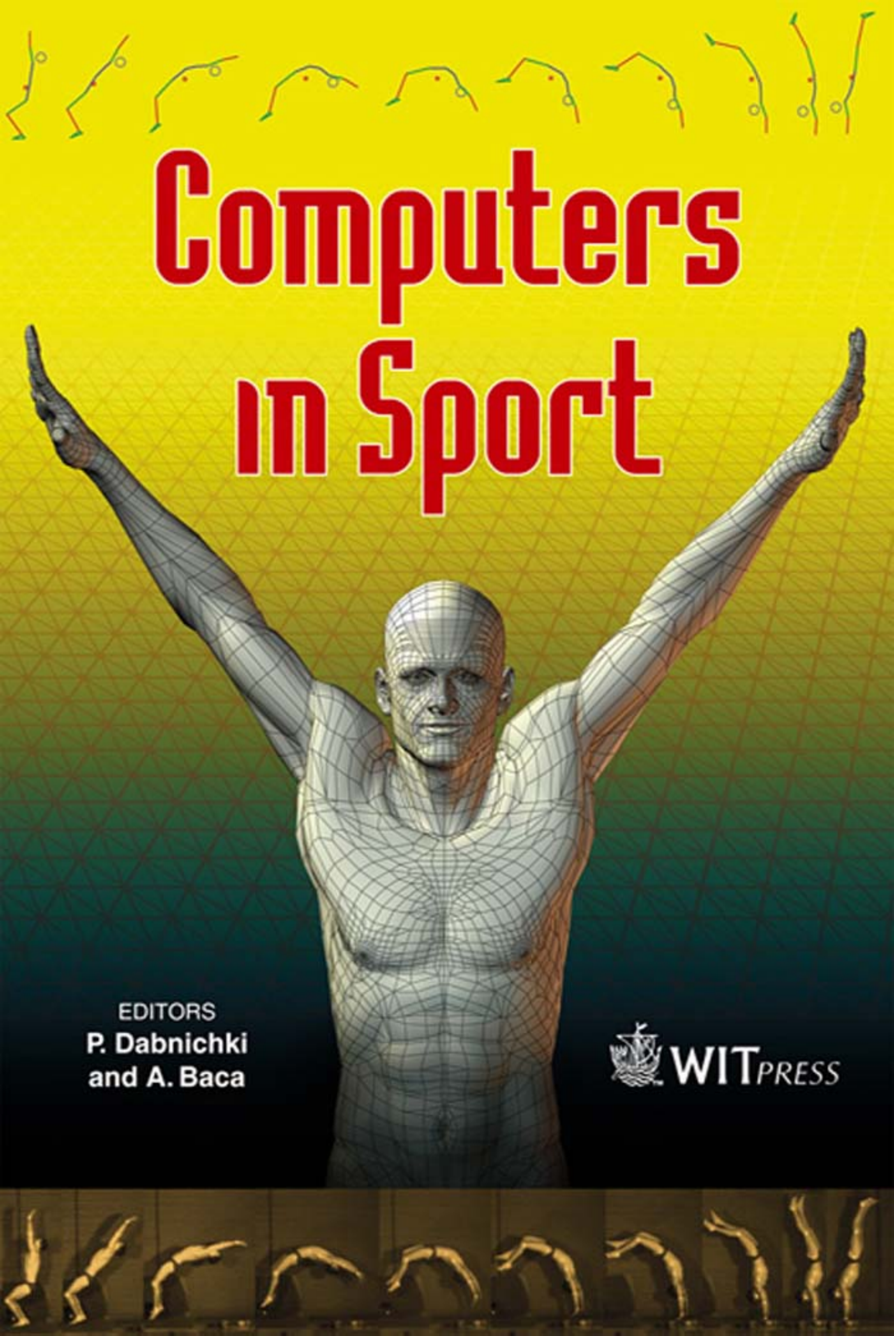

Computers in Sport

EDITORS
P. Dabnichki
and A. Baca

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Contents

Foreword

Any treatise on *sport* presents the editors with an immediate challenge – what is sport? The definition is complex and has been evolving for more than 2000 years. In this book we use the simple definition of sport as a collective term for games or competitive activities. Although it looks very broad, such a definition excludes some activities such as extreme sports and differs from the meaning of sport for the ancient Greeks.

Applications of computers in sport (to be understood in its broadest sense) have been reported since the mid 1960s. Statistical computations, numerical calculations in biomechanical investigations and sport documentation tasks were carried out. During the last decades, not only has the pure application of computers as a tool been continuously growing, moreover, computer *science* has become an important interdisciplinary partner for sport and sport science. Activities in this interdisciplinary field were and are strongly affected by developments in computer science. In particular, progress in hardware (processor speed, storage capacity, communication technologies), software (tools), information management concepts (data bases, data mining) and media (internet, e-Learning, multimedia) are of essential importance.

Throughout the last 30 years, a scientific discipline *Computer Science in Sport* has been established. Working areas have evolved, national and international associations have been founded, journals are published and congresses are organized regularly to present research activities.

The current field of activity in *Computer Science in Sport* comprises the following main areas of research:

- Multimedia and presentation
- Modelling and simulation
- Biomechanics and sports technology
- Data bases and expert systems
- Information and communication technologies

The papers presented within this book give a good overview on current activities in these areas and have been grouped accordingly.

Katz, Parker, Tyreman and Levy provide an overview of virtual reality, focusing on the most promising developments, especially in the area of sport and exercise. The systems presented are supposed to have enormous potential to change the way coaches and athletes approach training and performance.

The relentless progress in computer technology generates vast data that is difficult to absorb and analyse. It is even more difficult to communicate such analysis to the athletes. Baca discusses the multifaceted nature of feedback provision to athletes and coaches. He demonstrates the vast potential of feedback to influence motor learning; resulting in improved performance. In particular he demonstrates the possibilities afforded by techniques such as video analysis, kinematic analysis, feedback of results, kinetic feedback and their application in a number of sports such as gymnastics, table tennis, rowing and biathlon.

The chapter by Mueller highlights examples on how using computers to enhance social sports experiences. Long-distance sports are presented, which focus on physical exertion comparable to collocated sports, a shared experience although being geographically apart. This novel approach uses telecommunication technology, in particular, to enable participants to enjoy a social sports experience together.

One of the earliest areas of application of computer science in sport is coaching. Lames differentiates between three different stages of coaching – preparation, control and debriefing of competition – which create different conditions for support by computer science. His chapter starts with some remarks on the process of coaching, trying to make clear the requirements for giving support in this area. Technological standards for preparing and analyzing a competition are then lined out. A further paragraph describes the state of the art and possible developments in real time analysis of sports, which supplies coaches with tactical and strategic hints during a game.

Modelling of any complex systems behaviour presents a challenge in any science field. Perl focuses his attention on the formidable hurdles to researchers in this area. His evocative review illustrates that meaningful modelling in sport requires clearly defined terms and objectives could only be achieved by devising realistic rather than oversimplified models. This could only be achieved by the use of advanced techniques such as fuzzy modelling, evolutionary algorithms, artificial neural networks and pattern analysis, and antagonistic dynamics. Such complex approaches are made easy to understand through illustration of a variety of sport applications that illustrate the author's vast experience in this area.

The understanding of sport helps to understand ourselves. This philosophical issue may seem out of place in this book but Ferrein and co-workers demonstrate clearly that modelling of soccer decision making provides an important test in the development of artificial intelligence. This in turn helps sport scientists to better understand the complex decision making involved in the simple game of soccer.

Sport biomechanics and computers have been inseparable from the very beginning. The most valuable tool in this relationship has been the development of biomechanical models that are utilised in both performance analysis and equipment selection and development. Hartmann, Berti, Schmidt and Buzug highlight the importance of this approach for the progress in equipment development, performance improvement and well-being of the athletes. They highlight the intrinsic necessity for integration of modelling and biomechanical measurement in the modern biomechanics.

From ancient times the vast water pools on the planet have been perceived as both a barrier and a challenge to humans. Lauder highlights how computers allow this barrier to be broken and hence the provision of constructive feedback for performance improvement in water sports. He focuses his attention on swimming and kayaking. The complex issues and the need to use a variety of custom made devices in conjunction with computers are illustrated in this work.

Chi points out, how sensors and other ubiquitous computing technologies have slowly penetrated the arena of sports. He examines some examples of pervasive technology in sports and points to future directions. Trends and implications of utilizing sensors in sports are outlined; technological challenges in introducing sensors in various sports are examined.

In the final contribution, Wiemeyer discusses advantages and disadvantages of multimedia learning in sport and sport science. Different types of multimedia systems regarding learning are introduced. Based on these distinctions, pros and cons of multimedia learning are elaborated. The potential of multimedia as a research tool is discussed.

We hope that the reader of this book will have the same enjoyment reading book and that researchers from the mainstream areas of computer science (informatics), mathematics, bionics and robotics will find inspiration to apply their knowledge and skills in this exciting discipline. We also hope that the book will help to disperse the impression of authors being “lone wolves” by setting a series of publications in his area that will communicate both significant achievements and formidable challenges.

Arnold Baca and Peter Dabnichki

Preface

The concepts and the possibilities provided by information and communication technologies have influenced and changed practically all aspects of our daily life. Sport and leisure activities are no exception at all from this observation. The present book offers snapshots of situations where Information Technology (IT; i.e., computer hardware and software) has been really helpful in supporting sporting activities, or has the potential to do so. This is due to the ever increasing processing power, and to IT's capability of modelling and solving problems which are of great help for a variety of sports disciplines.

The present book offers such a wealth of information that the sheer number and the complexity of the topics addressed make it next to impossible to pay adequate attention to every author and to every subject addressed. But let me give you a few examples.

- *Coaching and training:* Here techniques are discussed which enable a coach to better prepare and to control the performance of the team members through special software tools.

- *Biomedical modelling and motion analysis:* These approaches try to give a better understanding of the movement of the human body, and to enable and support corrective and improving actions of the athlete. Most new techniques in that area are supported by small computing units such as sensors, actors, wearable computing – and particularly by wireless transmission technologies and ubiquitous computing.

- *Development of new sport games:* Computer technologies and computer networking allow the invention of new games and which are independent of the geographical location of the players (traditionally that distance has been rather small – in most cases dictated by the "range of sight" or even "range of reach" – but computers are not subject to such geographical bounds).

- *Sports and robotics:* Not only humans are able to perform sporting activities. Machines can be constructed to simulate or to practice various disciplines. A prominent example for that is the Robocup that clearly demonstrates the enormous progress in robotics – even if the global performance of soccer robots is still considered as somewhat modest by many.

- *New management tasks* for huge computer systems which can only be tested at mega-events which most often occur in sports (world soccer championship, Olympic Games...): Such mega-events require the co-operation of numerous computers (e.g., for the organisation of Olympic Games). They pose considerable challenges since such situations can hardly be tested in a suitable way prior to the event itself – nobody would be prepared to pay for such a test.

The area of sports (and in particular the support of sports through IT) is a particularly delicate one. Many ethical issues need to be addressed (e.g., in biomechanics), and computers can comparably easily be misused. Experience indicates that some (athletes or managers) will stop short at nothing if they can profit from it. The problematic nature of doping is a particularly difficult area – and perhaps therefore not fully addressed in the present volume.

I'm convinced that the present book is a very important step in order to improve the visibility of "computers and sport" as a discipline which is of highest relevance for the future – both scientifically and economically.

Professor Dr Dr h.c. Otto Spaniol

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1. Multimedia/Presentation/Virtual Reality

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Virtual reality

L. Katz, J. Parker, H. Tyreman & R. Levy
Sport Technology Research Laboratory, University of Calgary, Calgary, Canada.

Abstract

Virtual reality (VR) involves technology and visual art that allows a user to interact with a computer-simulated environment. These environments can range from a simulation of an authentic situation to the creation of a wholly imagined world. While most virtual reality environments (VREs) are primarily visual experiences (computer screens, large screen displays, multiple screens and stereoscopic displays) new tools are being developed that enhance the visual experience by addressing other sensory modalities (e.g. sound, tactile feedback and smell). VR has been used effectively to train astronauts, pilots, physicians, military personnel, and now, even athletes. While the cost of creating VRE is the most expensive type of computer development, the entry of game manufacturers into the field is drastically changing the cost of producing and using these environments. This chapter provides an overview of VR and focuses on the most promising developments in VR, especially in the area of sport and exercise. The implications of these innovations for other spheres of activity are also discussed.

Keywords: virtual reality, virtual environments, virtual reality environments, simulation, gaming, reaction time

1 Introduction

This chapter acquaints the reader with the issues related to virtual reality (VR) in sport and human performance and also highlights the potential of these types of environments to revolutionize the approach to equipping and training athletes and coaches. Extrapolation of the impact of this promising technology to other diverse fields is provided.

VR has been defined previously [1]. The most recent definition in Webopedia (www.webopedia.com/TERM/V/virtual_reality.html) is listed below:

> An artificial environment created with computer hardware and software and presented to the user in such a way that it appears and feels like a real environment.

> To 'enter' a virtual reality, a user dons special gloves, earphones, and goggles, all of which receive their input from the computer system. In this way, the computer controls at least three of the five senses. In addition to feeding sensory input to the user, the devices also monitor the user's actions. The goggles, for example, track how the eyes move and respond accordingly by sending new video input.
>
> To date, virtual reality systems require extremely expensive hardware and software and are confined mostly to research laboratories. The term virtual reality is sometimes used more generally to refer to any virtual world represented in a computer, even if it's just a text-based or graphical representation (19 February 2007).

VR is a small component in the overall use of technology in coaching and sport (see Figure 1). However, from a design, development and cost perspective, VR is the most intensive application and can incorporate a number of the others technologies as well (e.g. wireless technology and collaborative immersive environments over distance). These integrated systems have incredible potential to change the way coaches and athletes approach training and performance.

The model presented for computer-assisted coaching is a work in progress and includes the broad categories of managing, monitoring and mentoring. While VR is categorized under the monitoring (facilitate coaching) section together with simulations, it is clear that future development of VR systems will include many aspects of monitoring, managing and mentoring. Ultimately, sophisticated VR systems will incorporate a multitude of sport science components including data management; notational, pattern, performance and game analysis; biomechanics; physiology; and collaborative and distributed communications technologies.

For example, [2, 3] describe a real-time skiing system that models skiing technique, collect GPS survey data of slope and gates, triangulates the data to generate a mesh, obtains the anthropometric data of the skier, finds the optimized trajectory on the slope for the skier and creates a computer-generated visualization of the optimized trajectory which the athlete can use to study the course and compare it with other trajectories. By extension, this integrated system should allow the visualization to take place in a completely immersive environment including haptic devices that would enable the skier to virtually experience the course in high fidelity with emulation of both sound and weather conditions.

While military and medical evidence suggests that these types of environments are highly effective and efficient in improving performance the research in VR and sports is still in its infancy [1].

This chapter has been divided into six sections. Section 1 is Introduction to the chapter. In Section 2, an overview of VR and its application to sport is presented. Section 3 discusses the components of VR participant activity that are most pertinent to understanding performance (reaction time, anticipation time, reaction accuracy and presence). These components are identified and defined in relation to the transferability to the real world. Issues related to the background of the athletes (e.g. anticipation factors and level of expertise – expert vs. novice) are also discussed. In Section 4, the process of creating VR

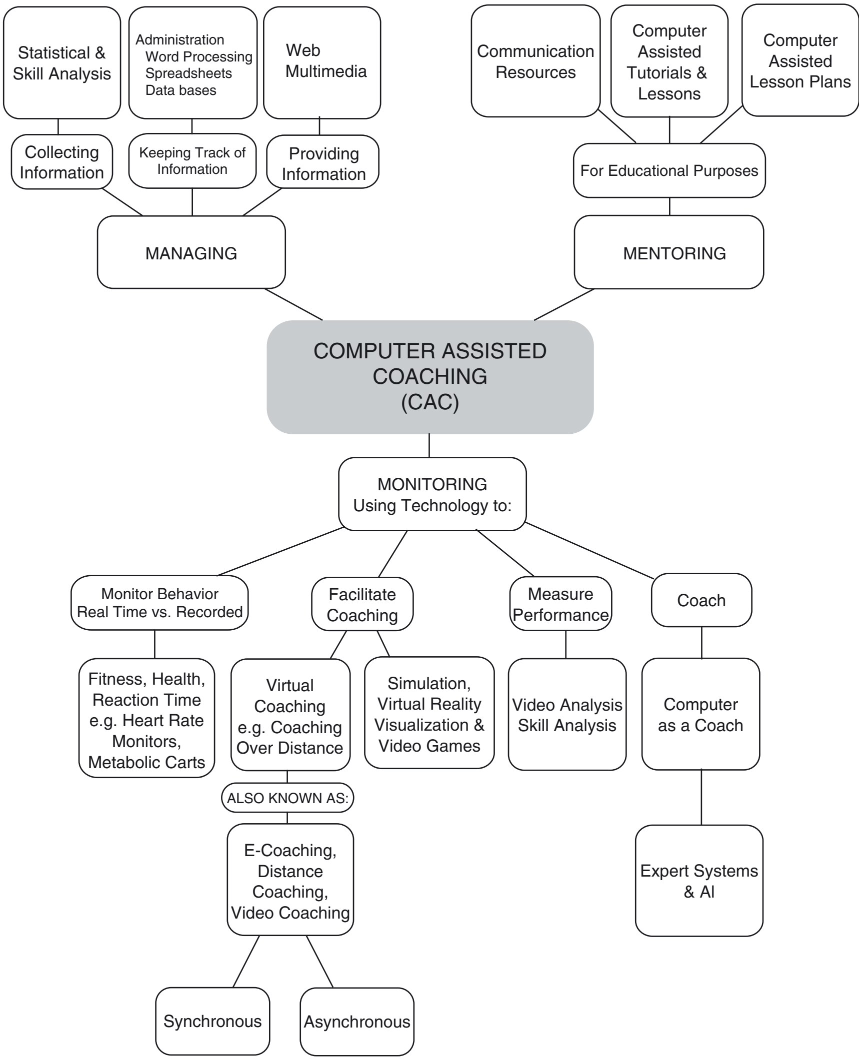

Figure 1: Computer-assisted coaching. (Copyright Katz and Wong (2006), reprinted with permission.)

environments is presented, including the use of graphics, audio, haptic devices and other sensory modalities. In addition, video games design and development are introduced, and their impact on VR environments is highlighted. Section 5 focuses on examples of VR sport environments including unique innovations. Finally, in Section 6, the implications of these VR developments for sports performance are discussed.

2 Overview of VR and sport

VR systems use technology to create environments that allow the user to actively participate and navigate in events or worlds that engage the mind and body. It is concerned with the realistic simulation of environments. This means giving a human subject a multi-sense view of a place and/or situation that does not exist, but that behaves as if it does. It could also give a simulated view of a real place, such as a specific sport venue such as the Calgary Olympic Speed Skating Oval [4].

VR was originally envisioned as an interface to remote-controlled vehicles or manipulators that were operating in hostile environments such as the ocean floor or a volcano interior. The idea was that a remote operator would perform better if the context of the actual environment could be presented to them realistically. Thus, the use of computer graphics or remote video along with audio and haptic feedback (touch) would be used to make the operator feel as if they were doing the real work on the actual site. The term for this is 'presence'. The degree to which the senses are engaged [e.g. whether three-dimensional (3D) or 2D, immersive or non-immersive, surround sound or no sound] is directly related to the considerations of design, costs of development, costs of equipment and the imagination of the user. Presence is discussed in more detail later in this chapter. Many organizations still use VR for training staff for operations in harsh environments. For example, NASA uses VR to train astronauts for working in the hostile environment of space [5].

Since sport requires extensive physical activity, it is a natural fit for VR development. The use of VR in sport is primarily connected with coaching and training. For the purposes of this paper, designing VR for sport can be conceptualized as optimizing performance through effective and efficient models that increase participation, enhance team play, augment individual activity and reduce the possibility of injuries through models for prevention and or rehabilitation as shown in Figure 2. The connection between sport and VR is clear: sport involves motion, physical activity and decision-making, while virtual environments have the capability to capture, analyse and reproduce the natural human movement realistically and accurately as well as provide the opportunity for athletes to apply strategies and tactics in a variety of situations with immediate feedback under controlled conditions. No other artificial environment has that potential.

In VR, participants enter a new environment that is created by a mix of technology and art. This experience comes through a variety of effects (e.g. visual, audio, touch, smell and motion). VR environments may be representations of real events or may constitute absolute fantasies such as in interactive multimedia, multiplayer fantasy games (e.g. *World of Warcraft, Halo, Second Life,* and *Call of Duty*). As noted above, developing VR environments is a time and cost intensive activity, but the airline, space, medical and military industrial complexes have established the cost-effectiveness of using such environments to prepare their personnel. Typically, VR environments are aimed at the professional (high-end) market, but the gaming industry, especially with the recent introduction of the innovative *Nintendo's Wii*™, game console, has opened the market to consumers

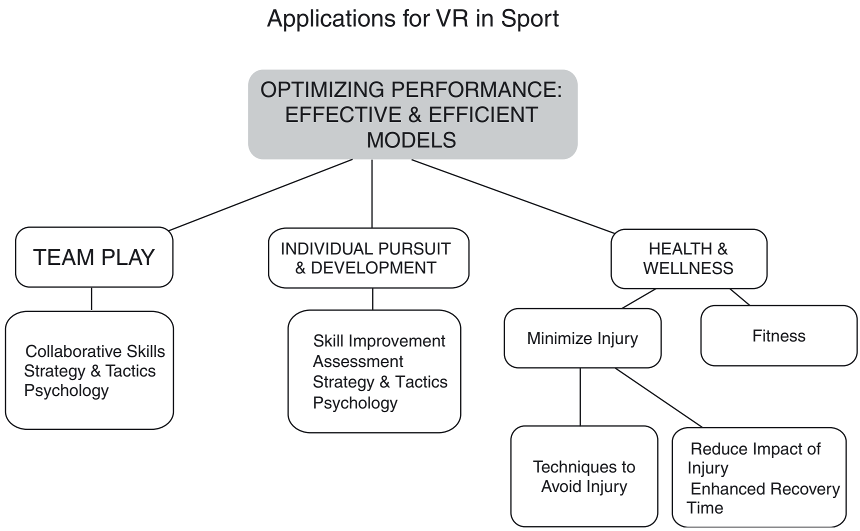

Figure 2: Applications for VR in sport.

and, potentially, amateur sports teams, which should revolutionize the cost and development dynamics.

Initial consumer applications of VR were in the computer arcades; for a few dollars, customers would be equipped with a helmet and earphones and could shoot monsters or ski down distant slopes. However, the original technology was not sufficiently mature, and the quality of the interface devices, graphics and audio was poor. As a result, VR developed a negative reputation. The power of small computers grew, and the methods for creating graphics and audio improved, bringing with it a significant improvement in quality. It is now possible to create highly effective environments on standard desktop computers, and unforgettable ones using full-scale workstations with immersive environments. VR is now commonly used for scientific data visualization such as for geophysical data analysis and medical imagery.

The most common virtual environment today is the 3D computer game, which is playable on most home computers. The user positions their online representation (avatar) within the virtual space using the keyboard and mouse, and the user can move about in that space with the view on the screen changing as a result. The avatar may also be a point of view (show the gun site and barrel for the biathlete). It is the ability to interact with the environment that lends reality to the system, not necessarily the quality of the graphics or sound. However, using special equipment does help the illusion. Special goggles can now be connected to a computer, which allow the wearer to see the environment in full stereo vision (3D), and head motions control the direction of viewing.

As society becomes more complex and automated systems become prevalent, there is less emphasis on physical skills. Consequently, individuals have less experience at reacting effectively in situations where automatic control system may fail [6]. This has led to airlines requiring pilots to spend significant amounts of flying time under manual control to maintain the pilot's skills, and has also been a driving force for the creation of virtual environments as places for pilots, soldiers and physicians, to experience low-frequency, high-intensity events to hone their skills (e.g. dealing with an engine fire in flight, night combat and brain surgery). In these situations, VR is used because of the high costs of making mistakes in the 'real world'. Effective simulations allow participants to learn skills, study the impact of their errors and learn good decision-making strategies. Consequently, VR and simulation have become vital components of training in these fields. Since sport is a relative newcomer to VR, it remains to be seen whether it can obtain the same level of importance as a development and training tool. A model for VR development is presented in Figure 3. Applying the model to sport-related activity is consistent with other action-oriented activities.

As can be seen from Figure 3, design considerations include:

- Creating the environment and setting the rules for the environment;
- Determining the nature of the interface between the system and the user;
- Establishing the data collection parameters and identifying the key factors in the participant matrix (e.g. willingness to participate, experience and purpose); and
- Verifying that virtual worlds respond in a realistic manner (e.g. physics and visualization).

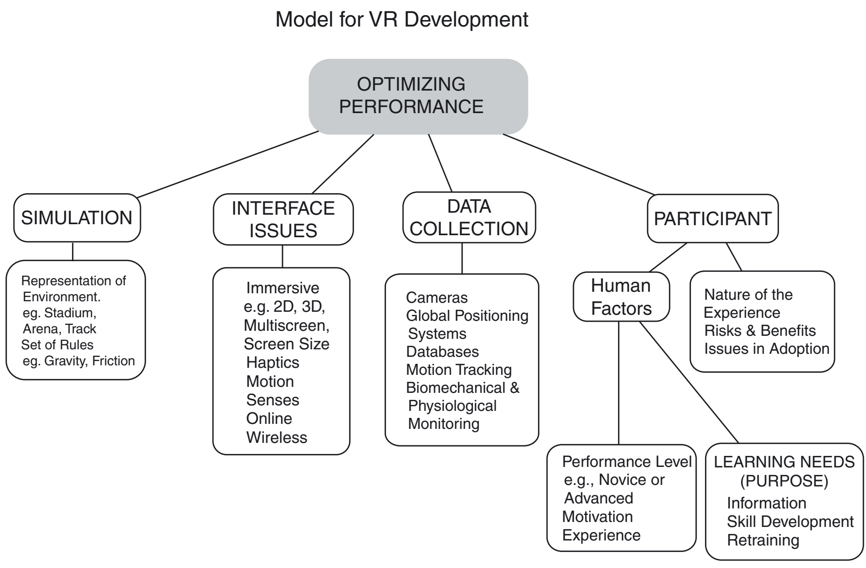

Figure 3: Model for VR development.

The technology currently offers the potential to individualize learning, enhance performance, be collaborative and interactive, supply virtual access and provide immediate feedback. As can be seen in the following sections, integrating the technical and design issues and measuring effectiveness are the major challenges.

3 Components of participant activity in VR and transferability

A critical aspect of VR is the nature of the environment that has been created and the degree to which the athlete might be abstracted from the real environment [7]. In VR, the athlete is taken out of the performance milieu and placed in an artificial situation (e.g. treadmill, virtual cave) where the senses of the sporting environment are simulated to varying degrees (see Figure 4).

The factors that influence the effectiveness of a virtual environment and its transferability to the real world have to be measured. From a sports perspective, one of the easiest variables to measure is how an athlete reacts to an event and the variables that affect the reactions. Some of these factors include anticipation, level of expertise (novice vs. expert), nature of the environment and strategies used. What follows are definitions of the factors which influence reaction to events and a brief discussion of some of these issues.

3.1 Reacting to events

One of the most important components of sports performance is reaction time and reaction accuracy. To help understand the role of these concepts in studying VR and human performance, reaction time, anticipation time, reaction accuracy and presence are briefly defined below.

Reaction time (RT) is the amount of time lapsing from the start of the visual sequence to the first movement of the participant in reaction to the event.

Figure 4: Hockey goalie reacting to shots in 2D and 3D environments golf swing analysed in real time in three dimensions (http://www.3dgolflab.com).

The anticipation time (AT) is defined as the time at which the first reaction was initiated, calculated from the earliest point during the visual sequence that a reaction could be expected. The reaction accuracy (RA) is defined as moving in the right direction and at the right time in response to the event.

Presence refers to the degree to which a participant actually believes that he/she is in a real environment and reacts accordingly. That is, the degree of difference between the reaction in a virtual environment vs. a similar reaction in a real environment. If a virtual environment accomplishes its goals, users should feel as if they are actually present in the simulated world and that their experience(s) in the virtual world matches what they would experience in the environment that is being simulated. Another term used to express the same concept is ‘immersive’. The study of RTs is a window into the cognitive, neurological and visual recognition systems of the participants.

Presence is clearly the most difficult of these concepts to quantify. However, the use of interactive virtual environments in the training of athletes has been observed to produce a physiological reaction similar to that of the actual game environments [8]. Using technology to maximize the potential of the training for the individual will have more benefits than ‘one size fits all’ because modern systems can adapt to the goals and needs of the specific participant [9]. By using traditional video and computer images for reaction testing, researchers have shown differences between genders, handedness and skill level [10].

Bideau *et al* [11] demonstrated that reactions in the VR world can match real-world situations. They used a cylindrical screen and three synchronized projectors for the VR environment, and a motion capture system with seven infrared cameras, to contrast the kinematics of goaltenders’ reactions in both artificial and real environments. The results showed highly significant correlations between the two environments ranging from 0.96 to 0.98. This study supports the concept that 3D sport simulations have the potential to allow participants to respond in similar ways in both VR and real game events.

Anticipation is another area of investigation. Using video and visual cues training with a joystick as the interface, Christina *et al* [12] were able to study the performance of a U.S. football linebacker. After 16 days of training on selecting appropriate visual cues, the player’s anticipation of plays went from 25% on day 1 to over 95% on day 16. The player was able to translate this ability to actual game play and improve his anticipation skills and game performance.

Even the nature of the VR environment (e.g. 2D vs. 3D) may have an impact on reactions of participants. In a pilot training project, Haskell and Wickens [13] demonstrated that 3D displays were best for maintaining flight parameters (e.g. lateral position, altitude and airspeed in following a flight path) and 2D displays were best for controlling airspeed. The results of the research may suggest that 3D displays are better for spatial tasks, whereas 2D displays may be the best for 2D tasks (e.g. maintaining airspeed).

Using a 2D, 2½D and 3D physical and virtual environment, Cockburn and Mckenzie [14] showed that the subjects’ ability to quickly locate items decreased as their freedom to use the third dimension increased. Participants indicated that

3D interfaces appeared more cluttered and less efficient. Clearly, designing effective 3D environments is critical to VR development.

3.2 Novice vs. experts

The research literature suggests that there are significant differences in the performances of experts and novices for a variety of factors. Identifying these factors can influence design considerations for virtual environments. Experts use perceptual strategies such as preparation, cueing, anticipation, scanning and focusing to reduce the quantity and enhance the quality of the data being processed, thus providing more time to react. Interestingly, most elite athletes are unaware of the way they process the information.

In her eye movement research laboratory at the University of Calgary, Canada, Vickers [15, 16] has identified a phenomenon which she calls ‘quiet eye’ (QE), a period of time when the gaze is stable on spatial information critical to effective motor performance. She uses the research knowledge to help performers guide and control their motor behaviour. The basic idea behind QE is that the brain needs a window of time to receive the right information to organize the movement and then control it while it is occurring. Focus and concentration through QE needs to be directed to the locations or objects that matter, while all else should be ignored. Vickers has been able to isolate visual cues in a variety of sports both in laboratory situations and in the actual sport environments and show clearly the differences between the approach of novice and elite athletes.

Very few sport studies have looked at experts vs. novices in virtual environments. In one example, Savelsbergh *et al* [17] used soccer goaltenders and penalty kick situations to measure the AT of experts (playing semi-professional) and the novices (playing soccer for recreation). The experts were more likely to make a save, made fewer corrections than novices and made the corrections closer to the foot impacting the ball than the novice players. The idea that experts will wait until foot impact adds more complexity to understanding the issues of RT, and requires more considerations with regard to strategy and whether experts are aware of the strategies that they are using.

Similarly, Williams *et al* [18] compared experts and novice tennis players who were asked to react to a tennis shot displayed on a large screen. The system measured the response accuracy and decision time. Results showed that skilled players were significantly quicker than novices, though no difference was observed in the accuracy of the results between the groups.

In another example, Mori *et al* [19] studied the RTs of expert and novice karate participants on measures of video attacks, reaction task, video reaction and choice reaction. Experts predicted the location of an attack faster than novices but both groups had the same accuracy. Experts were also faster in the simple reaction tests including in the video attack and location of the dot tasks. Given the nature and speed of the task, effective decisions have to be made before the attack action is completed. The work of Williams *et al* [20] with soccer players also showed that veteran players were better at anticipating pass destination and that experienced players tended to respond to the ball kick before the action was complete.

The data from RT and perception research has the potential to be used in the development of effective virtual environments, but virtual environments are expensive to develop and, as mentioned earlier, the literature is sparse on the connection between sport performance in virtual environments and its transferability to performance in real-life settings. According to Sebrechts *et al* [21], in areas of navigation and communication, performance gains are highly transferable. However, most of the work in these areas involves military situations. If one accepts the premise that learning in properly constructed virtual environments is transferable, then the next step is to discuss the nature or process of creating effective virtual environments. Since the game industry is the most highly diversified in terms of using VR-related technology, many of the examples in the next section relate to the game industry. Sport technology researchers may find it useful to employ existing virtual game technology as a starting point for testing a number of performance parameters.

4 The process of creating virtual environments

A virtual and interactive environment can be created using known methodology and design principles. A virtual environment is a computer simulation that has a complex graphics and audio interface that attempts to portray the setting in a natural way. An interface device, usually a mouse or joystick, is used to control the simulation in real time according to the preset rules of the environment. The graphical display shows the environment in which the user can interact with simulated objects using these programmed rules. For example, simulated trees and rocks are obstacles to motion, can be manipulated and have an effect on other objects in the virtual world.

Behind the portrayal on the screen is a simulation of activities and rules that are complex, and that are implemented by a complex set of computer programs. The heart of the system is the *artificial intelligence* (AI) system. This keeps track of objects in the simulated environment, notes collisions and interactions and computes the interactions. The AI may also control intelligent objects such as simulated characters, animals and robotic vehicles. The AI system repeatedly looks at all objects in its database, updates their position, detects collisions, makes choices, signals sounds to start and then allows the graphics module to update the display. This can be repeated as often as 80 times per second depending on the processing power of the computer.

Participant input is used to specify a change in motion and orientation of the user and any object under the user's control. Then the positions of all objects are given to the graphics system so that the next screen image can be drawn. Drawing each frame is a time-consuming process and largely determines the frame rate possible in most VR systems. Depending on the situation, more frames may be involved, such as incorporating animations or pre-recorded video, handling

AI controlled interactions, creating new characters and objects according to visibility rules, and so on.

If two or more users can be active in the environment at the same time, then much more is involved due to the fact that the game links users through high-speed network connections and user interactions are a part of the environment. The actions of all users must be taken into account for every frame. Even if there are only two users, either of them could move an object or collide with something, meaning that the position of objects and players cannot be known from just the conditions on any one of the computers. Messages are sent many times each second to relay updates to the virtual environment (server) caused by the actions of the many users (clients).

In summary, a VR environment is a dynamic, simulated environment that can be shared between users. Users often have a representation (avatar) within this environment and can manipulate objects as well as communicate with other participants through it. The simulated or virtual environment is represented in three dimensions and can have high-quality positional sound. The technologies available for providing input to these senses are briefly described so that the potential for future work in the area can be better understood.

4.1 Computer graphics: visual input

Of the technologies involved in VR, graphics are the most mature because they have been useful for many other aspects of computing. Scientific visualization was an early application of computer graphics, and drawing graphs of data was perhaps one of the first. VR applications require 3D graphics; this is the rendering, on a flat screen, of 3D objects as seen from a particular position in space. While it is true that computers have been doing this since the 1960s, it is only relatively recently that there has been the technology for drawing 3D scenes in real time.

Displaying a succession of images very quickly creates the illusion of motion such as that commonly seen in motion pictures and television. The frame rate is the number of images drawn each second. Movies have a frame rate of 24, television almost 30. The reason that movies look better than television is that the *resolution* and *quantization* are better; resolution is the number of discrete picture elements (or *pixels*) being displayed, and quantization is the number of colours or grey levels that can be displayed. All of these factors combine to define the complexity of the image. For instance, the cinematic image of 6 million pixels, each having 16 million possible colours at 24 frames per second, multiplies out to an amazing 6.9 gigabytes (thousand million bytes) sent to the screen each second. A slow computer could not accomplish this, which explains the need for modern 2-GHz computers.

Most consumers underestimate the technology that has been designed into a typical PC graphics card. They are designed to support modern computer games that operate at 60 frames per second and faster. The graphics card supports many drawing functions needed by software so that the PC does not have to dedicate processor power to drawing images. Thus, polygons, textures, stencils, distance maps and many other graphics algorithms that were coded once as software are now built into a U.S. $300 accessory card.

The graphics sub-system of the VR engine must construct a view of the world as seen from the user's perspective in that world, in colour and using the illumination specified, for each frame. This means a complete rendering every 1/24 seconds, or about every 42 milliseconds. Static VR environments are often based on a CAVE [22] model in which the user is surrounded by large, high-resolution screens that are usually projected from behind. A special input device that looks like a wand can change the apparent position and orientation of the user within the virtual space, and can also be used to select objects and manipulate them. This device is mouse-like and usually wireless.

When working with athletes, the geometry of the graphical presentation must be accurate. Many times, a judgment is made based on the apparent speed and relative position of the subject. In a baseball simulation, for instance, the velocity of the ball must not appear to change after the pitch is made, and the trajectory must be realistic. In order for these things to be true, there must be an accurate model of the physics of the real world underlying the graphics software.

A basic 3D graphics environment can be created on a typical home computer using LCD shutter glasses that allow the user to see left- and right-eye full colour images alternately on the computer screen. The effect is compelling, and the set-up is very inexpensive, usually under U.S. $100.

4.2 Audio in virtual reality

Much of the strong emotional impact provided by a modern VR system is generated by the audio components. Sound is a key indicator of motion, activity and effective content. A key aspect of sound is that it can be both heard and *felt*, especially at the very low frequencies. This gives an extra sensory channel, and one that is visceral – the ancient part of the human brain still associates these low frequencies with predators big enough to be a threat, and fear is one natural response. An eye-opening (or ear-opening) demonstration is to play a popular action game, first with the sound on, then with it off. It is amazing how much of the energy and emotional content is contained in the audio part of a game.

Computer games and VR systems use sound in three basic ways [23]:

1. *Music*: A great deal of emotional content is contained in the music alone. Motion picture directors know this well.
2. *Sound effects*: This includes ambient sound. If a car crashes or if a gun fires, it is expected that it would be heard. One should also expect to hear surrounding noises such as of running water, surf and wind.
3. *Speech*: Many games tell a story by allowing the user to listen to conversations, or even participate. In computer games, the user side of the narrative is often entered using the keyboard because currently computers are not very efficient at speech recognition and are even worse at speech understanding. The characters in the game speak and expect to be heard.

It is also expected that sounds will reflect the environment. Echoes are anticipated in large buildings, for instance, but not in the woods. Sounds should also appear to originate from particular points in space, especially if the source of the sound can be seen. All of these characteristics of sounds must be represented in virtual environments if they are expected to be convincing representations of real environments.

4.2.1 Computer audio and implementations

It is interesting that many programmers, even those with many years of experience and who know graphics and event-based programming, know almost nothing about how to manipulate and play sounds on a computer, and know even less about what a modern sound card can do. It is especially interesting because sound programming is, in many ways, much like graphics programming: the goal is to display something. There are object and character positions to be considered and rendering to be done, the listener's (viewer's) position affects the result, there are colours (frequencies) to be handled, and a special device is at the heart of everything (sound card/video card).

Most games and VR applications merely read sounds from files and play them at an appropriate moment [24]. These systems would be very dull indeed if the approach to graphics was the same. Graphical objects need to be moved, rotated, transformed and tested for visibility and collisions. Audio objects basically turn on and off, get louder or softer, and perhaps move from the left to the right stereo channel.

It is very valuable to stay a logical distance from the actual audio device, software is needed that will handle the sound card while providing a relatively simple interface that provides a high-level view and that works on multiple platforms. The *OpenAL* platform seems to fit the bill and will be used as an example wherever a specific one is needed [25].

4.2.2 Real-time audio synthesis

In the real world, very few events create exactly the same sound twice. Every bounce of a basketball sounds just a bit different from the previous one, and a slap shot from the blue line has a sound that varies depending on the stick, player, swing, ice temperature and precise distance from the net. Because the traditional way to use sound in a VR system is to play a recorded file, a user of the system will quickly become familiar with the files that are available. Also, the sounds may not be correct relative to the situation.

A solution to the problem involves the real-time synthesis of sounds from either examples, or from first principles. Creating sounds from first principles means using a knowledge of physics to determine what sound would be produced by, for example, a poplar-wood stick 6-foot long with a 9-inch blade striking a hard rubber puck at 2 °C with a velocity of 35 mph. This is quite difficult to do even if the correct parameters are known, so it is better to generate sound files using this method offline and use them for synthesis by example.

Creating sounds from examples is based on having a set of sounds that represents an event, and then breaking the sounds into a great many small parts that are called *particles*. The particles are reorganized into a new sequence, one that does not repeat for a very long time and yet has the basic audio properties of the original. Using this family of methods, it is possible to create hours of sound *texture* data from only a few minutes of real sound samples [26].

Sound effects such as gunshots and impact sounds are a bit more difficult to create in this way, but it is still possible. An *effect* is a short sound having a beginning, middle and end. There is essentially an envelope enclosing the audio data, rather like a modulation envelope [27]. This envelope can be extracted from captured samples of the real sounds and then synthesized as before, but while imposing the beginning, middle or end envelope structure, depending on where the samples are being placed.

Sound synthesis results in a more realistic audio presentation because unnatural repetition is eliminated. Unless a very large set of audio data is available, synthesis may be the only way to display realistic sounds for VR purposes.

4.2.3 Surround sound and 5.1-channel audio

The term *surround sound* refers to the use of multiple recorded sound tracks, each corresponding to a real speaker. The speakers are placed in front, at the sides and behind the audience, making them feel as if they are not just watching the action from the front, but are actually in the middle of it. One key feature of surround sound is that it can be used to accurately implement positional audio, where sounds appear to come from a particular location in space. Two speakers cannot do this properly because there will always be two places from where the sound could be coming, one in front of the listener and one behind. Five properly positioned speakers solve this problem. Correct positional audio is essential to a good VR experience. Most real sounds appear to have a specific source, and in some cases this is critically important. For example, when driving a car, it is necessary to identify sources of sirens and honks in cases of emergency.

The '.1' in 5.1-channel audio is a special low-frequency channel dedicated to the sub-woofer. Sounds at the frequencies allocated to this channel are too low for human ears to locate in space, but add a special effective component to the display. This audio channel is dedicated completely to textures (non-specific sounds) that one feels as much as hears. These sounds can be isolated and extracted from a well-recorded sound track using digital frequency filters. Most often, they are recorded separately and added after all of the other tracks are completed [28].

4.2.4 Audio rendering

In a virtual environment, all the objects are stored in the computer as data and are drawn on the screen as they come into view. The action of transforming a 3D model into an accurate image on the screen is called *rendering*, and is a highly technical activity that must be performed in real time. Real time in this case means quickly enough so that one cannot see the screen flicker, usually 24 times a second of better. Sound can be rendered as well, providing a correct sounding version of what is happening at any point in time from the perspective of the user [24]. In the case of sound, one can hear frequencies up to 16,000 Hz, and so regularly occurring artefacts or gaps at almost any rate will be heard. Usually, when audio is rendered in real time, the position of the sound-creating objects is used to generate a wavefront that is sampled at the point in space where the user or player appears to be in the environment. Multiple wavefronts are created and summed to create the overall effect, and then the sound is apportioned to the discrete channels. This is done for a discrete period during which the objects appear not to change position, just as in the graphics rendering [29].

The process just described would correspond to a method known as *ray tracing*. Using ray tracing, it is possible to compute wavefronts from direct transmission and after multiple reflections from objects in the environment. It is a very accurate way to render but usually takes a lot of computer power. Another method, known as *radiosity*, involves computing a wavefront caused by the exchange of energy between sources and surfaces in the scene. For graphics, this can be very expensive; for sound, it is sometimes a fair approximation to assume that any object will reflect a variation of the sound emitted by each source after a short delay. In audio rendering, the speed of sound is very relevant, whereas in graphics the speed of light does not enter into the calculations. The delay associated with each object is the time needed for the sound to get there from the source and then travel to the recipient. This model can be computed in real time, and is accurate enough for current technology, but is obviously not perfect.

Audio is a somewhat neglected part of VR, and is a backwater in research areas. It is receiving more attention lately, partly because of the impact good sound has in computer game applications. There are a number of promising areas of research, including synthesis and rendering.

4.3 Haptics and other sensory input

Returning for a moment to the baseball example: the subject, surrounded by large high-resolution graphics screens and 24-channel sound, sees the pitcher wind up and deliver a 100 mph fastball. The subject swings and hits, knocking the ball into far left field. Everyone present can hear the crack of the impact and see the ball fly towards the fence. However, for the user, if the impact of the ball on the bat cannot be felt, then a key aspect of the experience is missing.

Haptics is about creating a feeling of touch [30], but there are really two aspects to this. As just described, the basic impacts, pushes and pulls associated with object manipulation must be conveyed, and with realistic forces. Sliding a coffee cup across a table should require about 300 g of force, not 10 or 5000. It is this sense that allows the remote manipulation of objects. Considerable research is now being conducted in the area of remote control surgery sometimes referred to as telesurgery [31]. However, without a very accurate sense of force being fed back to the surgeon, it will not work.

The other aspect is touch and texture. Most people can slide a finger across a surface and tell a lot about it: whether it is sticky, smooth or bumpy. Even the size of bumps can be detected. These data are used for many control tasks, including grasping and catching.

As a general rule, the two aspects of haptics are implemented in different ways. Impacts and return pressure are usually imparted by a motor or solenoid. These can be small, and placed in multiple locations in clothing, tools and manipulators. Generally, texture is more difficult to create than force, and the required devices are complex. Often, there are touch transmitters placed in gloves worn by the subjects, and these impart multiple small touch sensations to the user's hands in a way that was specified by touch sensors at some remote site. Touch can be enhanced by sound; a rough surface like sandpaper has a characteristic sound when scraped, and hearing this is an important part of the experience.

As complex as haptics seems to be, smell may be as difficult. The human sense of smell is not very good when compared to that of some other animals, but it can detect very small number of molecules of certain chemicals and so is sensitive on some absolute scale. Smell is, in fact, a chemical sense, and the problem of remotely detecting the smell at a remote location is as complex as that of reproducing it for the user. In humans, smell is connected closely with emotion, and is, therefore, key to an effective sense of presence [32, 33].

There have been smell creation devices, but these have been based on what could be called *iconic odour*. The idea is to specify an odour by name, rather than by components. The smell *smoke*, for example, is one that could be generated. This would be as if colours were to be specified to the graphics system by name: draw *pink*, then *violet*. The problem is that any smell not *iconified* could not be produced; each smell has a specific chemical canister that issues the odour. It has been suggested that as many (or few) as 400,000 distinct odours exist [34] less than the number of colours that can be built from 24-bit representations now in use. It is not yet known whether scents can be constructed from a few basic components, as in red, green, blue (RGB) colour, or whether these can be simply generated and detected.

VR started by allowing a real environment to be viewed and manipulated, but now it is more common to model and view hypothetical worlds. The technology required to do this is complex, and involves distinct methods for each human sense. Typically, graphics are used for the visual sense, and audio for the sense of hearing. Haptic, or touch, technology is less advanced, and smell even less so. Taste has not really been attempted.

Important to sport technology are two other senses that are generally not included: balance and proprioception, and the technology, in each case, is either very expensive or non-existent.

4.4 Kinetic interfaces: a coaching revolution

Kinetic interaction is the use of physical motion of a human being to control the actions of a computer without touching a communication device such as a keyboard or mouse. A *kinetic video game* could be defined as a game that uses a computer to mediate game play, and that has, as a critical aspect of its interface, the input of information concerning the overall physical activity of the player. Activity is the movement of body parts that are interpreted by the computer to have specified meanings, but not motions that specifically manipulate computer input devices (keyboard, mouse, etc.).

In sport and exercise activities, motions have a specific and normal purpose: to hit a ball, to avoid being struck, to work a specific muscle group, or sometimes simply a scripted motion, as in Tai Chi. An interface to a game (or any software) is *natural* if the same motion used in the real-world situation is recognized and used by the interface, and means the same thing to the game. A *non-natural* interface causes an interruption in the *flow* of the activity being performed [35], and this often results in a splitting of attention that is not productive or amenable to the effective completion of the task being performed [6].

Natural game interfaces that effectively use human motions are not common because they must either use special devices or rely on a camera and computer-vision technology. While computer vision is usable for specific tasks in restricted domains, it cannot be used in general to detect human pose reliably or to identify human activities [36]. Vision methods are computationally intensive and do not work very well in real-time situations such as games.

The implication is that a game that needs to examine the activity and position of a player should arrange the situation so that it implicitly eliminates most of the ambiguity that is usual in vision methods. Games do this as a normal matter of course; they are built to give the impression that many more choices are possible than those, in fact, available. The other option is to develop special sensors to be used in this context. This track would be more expensive, so it may be necessary to develop new ways to use cheap, existing sensors in the game environment.

A good example of both methods, the use of an inexpensive vision device and the restriction of the game play to a simple range, is the Sony EyeToy and the games that effectively use this device. These games use a small set of very simple vision algorithms and a quite inexpensive vision input device, a web camera. The simple vision methods work sufficiently well because the task they are asked to perform is trivial – they do not have to recognize objects, but simply determine where in the image motion is taking place. Still, many of these games are seen as entertaining for some people for limited periods of time. It is naturally more difficult to extend the duration of interest and the general usefulness of the technology.

A major goal of developers is to improve the current technology associated with kinetic games and to develop more effective devices and software while keeping the cost down. The object is to provide ways to measure motion in many forms so that it can be made a key aspect of games. Aside from the potential for development of sport-related activities, the technology can be used to improve fitness in the game-playing population by providing an alternative to the existing sedentary games, adding more interesting and natural ways to communicate with games and other forms of simulation software.

There are currently a few dozen commercially available games that qualify as being kinetic games. There are thousands of video games in all, so a few dozen is a very small fraction of the total. It might be useful to examine some of these games to understand the kind of activity they can provide and to observe the nature of the interfaces currently available. This discussion is intended to illustrate the technology and to show a direction for games and VR objects in the near future.

4.4.1 Dance Dance Revolution

Dance Dance Revolution (DDR) is almost certainly the most successful example of a kinetic game, and of one that is used specifically for exercise by some. It was designed for the PlayStation, but a version runs on the PC. Indeed, there are clones of this game produced by various publishers on most platforms. Deborah Lieberman refers to it as the most studied serious game [37], but in spite of that there is relatively little known about how effective this game is in providing an aerobic experience.

The game is based on dancing. Dance steps are displayed on the screen while music plays, and the player is supposed to imitate the steps in time. The accuracy with which the player reproduces the choreographed dance steps is reflected in their score. The use of the phrase dance *steps* is for a specific purpose – only the steps are recorded, not any other motions by other body parts, because the steps are recorded by a special pressure-sensitive pad on which the player dances (see Figure 5).

The word ‘accuracy’ means ‘a timed coincidence of the specified step with the player’s physical step’. In all computer-mediated games, winning or achieving a high score is accomplished by satisfying the designer’s conditions, whatever they may be, and in this case synchrony is the main one. Tempo is up to the player, although music that is thought to be ‘hard’ yields more possible points. Music is the key to dance, and the game players are allowed a selection of music to which to dance, thus permitting a choice of tempo and difficulty.

Players of this game and similar ones tend to be young, and play an average of between 4 (arcade) and 7 hours each week. Assuming that DDR provides a significant level of physical activity, this means that it provides between 35 and

Figure 5: DDR input device (dance pad).

60 minutes of physical activity per day, enough to remain fit. Unlike most video games, this game appeals to both male and female players almost equally. It can be played at home, where it can be thought of as practice or a party game, and in arcades where it is a social activity. It is starting to be played at schools as an option in physical education classes.

The term *exergame* has been coined to describe games that have an interface intended to provide exercise or some degree of fitness advantage, or which generally involves physical activity and/or motion. The effectiveness of these games for fitness applications has been the subject of surprisingly little effort, and they each need to be compared against known exercise activities and exciting multimedia efforts such as videos. It would appear on first glance that DDR would provide a pretty good aerobic workout. In addition, video games tend to be intrinsically motivating [10, 38] to a particular target audience and this would suggest that players would voluntarily participate to an extent not usually seen in exercise activities. In some studies, it has been shown that using DDR raises heart rates to the level shown to be effective to meet the standards for aerobic fitness [39–41].

4.4.2 Other dance games

ParaParaParadise is a dance game that depends on arm motions, detected by overhead sensors. The term 'para para' is a reference to a Japanese structured dance, something like line dancing, which has not achieved a huge following outside of Asia.

Pump It Up is again quite similar to DDR, but some versions have the ability to measure hand/arm movements too.

In the Groove is the game so similar to DDR that there is now a lawsuit under way, and the *In the Groove* series could suffer significantly or even disappear as a result. *In the Groove* has been used in a few classrooms in the United States to some apparent advantage.

4.4.3 Other kinetic games

Samba de Amigo is an activity game played with a pair of maracas. As music plays, the players must shake the maracas to the beat, and in one of the three positions, they must shake the maracas to give an impression of a dance while playing.

EyeToy: *Groove* is essentially yet another dancing game, but the input device is now a camera. The player's image is projected into the video display that also displays faces and hot spots (see Figure 6). Touching these with projected hands results in a hit, and these must be timed according to the game and the music.

Operation Spy (a.k.a. *SpyToy*) is an interesting entry in the kinetic area, since it is not music or dance based. It is a collection of spy-themed games, each requiring a set of simple motions that are detected by the EyeToy camera.

EyeToy: *AntiGrav* is a sport game based on a fictional device – the hoverboard from the Back to the Future movies. In this game, the EyeToy camera tracks the user's face and does some colour tracking. When the user lean left, the board turns left. The game vision system recognizes jumps, steering moves, ducks and other body moves that make this game a good example of a natural interface (but not a perfect one by any means). It also hints at a true-distance multiplayer capability.

Figure 6: EyeToy: Groove captures a player's image and uses it as input.

Yourself! Fitness gives players the chance to lose weight instead of battling spies, soldiers or aliens. This game is currently being developed for the Xbox and is aimed at the female market. It features an artificially intelligent personal trainer, a feature whose efficacy remains to be seen. A real fear is that the AI will not live up to expectations in much the same way VR in the 1980s did not met expectations. There are at least two-dozen further titles that would qualify as kinetic, but almost all are variations on the themes described above.

4.4.4 Other input devices

Kilowatt SPORT is game controller that forces the player to overcome a pre-defined resistance to achieve a motion in a game. It can be adapted to many video games, including consoles. It is not what most would think of as a normal way to control a game, but it certainly involves physical activity and the game is a motivating influence. It can be adjusted to become more difficult as the user's buff level improves.

Eloton SimCycle is not a game so much as a device. It is possible to link the SimCycle Gamebox device to a PC and use it to control PC games. For example, it is a simple matter to have the speed at which the user is cycling directly related to the speed of the user's car in a PC driving game, such as Need for Speed. It is not really a natural interface, but it appears to be effective. It is also possible to use the SimCycle by itself with the exercise videos that come with it (see also the arcade game *Propcycle*).

Figure 7: Playing American football with the Wii.

Wii – is Nintendo's recent release. It has added a new dimension to console video game controllers and gaming interfaces through specialized signal-processing technology and motion sensing. Wii Controllers use multi-axis linear acceleration-sensing devices (ADXL330) developed by Analog Devices Inc. The ADXL330's three-axis motion signal processing allows the performer's body motion to control his or her actions in the game in real time. The ADXL330 is used to sense the motion of the game player in three dimensions of freedom: forward–backward, left–right and up–down. When the new controller is picked up and manipulated, it provides a quick and effective interaction with the system, sensing motion, depth and positioning dictated by the acceleration of the controller itself. Initial experiences with the Wii Console suggest it is relatively intuitive and realistic (see Figure 7). It appears to have fully 3D position-sensing capabilities and incorporates full multi-directional tilt functionality. A number of very interactive sports games are available for use with the system (see 'Wii have a problem' later in this chapter).

4.5 Basic kinetic game technology

Someone playing a kinetic game generally cannot use a keyboard or a mouse because he/she needs to constantly move around. There is also a little place for a story or narrative in such a game; the activity takes its place, in a manner similar to that of many driving games in that the activity and response of the player are key components, and there is little in the way of goals except to perform well physically. The obvious implication is that a key difference between kinetic games and others is in the interface. Because kinetic games depend on the motion of the player, the game interface must effectively measure some aspect of that motion. New and non-invasive devices must be used, devices that pay attention to the player rather than the other way around. Most of the time kinetic games use either contact-sensing game pads on the floor or a camera/vision interface.

4.5.1 Game pads/step pads

A game pad is really a large keyboard with fewer keys that lie on the floor and is operated by feet. Usually, there are between 4 and 12 ‘keys’, each one being a rugged contact switch. Pressing a key sends a code along an interface to the game system, like pressing a button on a standard game controller.

Games that use these devices involve dance, and dancing requires that specific keys be pressed by the player’s feet at specific moments. The game pad is meant to be used to match a pattern of steps stored within the game. If the player’s pattern matches the computer’s, then the score is high. Ideally the player does not walk around the pad, but jumps, pressing the correct pad keys while staying roughly in the middle of it. There is, of course, music playing, and visual inputs and feedback on the graphics screen.

Since there are only a few keys to be pressed and the graphics are simple, this is an ideal kind of game to be played in groups across a network. Very little information needs to be transmitted across the net, meaning that latency (time delay) can be minimized. In fact, the music does not need to be synchronized in a global sense, but just has to be locked to a timing channel. Player motions can be measured with respect to that local track, so the music playback can be done by the player’s computer from a local disk file, placing very limited demands on the network while still playing with multiple partners.

4.5.2 The Sony EyeToy

This is an inexpensive webcam that has been adapted for use as a game input device. To be specific, it’s a Logitech OmniVision OV519 CMOS image sensor with a USB interface. The EyeToy also has a microphone attached, and a red LED that flashes when there is not enough light for the camera to be effective. This is a good idea, but it seems to flash too much, meaning that it needs more light too often. The camera yields a standard webcam resolution of 640×480 colour pixels.

Computer vision is an intensive mathematical problem. Vision algorithms are usually implemented in software, and tend to be computationally complex (i.e. they take a lot of time) partly because they operate on pixels – picture elements. A computer image consists of a grid of coloured dots called pixels, and there are a lot of those in an EyeToy image (307,200 pixels, or 921,600 bytes; 3 bytes per colour). Unlike graphics, which is a relatively mature technology well advanced and well understood, vision has yet to demonstrate a robust, reliable solution to any of its major problems. Thus, most solutions that could work on a PlayStation or Gamecube in real time would be simple cases and and/or unreliable. This seems to be true of many EyeToy games at the present moment.

For instance, a simple vision operation is to determine the difference between two images. This is the basis of much of the EyeToy vision technology. If one assumes that the background does not move (the camera is fixed), then it is presumed that the moving object is the player. A moving object results in pixel level changes between two frames. Subtracting the corresponding pixels in two consecutive images results in a clear indication of where the player is moving (Figure 2). Background pixels become zero (or close to it) and the pixels that remain can be assumed to belong to the player. This can be done between each two consecutive frames (captured images) in a sequence to determine where a player is moving. If the player can be seen to be moving beneath the displayed icons on the screen, the action corresponding to those icons should be performed. This is the basis of the EyeToy interface.

It's also a simple matter to identify areas in an image that correspond to a particular colour. If, for example, the player wears a red tag on his or her left arm and a green one on right arm, it is simple enough to track the coloured regions between frames and determine if the player is leaning left, or right, or is crouching or jumping. The trick in using vision methods in a game is to know what methods are reliable, fast, and easy to implement and to find a way to use them in the game design [25].

4.6 Proposed technology

A major goal of development work in sport VR is to increase the character and quality of games that use kinetic interfaces, which should increase the overall activity level of players, and to improve the general fitness level and lower obesity rates of young game players. Game play can be made into a healthy form of exercise. Of course, the potential for using the systems to study and enhance the performance of athletes, both novice and elite, is also possible.

To further the main goals, it is necessary to develop some more kinetic interfaces so that they can be used in new game designs. A very useful feature of new interface technology is the ability to retrofit it to existing games. If players can use the games that they already own and enjoy, they are more likely to use the new technology and designs. Identifying kinetic game design principles would be a good idea too.

Finally, but probably most important, it is necessary to establish that the games actually serve a useful purpose in improving fitness, reducing obesity, raising health levels in the target population and enhancing performance. With these things in mind, we should first look at some potential new sensor technologies that could be used effectively in exercise games.

4.6.1 Pressure sensors

A computer keyboard, a mouse and the DDR dance pad are all various kinds of pressure sensors. In all cases, an impact on a specific part of the sensor is recognized and coded for transmission to a computer (e.g. a character code is sent). In most cases, the result is either on or off; the sensor does not detect a degree of pressure, only that contact was made. They are just simple switches.

The degree of pressure can be measured using any number of current technologies such as capacitance, piezoelectricity and inductance. The most practical sensor for this purpose is piezoelectric in which there is an electrical charge generated by a polyvinylidene fluoride film when it is stressed by an impact, being bent, squeezed or struck. The magnitude of the voltage created increases in proportion to the amount of pressure or bending. This voltage is sampled and converted into a numerical pressure measurement (pounds or pascals) by a computer [24].

These sensors can be cut with scissors and placed inside of a shoe [27]. The films are thin enough so that this will cause no discomfort. Now the pressure pattern of the foot can be used directly as computer input. If there is no pressure, then the foot is in the air. The time between consecutive contacts with the floor gives a fair measure of how fast the wearer would be moving. The pattern of pressure during contact says something about the nature of the contact. The DDR can be played without a dance pad, for example, jumping onto a left foot or right creates a distinctive pressure pattern that can be detected by a computer. The entire grid of pressures is sent to a PC, and a pattern recognition algorithm is used to match the pattern against those for that player that were used for training. Position of the foot and simple gait information can be determined in this way.

These in-shoe systems are being used at the present time as orthotic calibration devices. They are used in medical applications for such things as diabetes screening, monitoring the results of surgery, fitting orthotic devices and even for the analysis of athletic performance and for shoe design [42]. Thus, it is possible to purchase this equipment off the shelf and adapt it to the new purpose. An example is the F-Scan system [23] sold by Tekscan, Inc. It has a 60×21 grid of sensors (about four sensors per square centimetre). The number of sensors required for effective use will depend upon the nature of the application (frequency of sampling, accuracy of the data, duration of activity).

4.6.2 Accelerometers

An accelerometer measures changes in velocity. The most well-known use of these devices is for automobile airbag deployment, but these are also commonly used for inertial navigation, condition (wear) sensing for machines (i.e. vibration sensing) and even tilt detection. In the current context, they can be thought of as motion detectors.

Accelerometers detect accelerations in a particular direction, or axis, usually by detecting the force that the acceleration applies to the sensing element. To detect motion in an arbitrary direction, each of the three accelerometers are placed each at right angles to the others so that motion in any direction will create a detectable force on at least one of the devices at all times. This is called a three-axis accelerometer and can be obtained as a unit. The ADXL330, a device currently used in the Wii, is an example of a three-axis accelerometer that can be purchased very inexpensively.

If one of these units were placed on each hand and each foot, and perhaps some on the torso and head, it would allow the overall motion of a person to be measured. The system could distinguish between arm motions and foot motions, detect general gaze direction and give an overall degree of effort by integrating over all of the sensors. It is possible to play a variety of games including even soccer. A variety of physiological parameters could also be measured (e.g. calories burned). The use of these devices to measure the overall motion of a participant could facilitate development of novel applications.

A key application of accelerometers is estimating the player's position and orientation by dead reckoning. This information can be fed back to the system so that the graphics can be updated to display the view of the virtual world from the player's position. This is currently available to users of virtual reality goggles (also called head-mounted displays, or HMDs), but is not commonly used for screen displays.

4.6.3 Ultrasonic audio

Ultrasonic sounds are those that are higher pitched than humans can detect. Bats, dolphins and submarines use ultrasonic systems as position sensors (SONAR). It is also used for home security motion detectors. Potentially, it could be used with virtual environments. For example, an ultrasonic 'beep' that would be emitted by the participant could be detected through the use of three or more receivers placed in diverse parts of the environment. The time of the reception will differ as a function of the distance of the player from the receiver, and this places the user at a single unique position in the activity space. In other words, the system can tell where the user is at all times [9, 11]. Multiple players in the same room can be dealt with by using different frequencies for each player, or by using coded pulses.

Sonic positioning has also been used successfully for determining the position of individual limbs and general body pose, for dance applications as an example.

4.6.4 GPS and RF positioning

Global positioning system (GPS) uses radio signals sent from satellites to determine a position on the surface of the Earth. The method depends on having multiple satellites within range at the same time, and uses a very accurate clock to identify tiny time differences between the known satellite position and the receiver on the ground. Spatial resolution is too low for practical games, but can be increased by using multiple receivers at the same time (differential GPS). It is possible to build a virtual space with positional audio that uses a player's real position in 3D.

The signals sent by the GPS satellites are too weak to penetrate buildings. If the playing area is outside, then differential GPS can be used to perform the same tasks as ultrasonic positioning. Virtual track and field events are possible, for example, again with networked participants and audience [17]. Otherwise, there are radio frequency systems that can be used indoors [29].

4.6.5 Vision technology

A functioning vision interface that works reliably on a specific task is important. Participants expect intelligence from games and computer environments, and intelligence in this context implies vision and speech. The difficulty with vision is related to 3D concerns. Inferring depth from 2D views is hard, even with two cameras. Recognizing objects in any orientation is, likewise, difficult.

Avoiding the hard vision problems is a key to workable vision-based interfaces (see Figure 8). In current vision-oriented games, the player's image is captured in 2D by a camera in a fixed position. It is then superimposed on the game image.

Figure 8: Simple vision algorithms, in this case subtraction of two frames, are often good enough for VR and game technology. Two consecutive frames from a video. (Right) The bottom frame subtracted from the top (current) frame; this image has pixels that belong to the moving (varying) parts of the player and that are in the current frame as darker than the past frame pixel and the background. Taken from Vaclav Hlavac, Image Motion, http://cmp.felk.cvut.cz/.

The player tries to move body parts according to a plan defined by the game. The game defines these motions according to what is easy to implement, as opposed to what is interesting or challenging. So, effective hockey or soccer simulations involving a superimposition of one's 3D personage in a virtual court is still to come some time in the future. However, punching a virtual opponent in a 2D boxing match is much more likely, the latter being possible to implement in real time.

Another option is to permit the recognition of certain types of objects that are easy for the system to recognize. A ball, for instance, being the only circular moving object (of a fixed bright green colour, perhaps) is easy to recognize and to follow. Another option is to have the player manipulate small targets that are patterns, like bar codes, printed on an object card.

4.7 Retrofitting

It is possible to retrofit sensors to existing games. Consider a game such as *Half-Life*, a first-person shooter (FPS) game that requires a lot of running through dark tunnels. A pair of in-shoe pressure sensors as described above could be connected by wireless data link to a PC that would convert the signal into a character sequence. Left/right pressures and inter-step times would determine how fast the player was running and sonic sensors or accelerometers could determine orientation, or the direction in which the player was headed. Now, a game that previously used the keyboard and mouse can be used as a kinetic game.

Some massively multiplayer online role-playing games MMORPGs involve 'running' from place to place in the virtual world. The virtual running can now be converted into actual running. Changing the orientation of the player's body can change the direction of the running. The player is now playing with his or her friends by natural movement of the body.

From this discussion, it would appear that existing kinetic game technologies could be harnessed to:

- Research performance-related issues,
- Development of systems for training athletes in meaningful situations,
- Introduction of physical activity into video games,
- Building of simple VR environments, and
- Collection of relevant data to enhance performance.

5 VR environments designed for sports

For sport applications, VR programs tend to focus on training of physical skills. However, another potentially powerful area of exploration is the visualization of performance to develop cognitive awareness and psychological preparedness. While VR environments can use single screen or stereo systems, many of the new VR centres are transitioning to 3D immersive environments with three or four screens (VR caves). This is especially true in industry where the focus is on digital prototyping, design reviews, human factor studies, training simulators and process simulation. However, it should be possible to take advantage of these 3D centres to develop innovative sport applications that could also be rendered for single-screen portable computers allowing broader distribution.

In this section, a number of examples of VR environments designed for sport will be discussed, including a simulation of a bobsled run, a hockey goaltending simulation, a virtual environment for visualization in speed skating and a golf simulation for improving shots and choosing golf clubs.

5.1 Bobsled simulation

At the University of Calgary, iCentre (3D visualization cave), a prototype VR simulation, has been developed for training bobsled drivers. To be effective, the physical environment has to be well understood and the physics have to be accurately applied to the virtual environment. Training to be a bobsled driver takes considerable time, and because of logistical considerations, there are a limited number of practice runs available to the drivers. Typically, the drivers have to memorize the run and react effectively at high speeds to 'hit' the turns at the right point. Accidents are common and sometimes very dangerous, especially with novice drivers or with early runs on new courses. The 2010 Olympic Winter Games will be held in Vancouver, Canada, and the bobsled course has not yet been built, but the architectural work has already been done, so it is possible to build a virtual course based on the available data.

In the previous research conducted at the University of California, Davis demonstrated that simulators could accurately reproduce the motion of a bobsled down an Olympic track. In recreating the driver's experience, a display fixed to rotating pod was used to simulate a run down a track. The mathematical model used to determine the speed and location of the sled considered mass, gravity, friction, air-density lift, drag and the shape of the sled [43, 44].

At the University of Calgary, research on the development of the simulator for use in the CAVE environment began with discussions involving the bobsled coaching staff with regard to various considerations including the value to them of using a VR model. Other issues included the need for realism in physical feedback (e.g. sound, vibration, rotation, g-force), the level of interactivity (e.g. user control and response), biophysical parameters to be recorded (e.g. pulse rate) and multiple-point visualization. It became clear that it would be very difficult to emulate the actual physical experience, especially the g-forces. So, the focus was oriented to developing an accurate visualization of the course itself and the bobsled's movement down the course from the perspective of the driver. To be effective, calibration of the model entailed the correct physics. To accurately reflect the path, speed and movement of the bobsled, it was necessary to understand that the motion of the bobsled would be a function of drag, lift, frontal area, air density, sled mass, gravity, surface friction, and the temperature and density of the ice. Using Virtools to run the Havoc physics engine (www.virtools.com), a prototype was developed that simulated the physics of the bobsled. The initial test that was conducted at the Canadian Olympic Development Centre (CODA) training facility in Calgary involved the comparison of a virtual sled (see Figure 9)

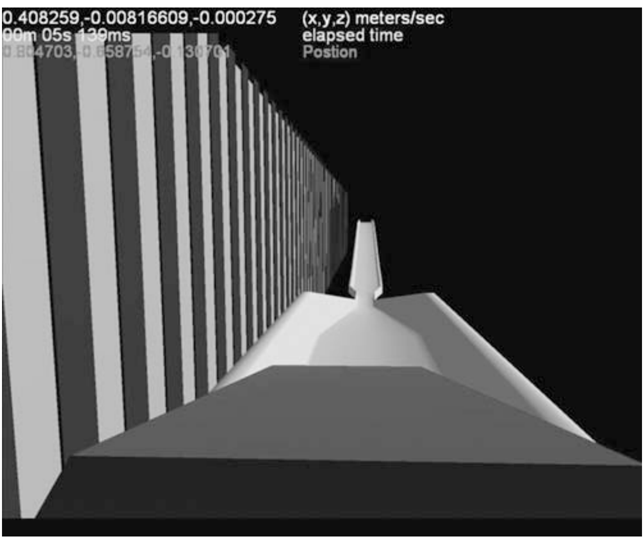

Figure 9: Test sled (CODA).

against the behaviour of a test sled with known properties (see Figure 10). The initial model considered mass, gravity and sliding coefficient of friction and provided a good approximation of the behaviour of the actual sled (see Figure 11).

In developing the prototype, consultations were held with a number of bobsled drivers and coaches. Feedback on the working prototype of the virtual

Figure 10: Virtual test sled.

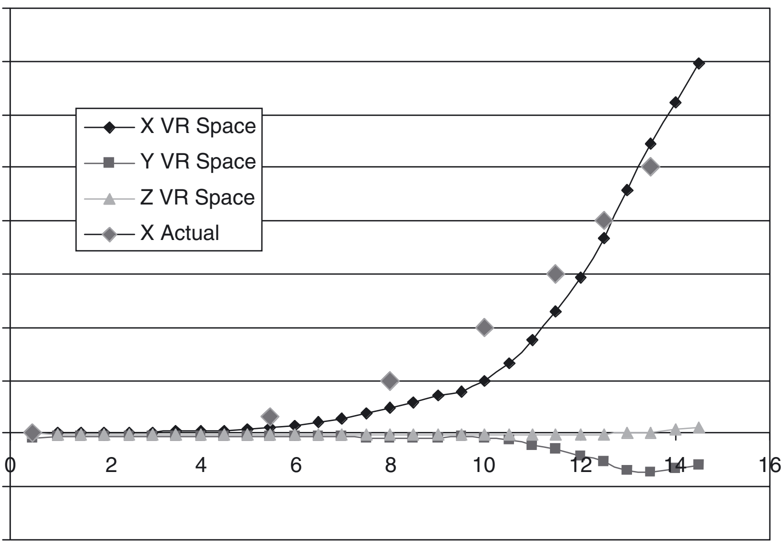

Figure 11: Comparison of simulation and actual distance time parameters.

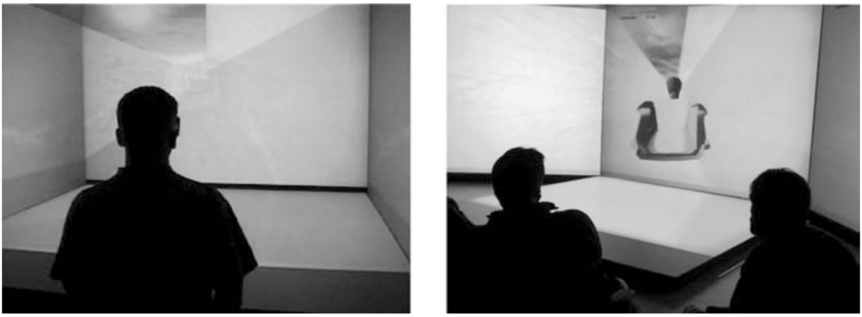

Figure 12: Test simulator iCentre CAVE without and with Avatar.

bobsled developed for the iCentre CAVE has revealed the importance of creating an immersive experience that can be shared by both driver and coach (Figure 12). One aspect of the CAVE environment critical to recreating the experience will be the use of 3D stereo projection. Having a sense of depth perception provides the pilot with an opportunity to learn the turns of a new track within the confines of a safe environment. In the next phase of this research, engineering CAD data for the Vancouver 2010 course will be used to evaluate the effectiveness of the virtual setting as a potential practice environment. If the virtual course accurately represents the geometry of the 2010 course currently under construction, it should be possible to test the ability of drivers to learn the course prior to an actual run. One goal of this research is to test the effectiveness of simulators as tools that coaches can use to acclimatize inexperienced pilots to the sensation of high-speed cornering and acceleration. It should also be possible for the drivers to practice turning and visualizing their actions together with the team psychologists. It is hoped that the drivers could improve both their RTs and psychological preparedness for the actual event.

5.2 Hockey goaltender simulation

Using a single-screen 3D environment, with recorded video of hockey shots, researchers at the Sport Technology Research Laboratory, University of Calgary, are using visualization to study hockey goaltenders and their reaction to hockey shots.

A variety of hockey shots (slap, wrist, snap and backhand) at different velocities, taken by elite right- and left-handed shooters, were recorded in both 2D and 3D formats. The videos are stored on a specialized random access videodisc recorder so that images can be played under computer control with less than a 2-second delay between shots if desired. Novice and elite, male and female goaltenders stand in a room with a large screen and react to the shots. The training environment is designed to look at performance with or without props (hockey net), sound (stick hitting puck and skates on ice) and 3D (2D vs. 3D). Testing includes physiological measurements (heart rate and motion direction) as well as reaction and AT. Goaltenders will also have physiological measurements taken during actual game situations for the purpose of comparison. The research questions include:

- Is there a difference in physiological responses in virtual environments when compared with actual game situations?
- To what degree does training in a virtual space change what the goaltender learn?
- Is there a difference in RTs to the same shot in two dimensions vs. three dimensions?
- Is there a difference between elite and novice, male and female hockey goaltenders in response time and successful movement?
- To what degree do goaltenders use reaction or anticipation in responding to the shot?
- Does shot type (slap, wrist, snap, backhand) and/or velocity impact decision-making?

5.3 Visualization in speed skating

In the last few Winter Olympic games, the accomplishments of Canadian speed skaters has raised the profile of speed skating. At the Olympic Oval, University of Calgary, Research has focused on the use of virtual environments as a tool to be used by coaches and sport psychology consultants as an optional part of speed skater's visualization training. In preparing athletes for the 2002 Winter Olympics, speed skaters had the opportunity to use a virtual environment of the Salt Lake City Olympic Oval as part of their visualization training [4]. In conducting this research, attention was focused on value of VR as part of a visualization program.

The virtual environment used in this testing program was recreated from images, video and architectural drawings of the actual Salt Lake Oval. Built in 3D Studio Max, the computer model was imported into Sense8 World Up, a program frequently used in simulation and game development (Figure 13).

Figure 13: The real environment compared to the virtual environment of the Salt Lake City Olympic Oval.

Figure 14: Speed skater and coach engaged in the use of the virtual environment of Salt Lake City Olympic Oval.

Athletes viewed the virtual environment in a laboratory with a 3D image projected onto a single 8 × 10 feet screen. Working with a sport psychologist, the skater places himself or herself at the start of a race and virtually skates through an event using a gyro mouse as a controller. Two electric fans placed at the front of the room were used to heighten the experience of moving through the virtual environment and to reduce the potential for motion sickness (see Figure 14).

The athletes participating in the project were interviewed before and after their Salt Lake Olympic competition. Finding from this research suggest that VR has a place in the training and preparation of athletes for competition by helping athletes practice visualization, which helps to reduce anxiety and increase focus at the actual event. Also, the visualization can be used by coaches and athletes to help develop strategy.

5.4 Visualization in golf

Golf is one of the most popular individual leisure pursuits especially in higher socio-economic classes. In addition, it has a highly paid professional sports component. As such, it is one of the areas where significant work has been undertaken to develop commercially viable simulations (e.g. www.istgolf.com; www.trugolf.com; www.holidaygolfusa.com; www.protee-united.com). Recently, the Motion Analysis Technology by TaylorMade (MATT) system has been installed in the Human Performance Lab at the University of Calgary. This system was jointly developed by TaylorMade-Adidas Golf Company (www.taylormadegolf.com) in conjunction with Motion Reality, Inc. (www.motionrealityinc.com). It is a unique visualization system designed specifically to both provide golf instruction and help players choose appropriate golf clubs based on detailed analysis of their swing.

Another unique aspect of the system is the development team: a company specializing in golf equipment research and player performance assessment, and a company specializing in motion capture, modelling and analysis technology. The University of Calgary Human Performance Lab is being utilized as a centre for studying the effectiveness of the system. The MATT system uses nine high-speed cameras to track the position of multiple passive reflective markers attached to the golf club and player. From the positions of these markers, a detailed 3D computer animation of the movements of the player and the golf club is created for review. The golf swing can be viewed from any perspective and can be manipulated to view any part of the swing including impact. Precise measurements of the golf swing are also automatically extracted and presented. These measures permit objective quantitative assessment of the golf swing (see Figure 15).

In addition, a launch monitor is used to measure the speed, launch angle and spin rate of the golf ball just after impact. This additional information is used to provide an assessment of the effectiveness of the golf shot using various clubs. On the basis of the swing measurements and demographic information about the golfer, it is possible to create a player profile that can be used to recommend golf equipment or to facilitate instruction.

The system can capture and playback the swing of a player using a high-speed motion capture system operating at 180 frames per second, which reduces blurring

Figure 15: MATT system in operation.

of the club. The nine cameras have on-board computers that capture and process the images and then transmit the data to the main computer, which integrates the results from the nine cameras to prepare the 3D reconstruction of the swing in real time. This enables the system in real time to:

- Provide viewing of the swing from almost any angle (even underneath).
- Identify address, transition, impact and the finish of the swing.
- Create various bodylines, highlighting the movement of various body segments.
- Generate centre of gravity movement information for the swing.
- Generate head path and swing plane diagrams.
- Create numerous objective, precise measurements of the golf swing.
- Show the club right at impact.
- Provide immediate playback of the swing, allowing the player to view his or her own swing from any vantage point.
- Capture and record shot performance (with the launch monitor).
- Measure impact location on the face of the club.
- Measure club head path and orientation at impact.

Research on the MATT system at the University of Calgary has looked at:

- Understanding the kinetic energy and angular momentum of golf swings [45],
- How shaft stiffness influences club head speed, and
- How stability (such as standing in a sand trap) affects the golf swing.

The system has generated some interesting research results, and it is not difficult to obtain volunteers for the research projects.

The examples described in this section of the chapter reflect the experiences of the University of Calgary researchers using virtual environments in sport. Numerous other research and development activities are ongoing that show great promise for the future, but the examples presented above provide a wide perspective on some of the issues that need to be addressed.

6 Implications of VR developments on sport performance

The potential for the development of virtual sports environments is quite promising. The haptic, audio, and design concerns in VR development are being addressed and graphic environments have made massive strides over the last 10 years, going from very expensive laboratory systems to the home computers with real-time rendering engines. The maturity of these technologies will allow the creation of systems that can place players and teams in environments to learn everything from defensive strategies to individual analysis of opponent idiosyncrasies.

The creation of massive multiplayer environments allows for ‘live’ performances in virtual life that intertwines with real lives in a variety of social ways. On a more physical level, there have been developments that allow for interactive ‘sport over distance’ [46] or ‘exertion interfaces’ (www.exertioninterfaces.com).

Koning [47] discusses these exertion interfaces as an opportunity for social interaction, which can improve the experience of sport in virtual environments.

The applications of various AI systems (neural nets, forward and backward chaining, and mathematical evaluation of positions using alpha/beta cut-offs) will enhance the development of systems that look for optimal play paths in one's own play or play vs. that of an opponent. It could also facilitate the training of players in environments that match expected game conditions (e.g. stadium, crowd, weather, footing).

Commercially, simulation and VR are 'alive and well' in the computer games industry. Games exist that simulate hockey, football and even luge (http://2ksports.com/games/torino2006). These simulation games have the potential of providing an amazing 'test bed' for research on training, education and performance. For example, a research study by Rosser *et al* [48] demonstrated that surgeons who played video games on a regular basis had significantly higher surgical performance (fewer errors, faster completion rate and higher scores) than those who did not play the games. Some of the surgeons even used video games to 'warm up' before surgery. Hopefully, funding agencies will understand the value supporting research in these areas.

Financial support for developing VR environments in sport comes primarily from organizations that wish to gain a competitive edge. This competitive edge includes improving technique, developing winning strategies, attaining peak performance, reducing stress during an event, visualizing athletic performance and using imagery to focus concentration. VR environments have the potential to assist in all of these areas.

Properly designed VR environments can provide the participants with the opportunity to train, explore, innovate, and enhance their performance at many levels. Using these environments has incredible potential, but there are inherent risks.

6.1 Wii have a problem

One of the primary features of VR environments is the ability to experience life-like events without the inherent dangers associated with actually performing in the real world. Unfortunately, programs like the Wii have their own problems associated with enthusiastic, if somewhat misguided, use (www.wiihaveaproblem.com). Injuries and damage sustained from using the Wii systems have ranged from broken windows and LCD screens to black eyes and broken bones. The closer researchers try to emulate physical environments, the more likely that problems will arise. When users enter the golf simulation described above, they have to sign a waiver indicated that they will pay for any damages caused during their participation since they are hitting real golf balls.

Another problem with immersive virtual environments is motion sickness [49]. Very expensive simulators such as the National Advanced Driving Simulator in Iowa (www.nads-sc.uiowa.edu), full flight simulators (www.cae.com) and amusement park rides that use expensive hydraulic systems provide simulations in which the movement of the system and participant mimic the movement and physics of the real environment so that the frequency of motion sickness is consistent with real-life expectations. In most other VR environments (e.g. those involving HMDs or passive displacement of the body), the level of motion sickness can be quite high. With HMDs, there is disruption in the normal sensorimotor control of the head that can create disorientation. Similarly, passive displacement does not have the normal patterns of forces and accelerations associated with the motion in a real environment. The absence of these normally occurring patterns of forces can lead to motion sickness [49].

These problems with virtual environments can seriously impact on performance effectiveness and the willingness of people to participate. Clearly, these issues need to be taken into consideration in the design of VR environments.

6.2 Environments

From a design perspective, researchers strive to create environments that are indistinguishable from the real world and/or that allow the users to:

- Experience pre-built worlds.
- Visualize 3D representations of a problem.
- Create worlds.
- Visualize abstract concepts.
- Simulate alternative environments.
- Articulate their understanding of a phenomenon.
- Visualize dynamic relationships within a system.
- Obtain infinite numbers of viewpoints within the virtual environment.
- Interact with events that are unavailable or impractical due to distance, time or safety.
- Collaborate within and between virtual environments.

To get the immersive effect, researchers also want to make the imagery as realistic as possible from a sensory (e.g. colour, auditory and emotional) perspective. Also, in many situations it is preferable if the users view the action from a first-person perspective (i.e. participant) as opposed to viewing the images as though they were watching the events unfold from a distance (spectator). However, there are times when it is useful to have access to multiple view perspectives, especially for analysis of performance.

From a design viewpoint, it is always important to understand the process from the perspective of the participant (e.g. skill level, experience, attitude and commitment). Equally important is to understand the issues associated with coaches' and athletes' willingness to adopt new technologies.

6.3 Final note

Plato suggested 'You can discover more about a person in an hour of play than in a year of conversation'. This idea can be applied to virtual environments and simulations in sport. For those who wish to be pioneers in a new and exciting field, VR in sport has many interesting opportunities.

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Feedback systems

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Abstract

As a consequence of advances in information technology, systems may be constructed which present relevant sports-specific feedback information to athletes during and shortly after training and competition. There is evidence in the motor learning literature reporting significant improvements of sports skill performance as a result of appropriate feedback. This paper describes some principles to be followed when constructing such feedback systems and presents examples from different sports.

Keywords: knowledge of results, knowledge of performance, sports biomechanics, augmented feedback, video feedback, eye tracking, pervasive computing

1 Introduction

In the extremely demanding environment of elite sport often fractions of a percentage point decide on the success or failure. Coaches and athletes therefore require effective ways to improve sports performance. Integrated and coordinated approaches from sports science (biomechanics, motor learning, exercise physiology, sport psychology, notational analysis), engineering and computer science guarantee a high level of training economy and enable to direct and control the training process continuously [1].

Feedback systems acquire, determine and present information on the motor task performed which is not directly observable. Information is either restricted to overall performance measures such as the release angle in the shot put ('knowledge of results' – KR), or gives specific information on how a movement is performed or should be corrected ('knowledge of performance' – KP).

In particular, biomechanics and notational analyses emphasize on giving feedback to coaches and performers, thereby requiring careful information management [2].

Computer science and technology provide valuable tools and methods for developing sports-specific feedback systems on performance, which often allow presenting the results in real time [3]. IT- and AI-based coaching tools offer a variety of options to give feedback on technical and tactical behaviour in training and competition. The acquisition and adequate presentation of biomechanical parameters, for example, can assist athletes in detecting the deficits and exploring the possibilities of improvements. Game analysis systems can provide valuable hints for perceiving strengths and weaknesses of the player/team or the opponent(s).

In addition, the application of data mining systems may be useful to extract implicit, previously unknown and potentially effective knowledge from motion databases. Often it is the hidden information in the data that is valuable. Because of the volume of data generated it is not possible for a coach to keep track of all the variables and the multiple combinations of variables. Consequently, tools may be helpful in mining the data sources for subtle and previously unknown patterns that might exist in the data pertaining to player performance, interactions and events on the court.

The present contribution uses a number of concrete examples to show how computer-based feedback systems can contribute to quality improvement in modern elite sports training.

2 General aspects

Several factors influencing the effect of feedback on learning or improving motor skills have been identified. Questions to be answered are if, how, when and how often feedback should be presented in order to enhance performance. There is some evidence, for example, that summary feedback (presentation after several trials) might be more efficient in retaining an improved performance than feedback provided after each trial [4]. The more complex the motion to be learned, the less the number of trials is recommended which should be included in the summary feedback [5]. Concurrent feedback (given during performance) is expected to be the most effective if it facilitates the learning of the critical characteristics or relationships as specified by the task-intrinsic (sensory-perceptual) feedback [6]. A minimum time interval (KR-delay interval) appears to be advantageous and result in a more positive effect on learning [5]. Based on research literature it may also be concluded that reduced feedback should be preferred to giving feedback after every trial [5]. A comprehensive review of the factors influencing motor skill acquisition is given by Magill [6]. At present, there are, however, still large deficits in research results on how the feedback should be provided most effectively.

In the sequel, examples of how modern computer technology can be used for augmenting the sensory-perceptual feedback athletes receive during performance or for giving feedback in general will be presented.

Several strategies have to be followed when designing or building systems for augmenting feedback [7]. The parameters should be as technique specific as possible and measured precisely and accurately without interfering with the athlete's movement. No disturbing sensors should have to be attached to the athlete or to his/her clothing or equipment (bat, racket, rifle, etc.). In addition, the results should be made available to coaches and athletes quickly (within an effective KR-delay interval) and comprehensibly. The latter aspect implies that special care has to be taken in the design of the presentation component of the feedback system. A graphical visualization should therefore, for example, be preferred to a presentation of pure numbers.

Because of these partly contradictory principles, certain compromises have to be made at times to get satisfying solutions.

A regular application of feedback systems in elite sport training requires mobile devices to be available at the actual location of the training. If this is not the case, their use is restricted to laboratory environments. This is unfavourable for the coaches and the athletes.

From personal experiences gained over the years it is concluded that only easy-to-use feedback systems are practically applied by coaches and that sports federations and associations often do not have a large budget at their disposal and therefore require low-cost solutions.

The first aspect implies that the time coaches have to spend for training with the feedback system has to be kept small. System developers should keep in mind that many coaches have little knowledge of how to use computers. Therefore easily understandable (graphical) user interfaces are essential. In addition, most coaches are not willing to carry out time-consuming installation or assembly procedures or to interact with the system during the exercise. User interventions to the systems during trials should, therefore, also be kept at a minimum.

Costs for deployment, maintenance and repair of feedback systems should be reasonable. In many cases only lower cost systems can be financed to equip several feedback stations.

Future efforts should concentrate on the development of rather low-cost, easy-to-use systems of high-quality supplying coaches and athletes with sports-specific and comprehensible feedback information.

The integration of modern sensor, information and communication technologies will provide additional means for developing absolutely novel systems to acquire and present data in training and competition. Various tiny, non-disturbing sensors and devices will be incorporated into the sports equipment or attached to the athlete. Mobile computers will acquire and present the data recorded; other systems will use telemetric methods to transmit the acquired data to receiving stations, which then will process and adequately present them. Portable devices, which are not bound to laboratory conditions, will be particularly useful.

It is rather likely that novel and rapid performance measurement and feedback tools based on modern information technology will become more and more pervasive in the training environment and in competition.

3 Systems and applications

The systems presented have been categorized according to the type of feedback, which is given. Two examples from table tennis shall illustrate how KR feedback can effectively be presented. Systems providing KP feedback have been classified in two groups: those that give kinematic and those that give kinetic feedback information. Biofeedback systems, involving the measurement and presentation of physiological information, such as electromyography (EMG), electroencephalography (EEG) or skin or skin temperature, are not directly addressed. An example from biathlon has been selected for demonstrating kinematic, one from rowing for kinetic feedback. The video feedback systems introduced at the beginning can mainly be assigned to KP, but do, however, include KR properties also.

3.1 Video feedback

Video technology in training has for a long time only been used to give KP feedback information by videotape replay. Details of the movement could thus be observed repeatedly or by utilizing the slow-motion replay capabilities of video players. The integration of video and computer technology has enhanced the presentation potential of video recordings. In addition to KP, KR information can now be highlighted and vividly presented.

3.1.1 Feedback systems for qualitative analyses

Several companies (e.g. the German company SIMI, http://www.simi.com/; the New Zealand company siliconCOACH, http://www.siliconcoach.com/ or the Swiss company Dartfish, http://www.dartfish.com/) have developed computerized video replay software for qualitative analysis [8] of sports techniques. The computer programs offered allow viewing several images simultaneously using video split-screen technology (Figure 1). This feature may also be applied for comparing, recorded with reference clips, and for recognizing differences. Drawing tools are integrated enabling to illustrate the videos on-screen. Angles and distances may easily be calculated.

In 1997, SimulCam™ technology was invented by Dartfish. This patented technology is based on the idea that whenever two athletes are competing at different times, but over the same terrain, their filmed performances can be merged into a single video showing both competitors seemingly competing together [9]. Differences in camera adjustments (pan, tilt, zoom) are computed and compensated automatically between the two recorded performances. The motions of the two athletes are blended resulting in a new video.

The stroboscope feature of such programs provides an interesting way of observing motion. This functionality makes it possible to create a single image with several superimposed snapshots of a movement or to produce a video clip showing selected body positions of a movement successively. The evolution of an athlete's movement over space and time may thus be vividly presented.

3.1.2 Interactive video systems

In order to better control the information received during video feedback, interactive video systems have become popular. Such systems enable to randomly access previously marked video scenes. Their use in sport dates back to the 1980s [10, 11]. During recording or afterwards the videos are categorized

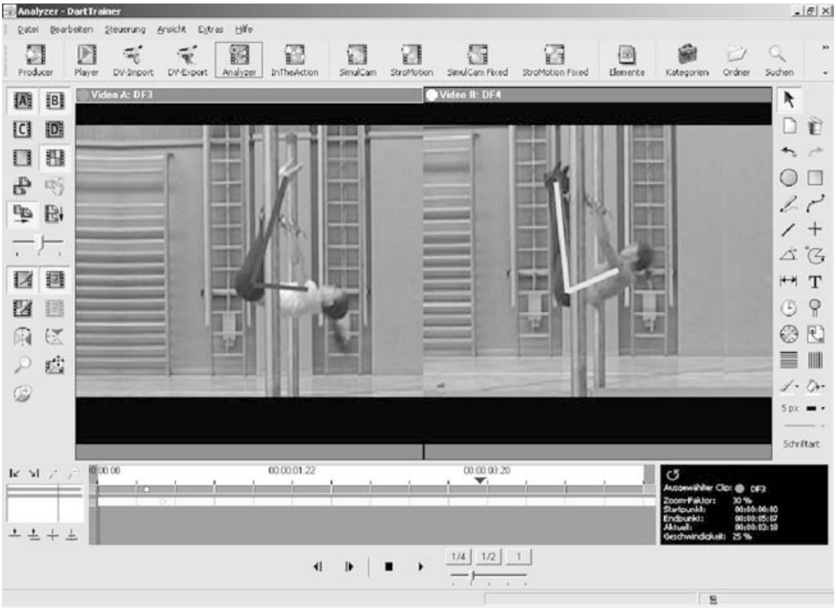

Figure 1: Split-screen technology. Screenshot from the Dartfish ProSuite software.

with predefined attributes and an index of events is created (e.g. serve, volley). Specific actions (e.g. all volleys) can then be retrieved from the index and presented one by one to the users.

Interactive video modules are often also an integral part of the computer-aided sports and game analysis systems. Numerous systems have been developed over the past years. They assist coaches in the systematic acquisition and analysis of the behaviour of one or more athletes. In addition to technical actions, such systems may also be helpful to investigate the overall motions of the athletes. Systems of that kind are used not only for developing databases on the behaviour of players or athletes and indicating areas requiring performance improvement, but also for giving immediate feedback [12].

As an example, a system for assisting table tennis players shall shortly be presented [13, 14]. The system provides feedback for the competing players during a tournament. A qualitative approach, similar to that described by Lames and Hansen [15], was selected for this purpose. In cooperation with trainers and players of the Austrian national team, a model was developed for a process-oriented description of the match. Hardware and software systems were then designed and developed to assist players and coaches during a competition (e.g. an international championship). Not an overall system was aimed at in order to analyse all aspects of playing behaviour of a player or potential opponent. Only specific information that allows an efficient and rapid assessment, interpretation and presentation of relevant properties of players and opponents is collected.

In addition to frame and initial data (grip, left/right-hander, first server, etc.), the user has to register values for the following attributes only:

- type of stroke (forehand/backhand, topspin, counter, block, defence, etc.)
- impact position of the ball on the table
- instant of service and moment when the point is finished
- type of error (out, net, etc.)

Additional variables are automatically derived from the primary attributes and some initial information (e.g. by indicating the type of error on the respective side of the interactive table, the system determines which player made the point; see Figure 2):

- number of set, point and stroke
- current score
- server and receiver
- length and direction of the stroke (short/long, left/right)
- winner of the point

Matches are recorded on video and, if possible, observed on location. Video capturing and rough evaluation may be done during the game enabling an

Figure 2: Software for match analysis in table tennis.

immediate video-assisted feedback afterwards. Beginning and end of rallies are thereby recorded by registering the respective time code. Further analysis of individual strokes can only be performed offline. A screenshot of the software developed for data acquisition and analysis is shown in Figure 2.

The results of the analysis, together with the impressions of the match observer, constitute the basis for the qualitative analysis. Assisted by the interactive video component of the software tool used, all scenes of interest may be selectively accessed.

Selected sequences may therefore be presented to coaches and players applying filter functions based on the attributes recorded. Normally, the filters used are rather wide (e.g. all services of player A) in order to result in representative and not too specific scenes. The presentation speed and mode may be varied. The coach and player(s) try to interpret the selected scenes and find peculiarities or reasons for conspicuous quantitative results.

Heart rates may be analysed in relation to actions observed in the match [3]. In a subsequent step, the time histories of the heart rates can be superimposed to the video recorded (Figure 3).

3.1.3 Eye-tracking systems

A further video-based approach used for gaining insight into the behaviour of athletes is to analyse their eye movements. Liebermann *et al* [12] hypothesize

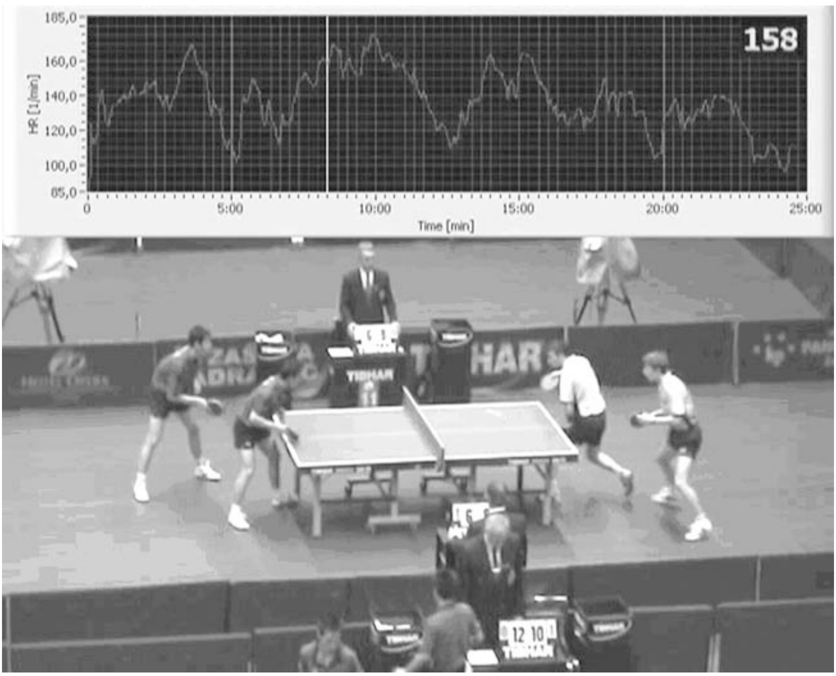

Figure 3: Synchronization of video and heart rates.

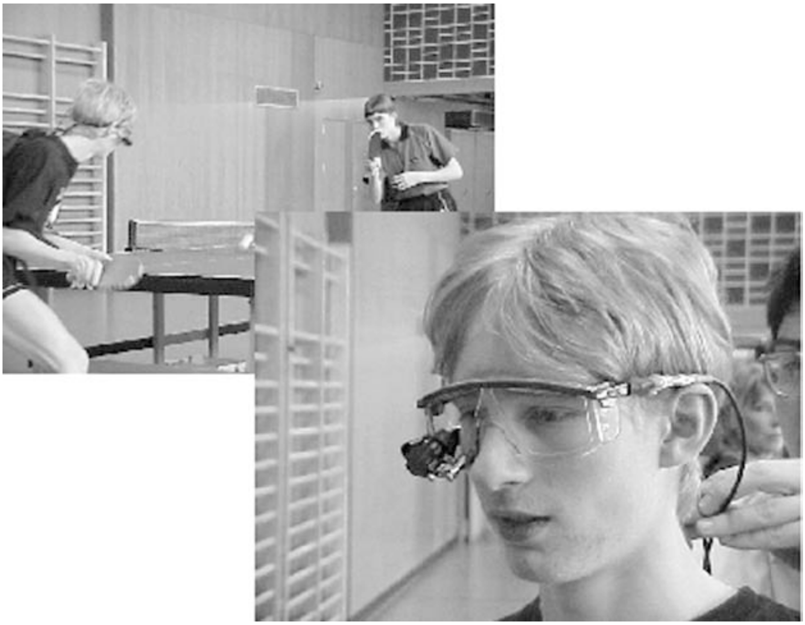

Figure 4: Eye-tracking system applied in table tennis.

that in slow events less experienced athletes might benefit from feedback on their eye movements when related to the eye movement strategies of experts. When analysing game sports, for example, it is probably significant, where the players look at for what amount of time.

Not long ago the eye-tracking systems used to be bulky and rather heavy. Recently, systems have been developed, which are applicable under competitive conditions to a certain degree. Figure 4 shows the application of the eye-tracking system in table tennis [3]. The eye-recording camera and that recording the area in front of the subject are fixed to special eyeglasses (right photo in Figure 4).

The position where the eyes look at can be marked in the video that shows the area in front of the person being analysed (Figure 5). The result allows evaluating the duration, the fixed positions and non-fixed areas.

Preliminary results given in Ref. [3] were that the player did not track an approaching ball before the ball crossed the net and that the eyes anticipated the position of the ball before it bounced.

3.2 Feedback of results

KR feedback is given when augmented information on the overall outcome of a performance is provided. It can be presented either as actual achieved values or by indicating the deviations from the desired values. The latter information can be supplied qualitatively (‘too slow’) or quantitatively.

Figure 5: Eye-tracking: position where the player looks at.

In table tennis, for example, performance parameters describing the outcome of one stroke are the spin, the position where the ball hits the table and the ball velocity. Systems that give immediate feedback on the quality of the ball just played are applicable in training. Besides directing and conditioning the technique, some motivational effects can be expected [16].

One training exercise, for instance, is to play the ball as long as possible. In this case, the frequency of an acoustic feedback signal may indicate the distance of the impact point to the edge of the table. Another exercise is to serve the ball in a way that the time interval between the first and second impact of the ball on the table is as short as possible.

Two types of KR-feedback systems shall illustrate the concept. The first variant is based on detecting impact positions of the ball on the table in real time [17], the second on acquiring ball impact intervals.

3.2.1 Detection of impact positions in table tennis

Figure 6 illustrates the set-up for measurement [16, 17]. Four vibration sensors (one redundant to increase accuracy) are fixed on the underside of one half of the table and connected to an amplifier, which itself is connected to a DAQ-system consisting of a notebook computer and a data acquisition card. Vibration signals produced by the ball hitting the table are registered by the four sensors. A software (LabVIEW®) has been programmed to calculate the ball impact position on this half of the table from these signals and to present the results graphically. A threshold algorithm determines the four instants of time, when the vibration signal arrives at the sensors. A triangulation method is used to calculate the impact

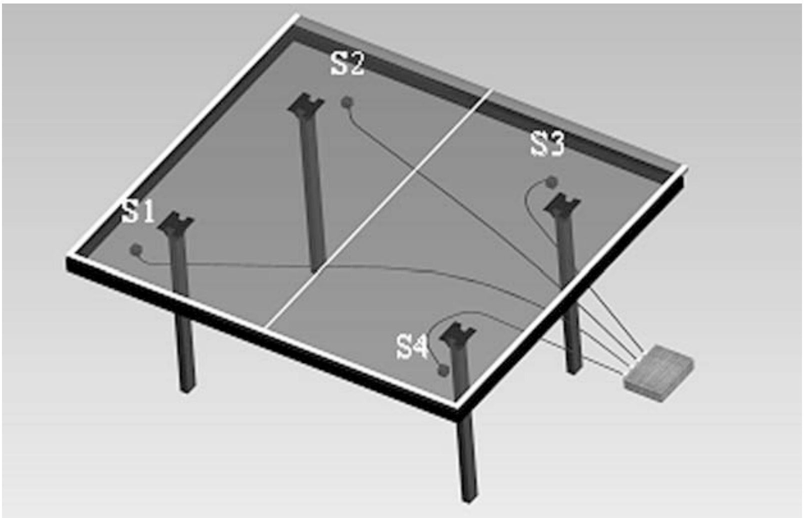

Figure 6: Set-up for detection of ball impact positions. S1–S4 denote the positions of the accelerometers fixed on the underside of one half of the table.

position from the four instants of time. The impact point coordinates x_T and y_T are calculated, which minimize

$$\sum_{i,j}(d_{ij} - t_{ij} \cdot v)^2$$

$$(i = 1\ldots4; j = 1\ldots4; i > j),$$

where d_{ij} are the differences in the distance from the impact point (x_T, y_T) to sensor i and sensor j, t_{ij} are the respective time differences and v is the velocity of signal propagation, which depends on material properties of the table.

The computer program developed displays the reconstructed impact points immediately after the impact. A circle representing the ball is drawn onto the calculated position into a graphic presentation of the table half. In addition, the numerical values of the coordinates are shown (Figure 7). The single shot mode presents the position of only the last ball played, whereas the continuous mode presents that of all balls played in a series.

Baca and Kornfeind [17] report an average accuracy of 0.020 ± 0.011 m within the area of the table at least 0.25 m away from the net, which is sufficient for practical applications of the system. Immediate, shortly delayed or summative feedback can be given to the athletes in training. No sensors have to be attached to the players or on the visible side of the table.

In typical applications of the system in training, a table tennis robot serves the ball in short intervals. The player has to return each ball into a marked area or to play it as long as possible. After each series of trials the player gets visual feedback on the ball impact positions (Figures 7 and 8).

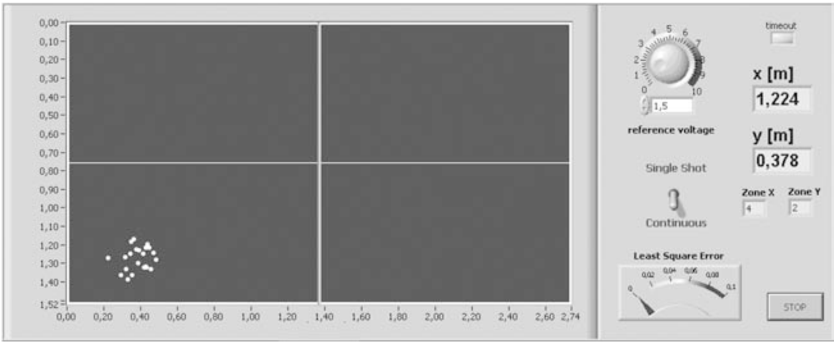

Figure 7: Presentation of a series of ball impact positions (continuous mode).

Figure 8: Feedback training using impact position detecting system.

The system may also be used to give feedback on impact positions and impact time intervals in serve training. Players are thereby able to study the precision and variability of different serve techniques.

3.2.2 Detection of impact time intervals in table tennis

The time interval between the ball's first (own side) and second (opponent's side) impact after a serve is strongly affected by the degree of spin of the ball. In the case of short serves, the ball bounces on the opponent's side a second time resulting in a second time interval. A low-cost system has been developed to determine these intervals.

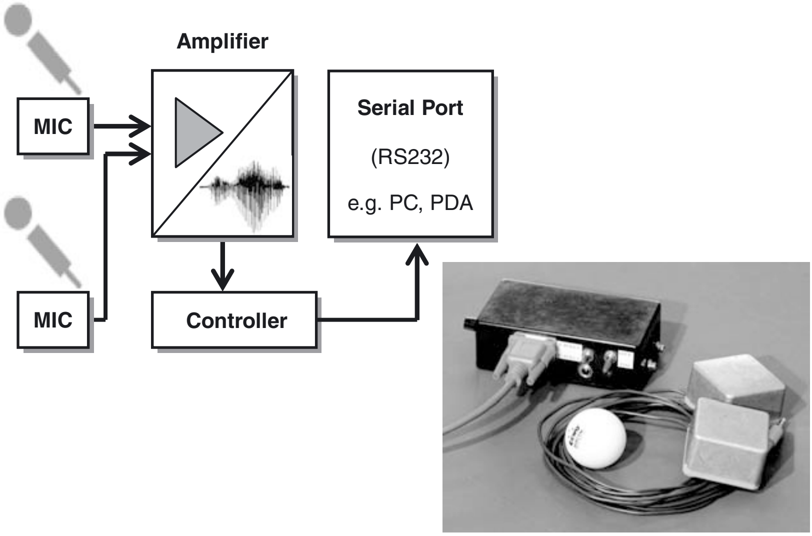

Figure 9: Left: Schematic presentation of the hardware required for calculating the impact time intervals. Right: Complete system without computer.

A ball impact on the table causes a typical acoustic signal. Two microphones are used for recording this signal, – both fixed in metallic boxes. The boxes are put near the net onto both halves of the table. The signals acquired from the microphones are preprocessed electronically and then fed to a microcontroller, which calculates the time intervals. Via a serial port the microcontroller is also connected to a PC, notebook or PDA, which then displays the results (Figure 9).

In addition to a numerical presentation of the time intervals, a speedometer informs about the player's performance graphically (Right: Green area – good; Left: Red area – bad; Figure 10).

The overall system is not bound to a specific table tennis table and can easily be transported to the environment (table, hall, etc.), where it is used.

Because of an automated system reset into a 'wait state' after a short period without acoustic impact signal, no user intervention is required between successive serves.

If the computer (PC/PDA) is connected to two monitors facing in opposite directions, two players standing on opposite sides can use the system simultaneously (Figure 11).

Typical exercises performed by the players include the task to play long services minimizing the impact interval between first and second impact or to play short services minimizing the impact interval between second and third impact in order to decrease the reactin time of the opponent. Youth players utilizing the system in serve training enjoyed the feedback training and were highly motivated. A kind of competition situation could be observed.

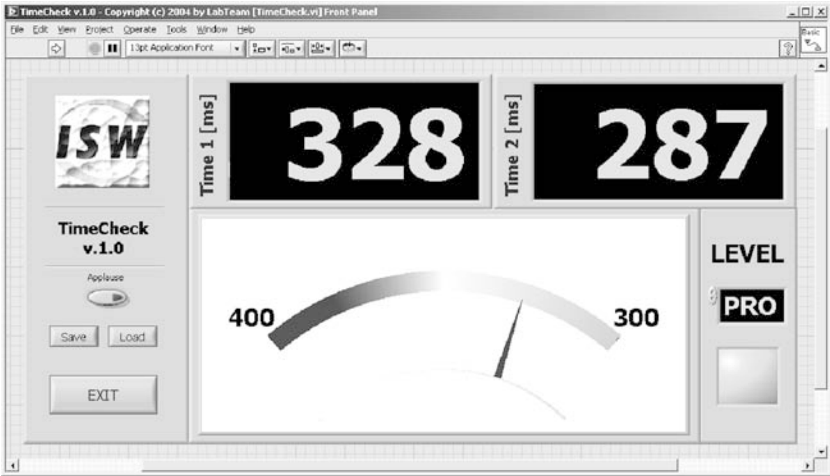

Figure 10: Presentation of impact time intervals. Time 1: First to second impact, Time 2: Second to third impact (short serves only).

Figure 11: Feedback session in table tennis. Two players receive immediate feedback on the quality of specific service techniques.

3.3 Kinematic feedback

Several studies confirm that under certain conditions feedback information on how movements are performed and on how they should be changed is superior to mere KR information on the overall outcome [6, 18]. In particular when learning or improving complex multiple degrees of freedom tasks, KP appears to be the more efficient variant of feedback. However, due to restrictions caused by technology, the main focus on developing feedback systems has long been on KR. Only with the growing potential of technology, KP-based systems have increasingly been constructed and applied.

KP is often concerned with feedback about performance kinematics. Positions, velocities and accelerations of the body segments as functions of time explain the motion characteristics. For acquisition and presentation of this information to athletes, motion capture systems are frequently used.

3.3.1 Motion capture systems

Video-based motion analysis systems are used to calculate kinematic parameters (e.g. rotation angles of joint movements, rotation velocities, rotation accelerations) from reconstructed trajectories of marker points attached to the human body. Most of the software solutions offered (Peak Motus® – Vicon, http://www.vicon.com; SIMI-Motion – SIMI, http://www.simi.com; APAS – Ariel Dynamics, http://www.arielnet.com) work with common video cameras and computer systems. One drawback of these systems is the rather long time interval between motion execution and the availability of the results. Immediate feedback of the kinematic parameter values is therefore not possible; fast feedback is limited [12].

Optoelectronic real-time motion capture systems overcome this problem. Specific digital optical cameras record the moving subjects simultaneously from different angles. The passive markers attached to the subjects are illuminated by strobe light arrays constructed from infrared LEDs, which are installed around the lens of the cameras. As the infrared components of sunlight interfere with this kind of lighting, these systems are mainly used indoor. Vicon's MX system (Vicon, see above) is a typical representative of this technology. In combination with the software Vicon Nexus, this system also allows the integration of digital reference video (see Figure 12). Three-dimensional (3D) information, such as the force plate ground reaction force vector or the calculated 3D marker positions, can be overlayed on the video image. In particular this feature provides a substantial progress for the applicability of such systems as a feedback tool for indoor training.

3.3.2 Marker-less motion capture systems

Using image sequences acquired simultaneously from multiple views, 3D joint data at each instant may also be reconstructed without the use of markers [19, 20]. Those kinematic pose parameters of a human body model are estimated, which result in a most similar appearance of its synthesized shapes to the actual shapes

Figure 12: 3D information overlayed on digital video. Screenshot from the Vicon Nexus software.

of the real subject in the multi-view camera images [21] – Figure 13 illustrates the principle. The body models used for this purpose are constructed either of simple volumetric primitives [21] or of freeform surface patches [20]. Difficulties, which complicate the estimation of body segment boundaries, result from noise, occlusions and shading. Because the resulting kinematic data compare well to those obtained from marker-based methods and the information may be made available in almost real time [20], such systems provide an interesting alternative as a tool for kinematic feedback.

Camera-based observation systems have also been developed to track whole-body motions of players in game sports (particularly in soccer) without considering the geometric structure of the body [22, 23]. The positions of players as functions of time are determined. For this type of investigation, the players are represented by points moving in two dimensions. Distances covered during a game classified according to the intensity of the motion (e.g. distances of walking, jogging, sprinting) are of specific interest. Since the late 1980s methods from image processing, pattern recognition and artificial intelligence have been applied to assess these problems.

In 1998 the first prototype of the computer vision system AMISCO was introduced. This commercial system, designed to be used in soccer, was based on computer vision. The company in charge claimed that the system measures the movements of all actors on the pitch (players, referees and ball) under competition

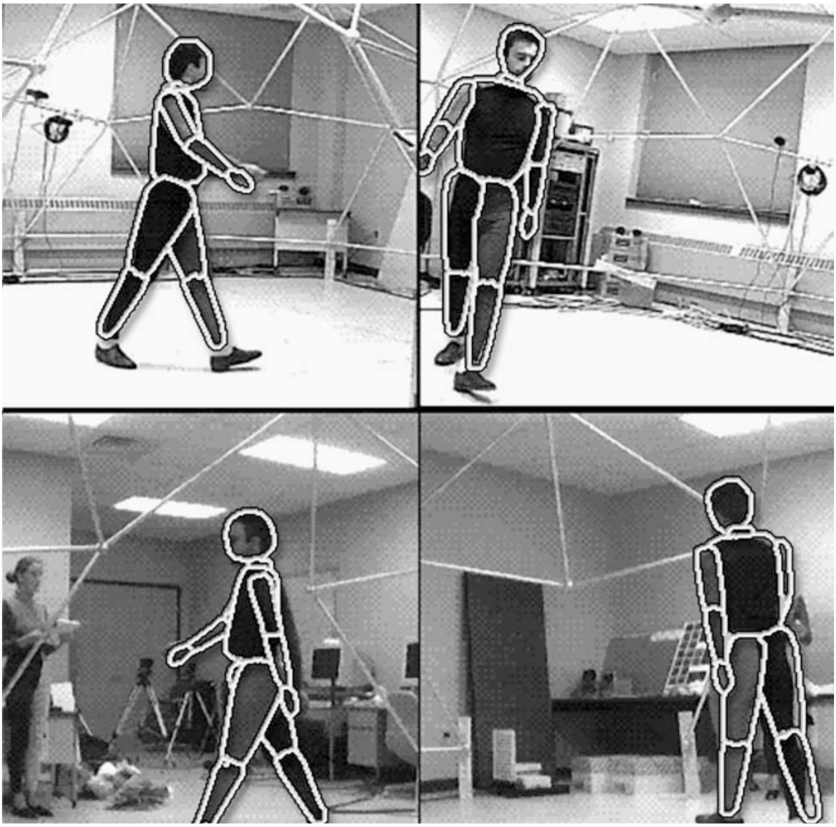

Figure 13: Matching a body model to the actual appearance in multi-view images (From Gavrila [24] with permission).

conditions [3]. However, information on how much user intervention was required during automated tracking remained marginal. Beetz *et al* [25] present a software system based on the evaluation of video streams provided by a set of TV cameras. The purpose of their system is to track players and ball and, moreover, to classify ball actions automatically.

If appropriately applied, such systems may assist coaches in providing feedback on the tactical behaviour of not only the individual players but also the entire team.

3.3.3 Transponder-based systems

Non-video systems with similar objective are based on the FMCW (frequency modulated continuous wave) technology (e.g. LPM from the Austrian company Abatec, http://www.abatec-ag.com; Trakus (Trakus Inc, USA), http://www.trakus.com; position-tracking system from Cairos Technologies and Fraunhofer

IIS (Germany), http://www.cairos.com). The position of freely mobile objects can be determined within a local bounded 3D area. Every object to be tracked by the system needs to be equipped with a lightweight transponder. Each of the transponders transmits a signal either periodically or after being uniquely addressed by a central control unit. The environment under investigation is surrounded by receiver stations, which receive this signal and determine the arrival time. This information (from all receive stations) is sufficient to compute the 3D position using a triangulation algorithm. Hence it is possible to refer to any object (transponder) independently and to receive its specific position in real time. Objects are thus continuously tracked and identified. This procedure is done simultaneously for all tags and is repeated continuously.

The system can be installed indoors as well as outdoors. Players are, however, obliged to wear special tags. Transponder-based systems are therefore applicable in training, but inappropriate for use in regular soccer matches.

Figure 14 illustrates a schematic view of a typical system's setup.

With a system as described in [26] (FMCW-based sensors, wide-range real-time network, processing unit with real-time capability) it was possible to measure the position of tags within an area of more than 10,000 m^2 with high accuracy (less than 10 cm) 1000 times per second.

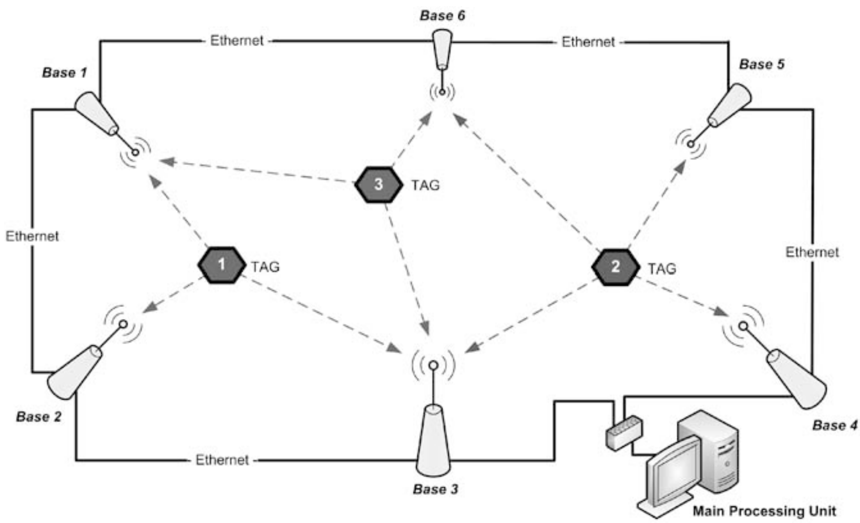

Figure 14: Set-up of a transponder-based tracking system, consisting of six receivers and three (active) transponders, which periodically transmit signals.

The possibility to transmit additional telemetry data (e.g. heart rate data) from the object to the master processing unit might be additionally advantageous for sports applications.

Transponder-based systems are superior to other known positioning systems (e.g. the GPS (Global Positioning System) technology), because the latter often cannot fulfil speed and accuracy requirements, especially in locally restricted areas outdoors as well as indoors.

3.3.4 Feedback of the motion of the rifle barrel in biathlon shooting

A sports-specific example from biathlon shall complete this section on kinematic feedback systems. Coaches and athletes are interested in the motion of the barrel of the rifle just before shooting. This is a crucial factor because of the preceding high exertions of the athletes. Feedback systems are applied which present information on this motion concurrent to or shortly after the shooting.

Normally, commercial laser systems (e.g. Noptel, Finland) are used to measure and store the hit point of the shot and the on-target trajectory of the alignment of the weapon. A major drawback of this method lies in the necessity of attaching the laser device to the rifle. In a recent study, positive, but only temporal effects of a high-frequency KP feedback provided by such a system to Finnish conscripts could be shown [27].

Alternatively, automatic tracking systems can be used to track and record the 3D movements of the rifle (and optionally the athlete), even in real time. In this case, markers have to be attached to the rifle (and the athlete). However, as stated before, such systems are rather expensive and difficult to use outdoor.

Baca and Kornfeind [28] developed a low-cost video-based system, which is able to track the 2D-movement of the muzzle automatically. A video camera is set up in a distance of about 7 m in front of the athlete in a laterally displaced position and records the barrel. The camera is connected to a notebook computer. A LabVIEW application program enables the user to start and stop the video acquisition, to specify the shape of the muzzle to be tracked and to track this shape automatically. Tracking is performed in a user-selectable time interval before the shot using image-processing algorithms. From the sound track recorded by the video camera, the instants of shooting are determined. Applying the results of a calibration procedure, the image coordinates obtained by the tracking algorithm are converted to object space coordinates.

Figure 15 shows an image of the barrel and the reconstructed trajectories of the muzzle.

On-target trajectories of the alignment of the whole weapon obtained by a laser-based system (Noptel) and the trajectories of the muzzle obtained by the video-based system were compared analysing biathletes from the Austrian Junior team [29]. High similarities in the vertical movements could be observed. However, in the horizontal movements shots with high as well as low similarities were encountered (Figure 16). The reason for these observations is the mainly angular movement of the rifle in the vertical plane during aiming and both the angular and translational movements in the horizontal plane.

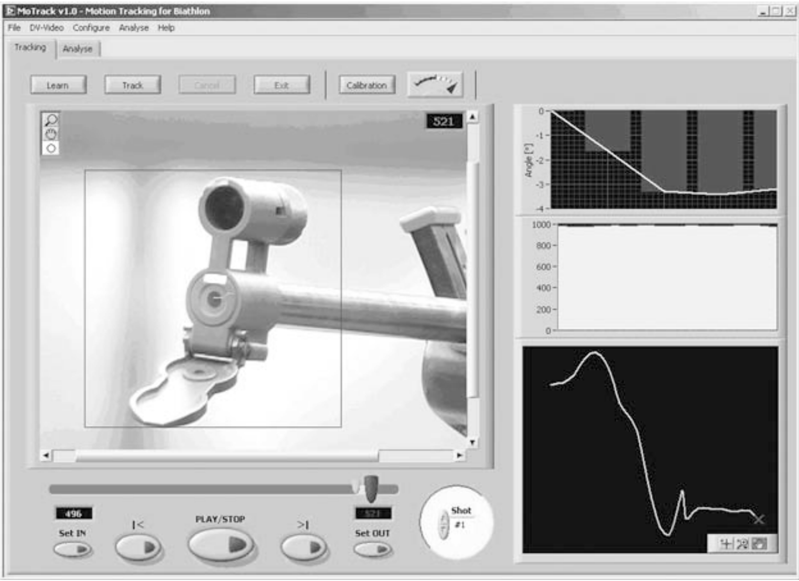

Figure 15: Tracking the barrel in biathlon. The plotted lines in the diagram represent the trajectories of a series of five shots.

The combination of laser- and video-based method could provide additional information on this translational and angular rifle movement and their compensations for each other.

3.4 Kinetic feedback

Another form of KP feedback is the presentation of kinetic information, such as (reaction) forces and torques, as functions of time. Again, this information should be available shortly after the event. There is evidence that concurrent force feedback, compared to delayed force feedback, may be detrimental with regard to retention performance [30] cited in Ref. [31].

The author is, however, not aware of any study investigating this effect in cyclic motions (e.g. running, cycling, rowing). As the motion variability between cycles in experienced athletes is small and cycles are continuously repeated, it is assumed that the temporal position of the KP information might be of secondary importance.

A feedback system for rowing shall illustrate the principle. In this sport, considering kinematic parameters only may not provide sufficient information [32].

Technique analysis in rowing involves the consideration of fine details of the movement of the rower with regard to the boat. In addition to kinematic analyses, the study of the kinetics of the boat-rower system provides the

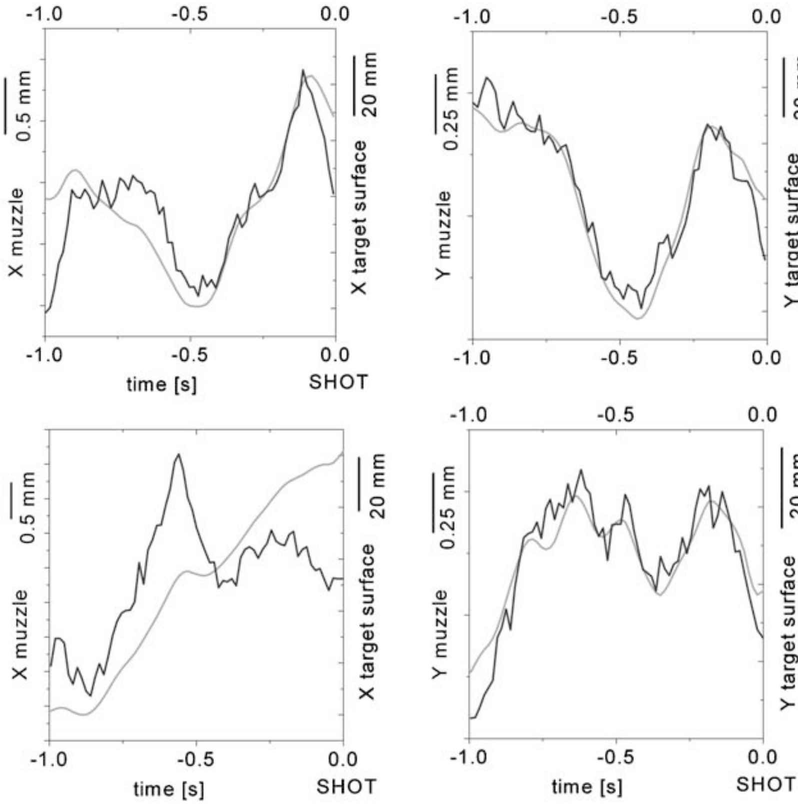

Figure 16: Trajectories of two sample shots from biathletes of the Austrian Junior team. Top: Shot showing a high similarity in both horizontal (X) and vertical (Y) direction. Bottom: Shot showing poor similarity in X-direction [29].

necessary insights into strengths and weaknesses (e.g. peculiarities in motion coupling) [33, 34].

Feedback systems incorporated directly in the boat are used in elite rowing [34]. Developments towards an integrated application of information and communication technologies can be observed. Broker and Crawley [1], for example, report on a system that measures oar bending and oar position of four rowers simultaneously as well as boat velocity. Data are processed on-board and transmitted to a receiver located on the coach's launch. Particularly useful in this area are systems based on standard mobile electronic devices, such as that proposed by Collins and Anderson [35], who couple a PDA with inbuilt Wi-Fi capabilities and a data acquisition card within an expansion box. The PDA captures the data from sensors mounted on the rowing boat and transmits it to a laptop, which processes and displays it.

Analyses of the rowing technique in the boat are difficult to realize and are very demanding in time and instrumentation. In many cases analyses are therefore based on rowing simulators (rowing ergometers) on land (e.g. Ref. [36]). In order not to draw wrong conclusions from the training sessions on land it is essential to compare the rowers' technique in the boat to that on the ergometer.

Baca and Kornfeind [37] have developed a specific set-up for this purpose. Units for measuring reaction forces in the foot stretcher (Figure 17) in two dimensions have been constructed. They record reaction forces at both feet separately and may be used in the boat as well as on the rowing ergometer (Concept II®) with or without slides (a construction that is attached to the legs of the ergometer, allowing the ergometer to roll back and forth during the rowing stroke). The construction is based on load cells and strain gauges. The (portable) units may easily be attached to the foot stretcher of the boat or of the ergometer.

In addition to the reaction forces the pulling forces also allow to draw conclusions on the rowing technique. In the case of ergometer measurements, a force transducer is connected to the chain attached to the handle. In the boat,

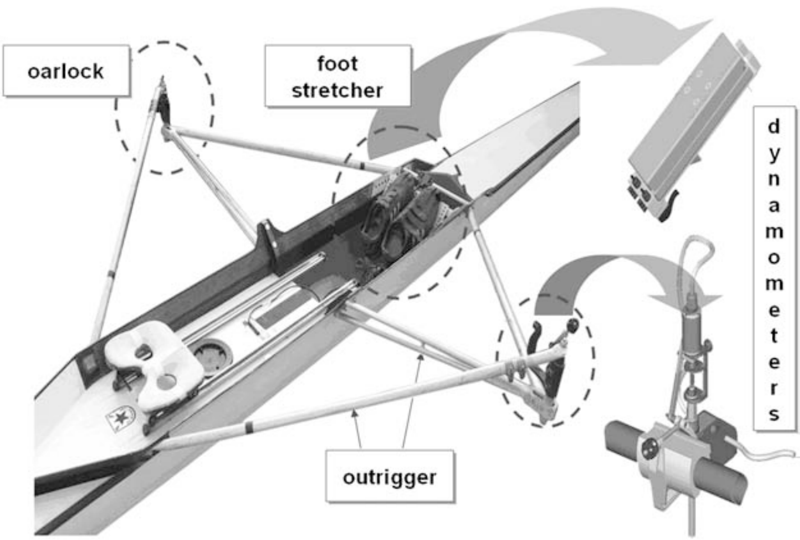

Figure 17: Measuring the dynamics in rowing. The dynamometer for measuring reaction forces may be attached either to the foot stretcher in the boat (depicted here) or to that of the ergometer. To measure the pulling forces, a pair of dynamometric oarlocks is attached to the outriggers.

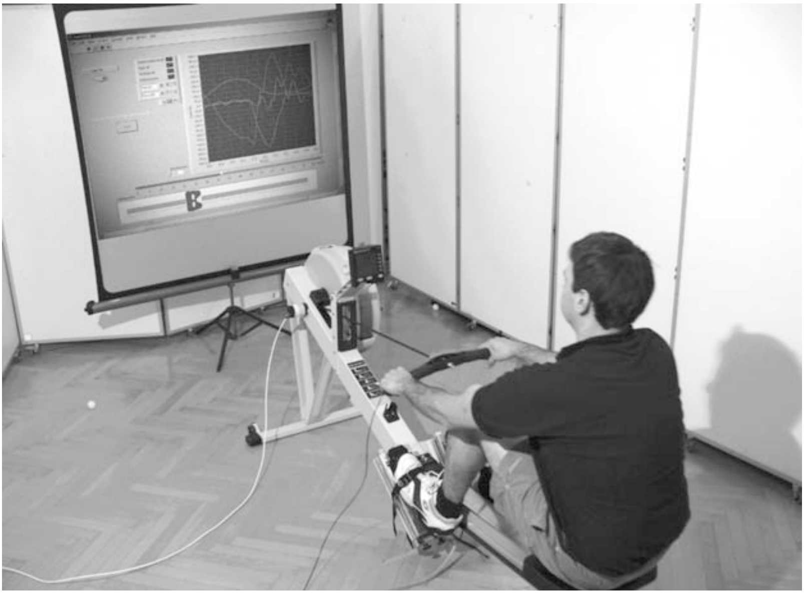

Figure 18: Kinetic KP feedback in ergometer rowing.

dynamometric oarlocks are used for this purpose. Data measured in the boat are recorded using a PDA with data acquisition capabilities.

Knowledge-of-performance feedback is given to the athletes on the quality of their technique.

In ergometer rowing, the time functions of the relevant kinetic parameters are concurrently displayed on a monitor in view of the rowers during motion execution (Figure 18). The rowers are thereby able to discover how changes in the movement pattern may alter the shape of the curves in the desired direction. In addition, a series of successive strokes can be evaluated and presented in the form of summative feedback.

In the boat, the data recorded are wirelessly transmitted to the coach offering the possibility to view and comment the information in almost real time.

4 Conclusions

Real-time and rapid feedback systems as well as sophisticated systems for collecting and analysing sports-specific data provide innovative and effective support to coaches and athletes. Powerful video and IT-tools as well as wireless technology facilitate the development of user-friendly systems which are specifically oriented towards their needs. It is of particular importance for the success of such systems that the relevant parameter values are acquired exactly and that the feedback information can be made available to coaches and athletes quickly and comprehensibly. The latter aspect implies that special care has to be taken in the design of the presentation component of the system.

If these aspects are considered, novel and rapid performance measurement and feedback tools based on modern information technology will become more and more pervasive in everyday training.

It should, however, be kept in mind that in spite of the motivational effects which often can be observed when applying computerized external feedback systems, objective evidence of sustained effectiveness is difficult to provide.

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Long-distance sports

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Abstract

The merging of sports and computer technology has been mainly focused on supporting performance enhancement of professional athletes or, on the other end of the spectrum, simulating professional sports competitions for entertainment purposes in computer games. Less work has been undertaken on using computers to enhance social sports experiences. Long-Distance Sports is a novel approach using telecommunication technology in particular to enable geographically distant participants to enjoy a social sports experience together. The Long-Distance Sports presented here focus on physical exertion comparable to collocated sports, a shared experience although being geographically apart and social interaction between the players during casual sports play. Two systems are presented that have been tested by hundreds of players. *Breakout for Two* is a soccer-like game that uses distributed targets on a life-size videoconference to enable a sports experience between two players who each kick a real physical ball. *Airhockey Over a Distance* creates an increased sense of a shared space across the distance by having puck cannons shooting out real pucks on the remote end to enable a game of airhockey between geographically distant players. The results from these implementations indicate that Long-Distance Sports can be a valuable contribution to society by supporting interactions between players who are spending time apart in which they can achieve both a work-out and socializing.

Keywords: exertion interface, airhockey, physical, tangible, videoconferencing, active, exhausting, sweat, team spirit, social interaction, computer-supported collaborative sports

1 Introduction

Sport has many advantages; in particular health and social well-being have been attributed as major benefits. From a physical health perspective, sports can contribute to a healthier body, reducing the risk of obesity, cardiovascular disease, diabetes and other diseases [1, 2]. From a social and mental health viewpoint, sport is believed to teach social skills [3], encourage team-building and support individual growth and community development [4]. Some argue that sport can foster social integration and personal enjoyment [5, 6], provide opportunities to meet and communicate with other people, bring people together from various cultural backgrounds and contribute positively to self-esteem and well-being [7]. Although some research asks for further proof of specific benefits [8], there seems to be a considerable amount of evidence in favour of a positive relationship with physical and mental health [7, 9].

The social benefit that can increase participants' well-being and mental health has been pointed out as being also of benefit to the growth of social capital [10, 11]. The author of the book 'Bowling Alone', Putnam, argues that social capital requires social networks, which are most effectively developed through participation in shared activities [10]. He warns of a further decline of social capital if people continue to reject opportunities for social activities such as bowling, which used to increase our social capital: he identifies correlations between high levels of social capital and high levels of economic prosperity, improved health and educational attainment on even a national level. In particular, sports participation provides a focus for social activity. It can be helpful in facilitating social introductions, provides an opportunity to develop networks and reduce social isolation, and hence has potential to support the development of social capital. Sports activities can facilitate bonds between people, resulting in loyalty and team spirit. Sports clubs not only function as a place to exercise, but also as a social space, Putnam argues. Team sports in particular are considered as character building. International sporting events also demonstrate that sports have the ability to overcome the language barrier. However, with current sports, participants have to be in the same physical location.

The use of computing technology in sports applications has been mainly focused on supporting performance enhancement of professional athletes or recreating professional sports competitions for entertainment purposes in computer games. Less work has been undertaken on using computing technology to support the social benefit associated with sports. The work presented here aims to demonstrate that there is potential for computing technology to support these social benefits in sports, hence creating social capital.

2 Trends

Computing technology has been mainly used to support professional sports, hence reached only a small portion of all active sportspeople. Computers used to be very expensive and therefore only accessible to rich organizations that had to justify a return on investment, often in terms of new world records or an increase in gold medals. Nowadays, the advances in computing power and the decline in hardware costs have made the use of computers in sports accessible for hobby athletes and casual sportspeople.

The other trend in the convergence of computing technology and sports has been the remarkably successful area of sports simulations on home computers and consoles for entertainment purposes. Although these sports games often support network play, they are criticized for their social isolation of players, in stark contract to the social benefits associated with physical leisure activity described by Putnam [12]. Second, these games also contrast with the health benefit associated with sports: their game pad or joystick interactions using simple thumb presses are distinctively different from the full-body movement interaction exhibited in sports, and hence these games have been associated with a sedentary lifestyle. The physical exertion, however, is an essential part of the sports experience: sport is '… play that is accompanied by physical exertion …' [13]. Only recently, the video games market has realized this potential and accommodated for these kinds of activities (see [12]).

3 Approach

The concept of Long-Distance Sports assumes a correlation between the physical exertion that is exhibited in sports and the benefit that is associated with casual sports activity, which seems supported by early research in this area [5, 8]. The concept of Long-Distance Sports aims to utilize the benefits associated with collocated sports and apply them to a distributed environment to support a physically exhausting activity between geographically distant players. The demonstrators described below therefore utilize an 'Exertion Interface', an interface that deliberately requires intense physical effort [14] to enable a sports-like experience for the players. The aim is, however, not to replace an existing sports experience, but rather to provide sportspeople with a comparable activity when their sport partners are not available because they are located far away. In addition, sportspeople often have difficulty finding local fellow sports partners with similar physical capabilities in order to ensure a mutually enjoyable experience [15]. One possible way to overcome this challenge is to expand the range of potential exercise partners by allowing people to engage in sports activities with remote partners.

4 Long-distance sports

To provide the opportunity to experience sports with long-distant partners, we are augmenting interactions familiar from traditional sport activities with computer technology to create new sports experiences for geographically distant players. This approach aims to promote similar mental and physical health benefits as in collocated sports activity, with the particular aim of supporting social connectedness between remote players. By utilizing the design lessons learned from collocated sports activities, we believe that new types of computer-mediated sports experiences have the potential to support social connectedness between remote players and maintain the bonds of friendship similar to traditional sports.

The next section describes two prototypes that showcase what we call 'Long-Distance Sports' or 'Sports Over a Distance' [16].

5 Breakout for Two

Breakout for Two is a combination of tennis, soccer and the computer game breakout played by two geographically distant players with a real, physical ball and a large-size videoconference (Figure 1). The name derives from the classic computer game breakout in which a player destroys blocks in order to 'break through' to the other side. With *Breakout for Two*, we aimed to utilize an exertion interface [14], which would physically exhaust the players. We hypothesized that such an exertion interface would create an increased connectedness between remote participants in contrast to non-exertion keyboard interfaces provided by most computer and video games.

Breakout for Two is a sports game for two players, or four players if it is played two-on-two, who are not in the same location. The emphasis is on the physical exercise of kicking and chasing a ball, combined with the social interaction of passing. In *Breakout for Two*, both players throw or kick a soccer ball against a hard-surfaced wall. On each wall, there is a projection of the remote player, enabling the participants to interact with each other through a life-sized video and audio connection (Figure 2).

Eight semi-transparent blocks are overlaid on the video stream, which each player has to strike in order to score (Figure 3).

These virtual blocks are connected over the network, meaning that they are shared between the locations. If one of the two players strikes any of them once,

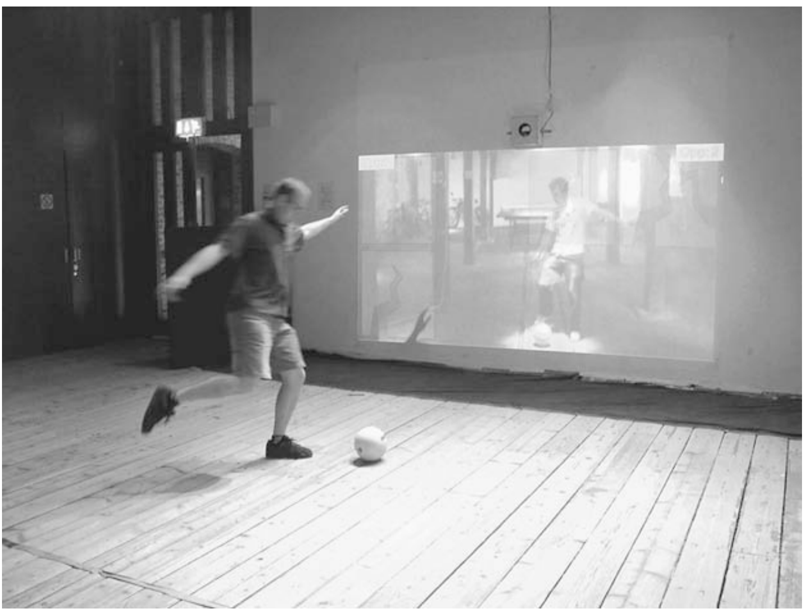

Figure 1: Breakout for two.

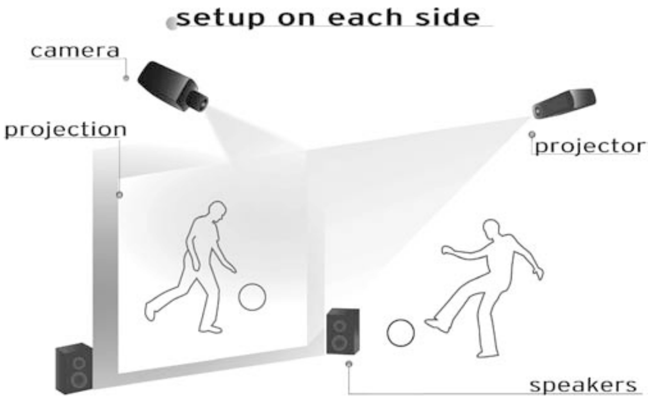

Figure 2: Set-up.

Figure 3: Semi-transparent blocks overlaying the video.

they ‘crack’. If that block is hit again, it cracks more. On the third hit, the block ‘breaks’ and disappears. This analogy was chosen to portray the idea of ‘breaking through’ to the other person on the remote end. The player would only receive a point if the block breaks. This scoring theme creates an interesting, strategic game because the players can watch what the other player is doing, waiting for him/her to hit a block for the second time, so they can then snatch the point by hitting it for the third and final time. In order to avoid a purely tactical game and encourage intense physical activity, an impact-intensity measurement component was added. If the player hits the block hard, it would not only crack a little, it would crack twice. A really hard strike could even break the block completely in one go. For this, the impact intensity was measured and mapped onto a 3-point scale. The harder the player hits a block, the more it cracks.

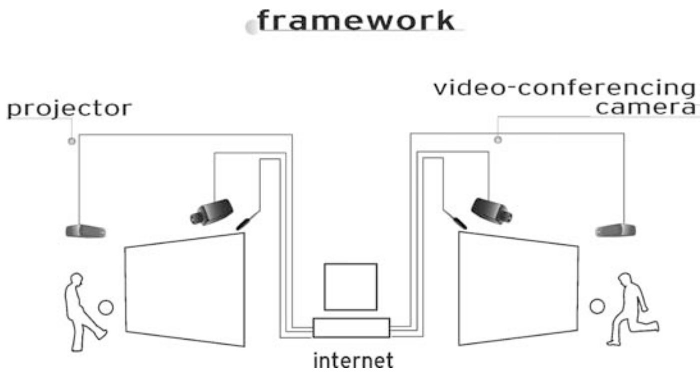

Figure 4: Framework.

The experience is much like being on a tennis court, with each player occupying his/her part of the field and the wall representing the net or boundary between the players (Figure 4). For the players, it feels as if they are separated by a glass window. They hit the ball in the direction of the other player, and it comes back, bouncing off the wall. This approach of a split court addresses the issue of physical body contact exhibited in many collocated sports, therefore the game is oriented on games such as tennis or volleyball, which separates players through distinct parts of the court. *Breakout for Two* focuses on a new sports experience, but leverages the familiarity of existing sports, making it accessible to anyone who has played with a ball before (Figure 5).

The virtual shared blocks support this approach, ensuring a direct interaction between the two players. Unlike, for example, a connected gym with a videoconference, where both players exercise while chatting with each other, *Breakout for Two* supports the idea that the actions of one player depend on the actions of the other player, allowing for strategic play and hence facilitating a sports experience rather than just an exercise.

5.1 Technical implementation

The players should be engaged in the sports activity, and not be aware of the technology, unlike for example in a training environment where the technology can be more exposed to the athlete (Figure 6). Enabling the distributed experience therefore requires a pervasive computing set-up: a camera seeing through a tiny hole in the wall provides the videoconference to the other player. Two additional cameras, mounted to the side of the wall aiming to capture a narrow area just in front of the wall, track the ball in order to calculate the ball's speed and impact location using vision detection (Figure 7). One camera is mounted to the side of the wall, detecting the vertical dimension, the other camera is mounted on top, facing down, measuring the horizontal component of the ball striking the wall. This video tracking of the ball allows to play even fast ball games such as tennis.

Figure 5: Two-on-two is also possible.

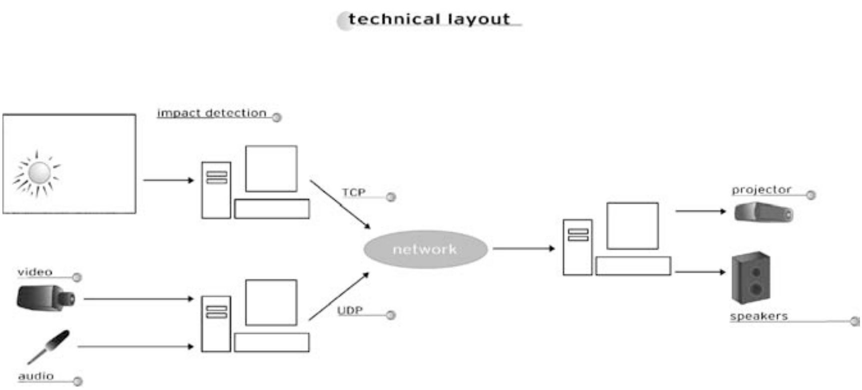

Figure 6: Technical layout.

5.2 Evaluation

Breakout for Two was evaluated against a keyboard-controlled networked computer game [17]. Fifty-six participants were split up into pairs, and were asked to play either *Breakout for Two* or an analogous computer game controlled with a keyboard, which utilized the same life-size videoconference. For each game, the

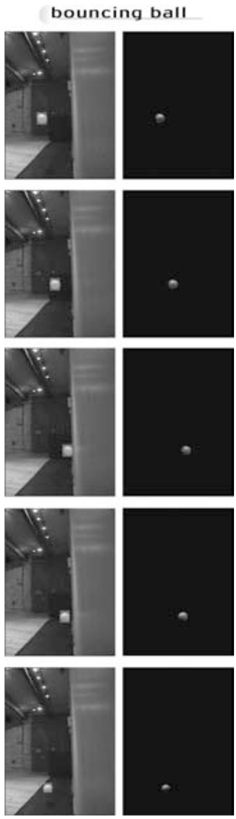

Figure 7: Vision detection of the ball from side camera.

two players were in two different locations and had not met each other before; in fact, the first interaction they had was through the videoconference.

The statistically significant measures showed that the exertion-game players rated the interaction with their new game partner higher in contrast to the keyboard players: they said they got to know the other player better, had more fun, became better friends and, surprisingly, were happier with the transmitted audio and video quality although the quality was identical between the two games. Almost all of the players in the exertion group were very exhausted after the game. Most of them told us that it was much more exhausting than they thought it would be. Indeed, the game can be very demanding and fatiguing. Some players were getting so involved that they were seriously out of breath and their shirts heavily sweaty. We had to put a water cooler close by because we got concerned that some participants might become dehydrated.

We also demonstrated *Breakout for Two* in a non-laboratory environment; the first test was at NextFest in San Francisco [18]. It is an annual technology world fair organized by *Wired Magazine*, and attracted 24,000 visitors in 3 days. The overwhelming rush gave us the opportunity to stress-test our equipment with thousands of visitors and to acquire extensive feedback.

We encouraged playing two-on-two in order to increase the throughput. Most players teamed up with their friends or family members to form a team of two, so most local teams were familiar with each other, whereas there was generally no prior connection between the local and remote teams. General comments by the players were 'Great!', 'Very exhausting', 'That was fun!' and 'I liked playing with my dad'. The teenagers, especially, were generally supportive of each other, often handing over a ball to a not-so-capable player. Even if a team was losing, we did not come across any serious blame among the players for the defeat. One of the players was in a wheelchair and played equally with non-handicapped players.

An obvious, but unexpected, cultural difference became apparent when we demonstrated the game overseas: Unlike Europe, where players mostly kick the ball with their feet, players in the United States mainly throw the ball. Soccer or football plays such an important part in European life (most Europeans play soccer in their youth) that the most appealing use of the ball seems to be to kick it. In the United States, where sports such as basketball, baseball and American football are part of the mainstream culture, players seem to be immediately drawn to throwing the ball with their hands. A young family visiting from Ireland proved the point: the children played with their dad by kicking the ball, although all the previous and following players threw the ball. When the ball was kicked, it was mostly by girls, probably because soccer is more popular with girls in the United States. One of the few players who kicked the ball was an ex-professional soccer player whose tactic was to stand way back and hit the blocks very hard in one go.

Breakout for Two was also presented at a broadband conference in Scotland (Figure 8). The target audience was very different from the one at NextFest: Businessmen and decision makers from international corporations in the broadband industry formed the main pool of attendees. Most attendees wore business suits, quite unpractical for a *Breakout for Two* session. General comments by the business people were naturally more of a financial nature: 'When can we buy this?', 'Why does our local pub not have it?', 'We could use this for our youth event'. The business players seemed to be more interested in playing matches with their colleagues than with strangers, and talked more with each other after a game. They debated more often than people at NextFest did, as to whether a hit was wrongly counted as one or two hits, and were more likely to follow a 'hard-kicking' tactic than the young players at NextFest. Their interest was mainly in 'releasing stress', having a social kick-about with their colleagues while still being very competitive.

This evaluation showed that if an interactive game requires intense physical activity, it can work better at fostering connectedness than one that lacks it. Physical activity encourages social interaction and affects one's overall well-being, and *Breakout for Two* demonstrated that this is now possible over a distance.

Figure 8: At a business conference.

5.3 Lessons learned

From our experiments with *Breakout for Two*, we had learned valuable lessons in regard to combining sports activity with computing technology. We believe there are three main reasons why our approach with a real, physical ball is superior to a virtual ball solution:

1. *More 'sports-like' experience.* The force-feedback of a real, physical ball creates an exertion that is essential for a 'sports-like' experience. Limited force-feedback technology, such as vibration, does not give justice to the rich interaction of a real, sometimes painful contact exhibited in sports.
2. *More direct connection with other player.* A real, physical ball frees players from head-mounted displays, which are often present in virtual games. Players can more easily make eye contact, and therefore, fully engage and interact with the other player. Being able to establish eye contact is particularly important in tactical sports such as tennis, where the player tries to 'read' the upcoming serve of the opponent.
3. *More durable equipment.* Physical, 'technology free' game pieces allow the players to concentrate on the interaction and not worry about damaging fragile hardware.

We believe the game structure was successful because it did not emulate, but drew from existing sports games. The player's movements and strategies resembled those observed in tennis. The players had to juggle elements of physical exertion (chasing the ball) with elements of tactics (hitting a block three times or instantly getting the point by hitting it extra hard). In the beginning of the games, both players were often equally quick in hitting the first couple of blocks. Once there were fewer blocks left, players often paused and started to develop strategies, assessing their own and partner's fitness levels and ability to hit the blocks hard or accurately. On the basis of this assessment, players often got closer to the wall, dribbling the ball and trying to hit the blocks with accurate shots. Others hit the ball very hard from further back, aiming to score points with single hits. The players often reassessed their tactics and varied it according to their own performance, and also the tactics of their opponent. Similar to tennis: a serve-and-volley player does not always play at the net, but varies it in order to irritate the opponent. However, *Breakout for Two* is neither tennis nor soccer, but rather a new type of sport, a long-distance sport.

6 Airhockey over a distance

Airhockey can be seen more as a leisure activity than conventional sport; however, just like a sport, it is competitive, requires fast hand–eye coordination and reflexes, and there are championships and leagues across the world. Nevertheless, *Airhockey Over a Distance* provides a valuable addition to the Long-Distance Sports domain for two main reasons. First, leisure activities and social sports can be of overlapping nature; leisure activities have also been attributed with benefits such as the capability of fostering companionships and friendships, and positive consequences for psychological well-being by promoting positive moods [1, 19]. Second, *Airhockey Over a Distance* demonstrates where the future for sports that separate the players by a middle line might be by allowing two geographically distant players to enjoy a match with a shared sports object. In *Breakout for Two*, the two players are conceptually separated by the wall with the videoconference over which they communicate, just like the net splits the court in half in tennis or volleyball. The players in these sports stay on their half of the court, and never cross the middle line. The ball, however, travels across the net, and is the main object of physical activity. *Breakout for Two* uses virtual blocks to emulate the experience of an object travelling across the boundary line, but ideally, the ball should hit the videoconference, travel across the distance and magically come out at the other end. *Airhockey Over a Distance* demonstrates a simplified version of this concept by limiting the interaction area to the surface of an airhockey table. It seems plausible, however, that future instances can deal with a three-dimensional (3D) situation and therefore support a larger range of sports games. *Airhockey Over a Distance* demonstrates, on a small scale, that the fast and physical intensity known from sports can be retained in a distributed environment, and aims to show the potential this approach has for more complex traditional sports endeavours.

Figure 9: Airhockey Over a Distance.

Airhockey Over a Distance [20] allows the object of interaction, the puck, to replicate its appearance across a network in a game of airhockey (Figure 9). Unlike in virtual simulations [21], the puck is a real, conventional airhockey puck that disappears on one end and is shot out on the other.

In airhockey, competing players try to score points in the opposing player's goal with a small round bat. The puck glides on a layer of air, pushed through hundreds of small holes, minimizing surface friction and thus enabling quick game play. Traditional airhockey is an accessible game as it does not require special skills nor does it have complex rules or a steep learning curve (Figure 10). Our system of *Airhockey Over a Distance* tries to replicate a similar experience between players, but across a network. Unlike in *Breakout for Two*, players appear to have only one puck, which they shoot 'through the network'. The players hit a real puck back and forth, trying to score a goal. The table is figuratively split in half and the two ends are networked.

Each player is recorded by a camera and the video is displayed on the screen of the other player, creating the illusion of playing together on one table (Figure 11). This videoconferencing screen is placed in the middle of the table, with a small area of space for the puck to slide under it. A projector installed above each table

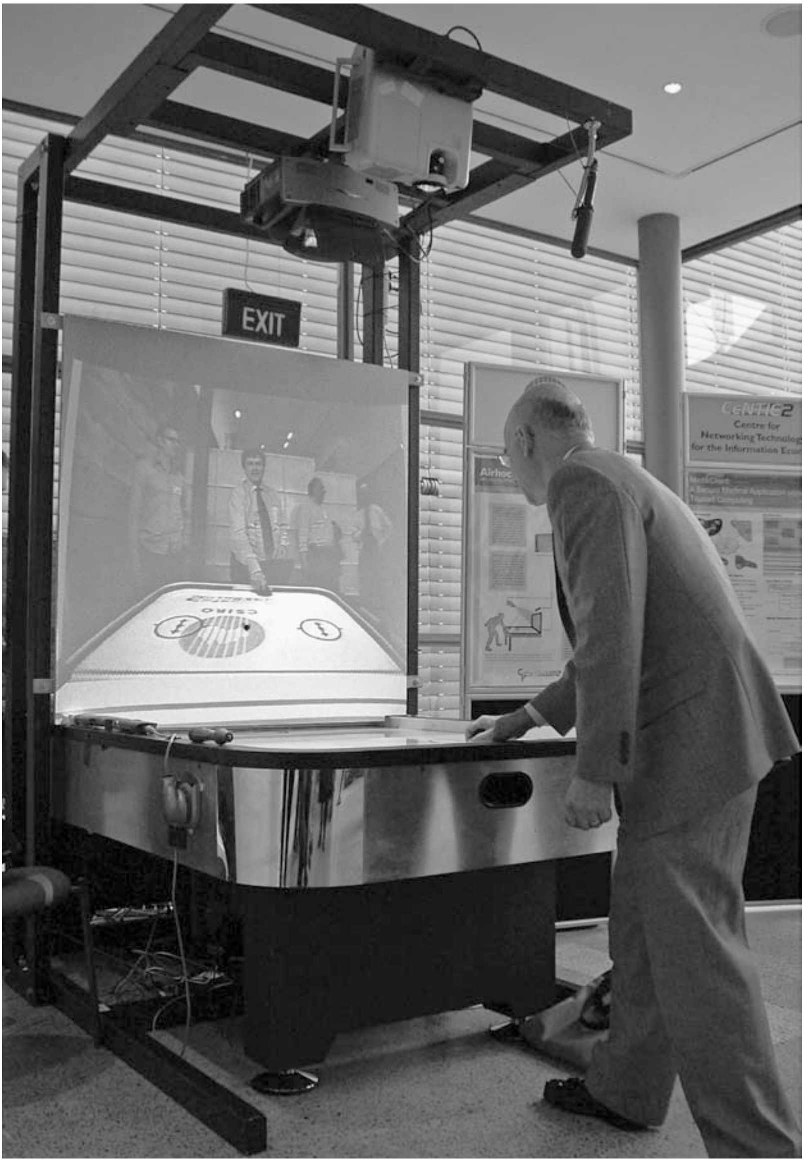

Figure 10: The set-up of Airhockey Over a Distance.

projects the video of the other player onto the screen. When a player shoots a puck across the halfway line, it disappears under the videoconference projection surface and is collected in a catchment tray behind the screen. At the instance it crosses the centre line, the puck is detected by a sensor which triggers the networked software. Once the software receives the signal, it triggers one out of

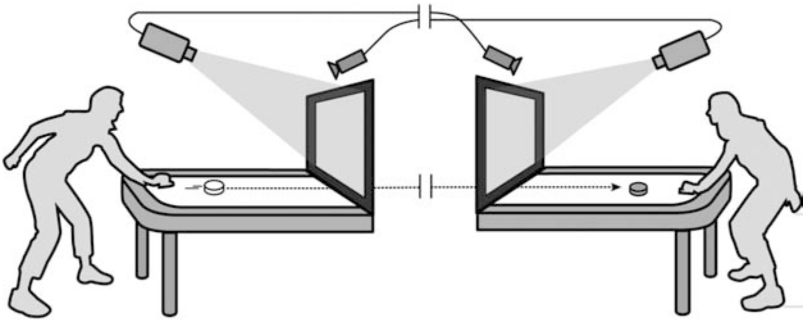

Figure 11: The puck travels 'through' the network.

four rotating puck cannons on the other table to fire out a puck (Figure 12). These cannons rotate around an axis, and a trigger mechanism pushes the current puck towards a spinning disc at the bottom, which shoots out the puck. This implementation can deliver similar speeds than a conventional airhockey game. Informal tests in the laboratory with the maximum speed the cannons shoot the pucks out resulted in pucks that were so fast that none of us were able to react to them. The cannons hold enough pucks for several games. For the players, it appears like they are passing a real, physical puck back and forth between each other through the network.

6.1 Evaluation

The aim of *Airhockey Over a Distance* is to demonstrate that a physical activity can contribute to an increased connectedness between geographically distant players. The physical passing back and forth of a real, physical object can facilitate an enhanced sense of a shared space for the players (Figure 13). Mechanical details like the precise replication of the puck's movements were not the goal of this demonstrator, but rather the concept of physical replications of sports objects for future Long-Distance Sports. We therefore focused on acquiring feedback from players to comprehend their experiences while playing and interacting with the system to inform future designs.

Airhockey Over a Distance was initially demonstrated to an audience of 100 researchers (who were not part of the development), of which 40 played the game (Figure 14). Subsequently, the system was stress-tested at a public event with about 30,000 visitors. The airhockey tables were set up in two different rooms from which participants could neither see nor hear each other. At both events, the reactions were very positive, and long queues indicated the popularity of the system. The uniqueness, familiarity and quick game pace of the system evoked an excited response from participants. Many players coordinated their friends' waiting time so that they could play together; this indicates to us that the game experience differs whether you play with strangers or people you know. Although

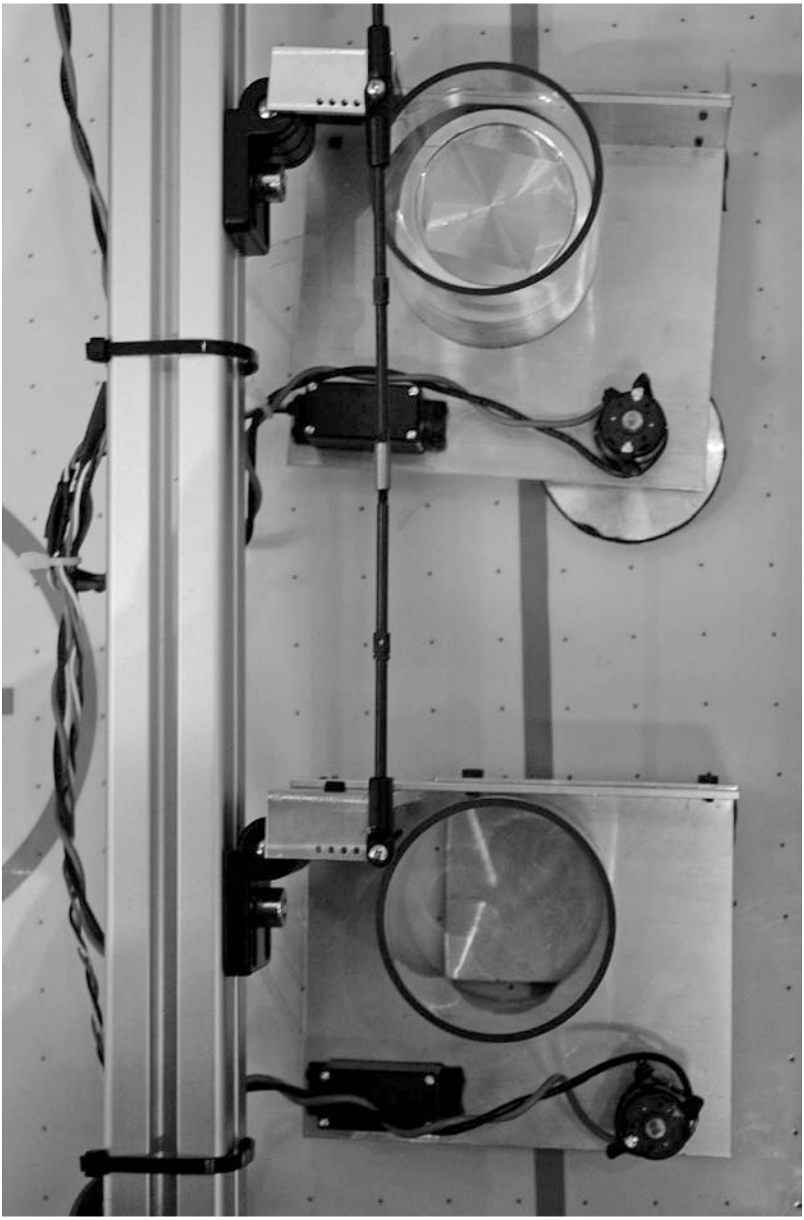

Figure 12: Birds eye view of two of the four puck cannons.

the audio environment was less than perfect, we observed a relaxed atmosphere between the players, who showed ‘thumbs up’ to each other or swore at one another. We recorded comments such as ‘This feels like playing on one table’ as supportive to our initial objectives. Also, sometimes really hard hits made the puck fly off the table, which triggered laughter and amusement by both players.

Figure 13: From a player's perspective.

Although the puck's trajectory was not replicated at this stage, the participants took it with bemusement and one participant in particular found an interesting viewpoint: 'This feels like my first salsa lesson, I'm slightly confused, but it's a shared experience to talk about'. Another participant exclaimed, 'If you could get pucks to line up, I think that's the only thing that's missing, other than that, I think it's pretty cool … very cool'. Other players took things 'in their own hands' and stopped and placed the puck with their hands in position, which is illegal by the airhockey rules, and elicited complaints by the remote player. Especially

Figure 14: Side view of Airhockey Over a Distance.

those ‘cheats’, facilitated by the physical presence of the puck, often lead to social interaction between players, hence contributing to an enjoyable experience as known from collocated sports.

We also distributed a questionnaire amongst the players and analysed 32 responses from 30 male and 2 female players. Thirty-eight percent were under 25 years old, 38% between 25 and 35, and the rest older. The participants had to rate statements on a typical Likert scale [22] from ‘strongly agree’ to ‘disagree’. Most participants (26) agreed with the statement that even if the returned puck did not have the anticipated trajectory as expected from the videoconference, it did not affect their interaction with the other player. The majority (31) stated that they had fun with the game. Twenty-four participants said that they wanted to play longer, and 15 said that the game created some sort of bonding between them and the other player (8 were indecisive). Twenty-two players confirmed that they had a sense of being in the same room with their opponent (4 were indecisive).

Even though this was an informal evaluation, we were able to observe that participants had a shared experience with their game partner. When being interviewed about the game experience, an enthusiastic participant commented, ‘I'm taken with this … you could have a true interaction with someone, they could make you laugh, they could make you swear … that kind of interaction is unique, without abusing the word’.

7 Application

We envision *Airhockey Over a Distance* to be played in places that already provide socializing opportunities. Arcade parlors are a possible venue for

Airhockey Over a Distance in which collocated airhockey tables are already installed. Placing connected airhockey tables into community clubs could enable members to get in contact with people from different countries to facilitate the learning of other cultures and languages. Installing systems in hospitals might help inpatients combat loneliness by providing the opportunity to play with family and friends as well as peers in other hospitals.

The casual gaming aspect of *Airhockey Over a Distance* suggests a similar application domain to *Breakout for Two*; however, due to the smaller space requirements, implementation is more feasible in airport waiting areas or other smaller areas where participants are separated by their loved ones and want to stay in touch through an engaging activity that provides a sportive challenge.

Long-Distance Sports can support a sense of connectedness between friends who live geographically apart, and the depicted systems were designed with this user scenario in mind. Due to the ice-breaker potential of casual sports, they can also be used for introducing strangers, as demonstrated in the evaluation of *Breakout for Two*, in which the team members got to know one another through the videoconference. Long-Distance Sports can also support or initiate the dialogue between players who do not speak the same language: international competitions and sporting events such as the Olympics or the World Cup demonstrate that sport can be a universal language for bringing people together. Professional athletes could also use long-distance sports not only to compete, but also to train with remote fellow sports partners. Once players reach a certain level of sophistication in their sports, it can be difficult to find appropriate training partners who exercise on the same level without travelling extensive distances. Systems that support training with geographically distant sportspeople could contribute to the training effect, resulting in increased performance by the individuals.

If individuals could use Long-Distance Sports to their advantage, it could be envisioned that teams could also benefit from such an approach. Furthermore, instead of supporting one team in one location, the other in the remote place, it could be possible to change the notion of what constitutes a team by swapping the team partners: the local players' opponents are collocated, but their teammates are in a remote space and vice versa. This could lead to more challenging team constellations and might also contribute to an increased dialogue between participants due to the fact that the teams can be interchanged more easily.

It has also been suggested that long-distance sport systems could not only help professional athletes, but support amateurs in finding suitable exercise partners [15]. For example, joggers could not only use telecommunication systems to stay in touch with jogging friends who moved away, but also use this in combination with a searching tool to find partners worldwide who run at the same time, the same distance, at the same speed in order to enhance their sporting experience.

Long-Distance Sports could also contribute to a community effect by supporting the social exchanges between groups: one can envision a community-based Long-Distance Sports system installed in two public places of two sister cities. Instead of supporting the usual exchange between a few individuals of the two sister communities, this approach could allow for a more bottom-up exchange between almost anybody in the two groups: people could visit the Long-Distance Sport facility, meet new people from the sister city through the mutual exercise and maintain friendships through regular games.

Casual sporting games could help business people who travel often to stay in contact with their young children at home. Hotels and airport lounges could offer Long-Distance Sports facilities that allow frequent flyers, although away on business, to exercise with their children. With the increase of bandwidth availability on planes and the installation of gyms on large aircrafts, travelling executives could use their idle time to play a sports game with their families, achieving several benefits: they stay in contact, can update each other on their daily lives, use the game as facilitator to engage in an activity together and profit from the joined physical exercise, resulting in better health.

Taking the long-distance aspect to an extreme could be the mutual sports experience between people on earth and participants on space missions. The loss of muscle mass and strength while being in space is of concern on long-term missions. While the use of exercise programs to combat this is still under investigation, being able to engage in fitness activity with loved ones on earth is likely to be welcomed by the isolated astronauts.

7.1 Applicability of existing sports

The Long-Distance Sports depicted here focus on a physical experience that takes place on two sides of a videoconference, related to a sport in which players act on two sides of a net, for example tennis. Other sports, such as cycling or cross-country skiing, involve covering a certain distance in the shortest possible amount of time. The players do not necessarily 'need' one another to achieve their goal, and one could assume that a long-distance version of such sports could be easily achievable by letting participants run or cycle their distance on their own, and afterwards let the competitors compare their times on the Internet with one another. However, participants in competitions know that the presence of other sportsmen, trying to achieve the same goal in a faster time, may help them to achieve better results. The presence of others facilitates a competition that is conducive to performance enhancement. Ijsselsteijn *et al* [23] reports on an experiment with augmented exercise bikes: '… where the presence experience was stronger, participants reported more interest and enjoyment, and they exercised harder'. This presence is essential for the experience, and the recreation of such a sense of presence of the competitors is one of the main challenges of successful Long-Distance Sports.

8 Conceptual position

The traditional influence of computers in the sports domain was dominated by the need of professional athletes to increase their performance; computers were expensive, and only teams with large budgets could afford computing technology to enhance their training capabilities. With the advent of cheaper, more powerful and easier-to-use technology, many amateurs use computing power to enhance their sporting experience: joggers use MP3 players to play back motivational instructions or music to distract their mind, cyclists use small computers on their bikes to measure distances, users of treadmills use electronic heart rate monitors to stay in their optimal heart rate zone, runners track their distances with GPS devices, and hobby coaches tape their team's performance on consumer cameras for later analysis. These examples show that sports hardware and software, initially used by professional athletes, have now been adopted by hobby athletes to enhance their experience. Possibly due to their history, most of these technological advances are training tools aimed to measure individual performance. Not many of those support the interaction between teams or are used directly during sports play, but rather for analysis afterwards.

The domain of Long-Distance Sports seems to have originated from an opposite direction: the examples described, with their focus on social interaction between players, were initially aimed towards amateur sports people, and focus on enhancing the mutual sports experience during, not after, game play. The advances of telecommunication technologies especially make Long-Distance Sports possible. In particular, the videoconferencing quality predetermines a use in casual sports, where certain glitches in transmission might be acceptable and can be forgiven with a laugh, as experienced with the prototypes described above. However, these teething problems are probably not acceptable for professional sporting events, and technology needs to advance before it is suitable for such use. On the other hand, the focus of current implementations of Long-Distance Sports on amateur sports experiences might serve as a useful test bed for professional applications, and open up new opportunities for using computers in the professional sports domain. We might even see professional Long-Distance Sports Olympics in the future.

Figure 15 shows the conceptual position of long-Distance Sports in the sports and computer domain with the focus on casual physical experiences and the use of networking technology.

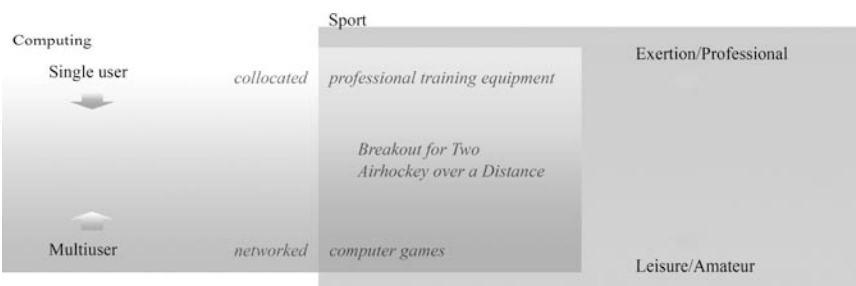

Figure 15: Conceptual position of long-distance sports.

9 What computing and sports can learn from long-distance sports?

Computing technology helps to bring the vision of Long-Distance Sports into practice. The sports computer science research community can learn from the Long-Distance Sports domain how to support casual athletes, in particular their aim for social interaction, in contrast to pure performance enhancement. The computer science community, on the other hand, could benefit from the Long-Distance Sports examples how to build robust technology that can withstand the roughest user input. The sports community can gain ideas from the Long-Distance Sports approach on how to provide novel experiences that might attract new user groups: for example, researchers have realized the potential of Dance Dance Revolution, an exhausting dance arcade game [25], to engage teenagers that otherwise cannot be excited about sports activities. They therefore installed these machines in public schools in the US state of Virginia to address the issue of obesity amongst school pupils [24].

10 Related work

Other developments of augmenting sports with computing technology have gained increased attention over the last years. Most systems for casual sportspeople focus on tracking progress for performance enhancement, for example heart rate monitors and GPS watches. Most of these devices support a single user only; multi-user support mostly occurs after the exercise by comparing pace timing on the Web with others [25]. Most of these devices fall short in terms of social interaction, or require the partner to be present in the same physical location and do not support the creation of teams. With our vision, we aim to address these issues.

There is only a limited number of examples of sports systems available that can be played over a distance; however, the current increase in commercially available exertion interfaces combined with advances in telecommunication technology suggests that we will see many more in the near future [26]. An earlier mention of the term Long-Distance Sports has appeared in a study by Marriott [27], but it focuses on commercial products. From a research perspective, *Computer Supported Collaborative Sports* [16] investigates the design of computer applications which require sportive input activities to gain collective game experiences, mostly executed over a distance. It differs from the current approach by spanning the entire scope of multi-user competitive or cooperative settings, also including settings of mere co-presence (riding bicycles individually in a shared space), where competition or cooperation is not required to achieve goals.

A networked gym system is *NetAthlon* [28], which allows riders of exercise bicycles to race against other remote riders, represented by 3D avatars, using either a screen on the handlebar or a head-mounted display. However, it does not support audio or video interaction between the cyclists. The *Virtual Fitness Center* [29] uses a similar approach with exercise bicycles positioned in front of a video screen. The physical movements conducted on the exercise bicycle are used as input to modify the representation of 3D virtual environments from map information. Reversely, the map information affects the pedaling efforts. *Push'N'Pull* [16] is a networked exercise machine, which the players use as interface for a cooperative game, supported by a high-definition videoconference.

An early example of a ball sport over a distance is *iball* [30]: a player throws a ball into a basket, a detection mechanism recognizes and transmits this information and pops a ball out at the other end, creating a simple basketball game between two players. Even an earlier attempt (built in 1986) of distributed physical activity over a network is *Telephonic Arm Wrestling* in which the player arm-wrestles the opponent over a phone line [31]. The idea of arm-wrestling an opponent far away has been implemented in several museums across the United States to demonstrate this concept [32]. *Tug of War* has also been networked: At the New York Hall of Science two teams of high-school students were involved in a tug of war 13 miles apart from each other [33]. More exertion interfaces are described in Ref. [34].

The advent of a new style of computer games with a sports theme has also arisen. The move of Nintendo away from a traditional game pad as input device for their latest console signals that the entertainment market will incorporate more sportive activity: The console comes with a controller that contains accelerometers. In order to hit the virtual tennis ball, the player uses the controller like a racquet [35]. Another example is *EyeToy Kinetic* [36], a personal training workout game, which tracks a user's body movements using a webcam to provide a personalized workout program right in the living room.

Lawn and Takeda [37] define an 'action interface', which enables remote participants to play table tennis together. The players make an arm movement as if they are trying to hit the ball; however, the ball exists only on the screen, so the players never experience a force feedback regardless of whether they hit the ball or not. The authors suggest such a system for rehabilitation.

The *Bodypad* [38] supports exerting body activity as input control through pressure sensors on the hands and legs, replacing button presses. Two players can fight each others' avatars, but only in front of the same screen. A multi-player arcade game is *Virtual Arena* [12], where the body movements of the players are tracked and mapped onto fighting avatars, so the players are able to hit one another without getting hurt. The two players are standing next to each other, looking at a screen with their avatars in front of them. Although there is currently support for only local play, it seems plausible that this system could easily be expanded to work across remote locations. *Table Tennis for Three* [39] is a table tennis game that three players can play together simultaneously, even when they are geographically apart. The game play works similarly to *Breakout for Two*, but supports three players at once through a split-screen videoconference. In *Jogging the Distance* [15], O'Brien *et al* investigate the social dialogue between joggers and suggest using a spatial audio channel that plays back the other jogger's audio relative to their running speed. The authors believe the computer-augmented social audio support can motivate the participants to jog longer more often. Tennis Sensation Pro [40] is the winner of a product design engineering competition that allows blind people to experience a tennis game through the use of (proposed) spatial audio and a force-feedback racket. Although not clearly demonstrated, but accommodated for, networking the motion system could allow for games between geographically distant players.

11 Future work

We demonstrated that the augmentation of sports activities with computer technology can support casual sportspeople and allow for social interactions. Our prototypes show that a shared physical activity between geographically distant players is possible. However, there are still many challenges ahead and many opportunities yet to be explored.

11.1 Asynchronous long-distance sports

The aforementioned prototypes utilize a videoconference as main communication channel between the participants, hence supporting a synchronous interaction (besides a small network lag). However, if players from different continents want to participate in sports together, they might encounter the problem of finding a suitable time for both of them, being in two different time zones. This problem is intensified if participants join from several different places, increasing the number of different times to accommodate for. Although Long-Distance Sports eliminates the need of being in the same location, it does not affect the synchronous aspect of sports, the fact that sportspeople exercise with one another at the same time. Although technology probably holds potential to address this issue, the asynchronous realization of a shared sports experience has yet to be successfully demonstrated.

11.2 Scaling of long-distance sports

So far, the focus has been on supporting two geographical sites with one or two players each, similar to conventional sports with one or two players on each half of a court. However, how does this concept scale, not only supporting larger teams than two, but also multiple sites? Technologically it is easily deployable to attach additional nodes to the network, but how does the game play need to adapt in order to support three airhockey players? How about 100 playing simultaneously?

These open questions pose many opportunities not only from a computer science viewpoint, but also from a sports perspective, because the nature of how we participate in physical exercise with others is challenged by these novel concepts. We might have a different understanding of sports in the future from the one we have today, and might not think twice about exercising with others in remote locations, coming together with people far away, making the world a smaller place.

12 Are we going to play long-distance sports soon?

A commonly asked question is 'So are we going to play Long-Distance Sports soon'? This often comes from participants who got a taste of it having played some of the available prototypes. We will probably not be able to see traditional sports competitions such as football, basketball or volleyball being played by participants that are located in different countries any time soon. The technical challenges might be too complex and professional leagues might not have a demand for this. What we could see happening, however, is a drive towards Long-Distance Sports from the computing, in particular the entertainment area: computer games incorporate more and more physical body movements as input controls with the advance of smaller and cheaper sensing technology and advanced processing power. This trend is supported by the recognition that most developed nations face an obesity crisis, and computer games can reach children and teenagers that have otherwise no interest in traditional sports. Parents might prefer buying games that support physical activity for their children to games that simulate killing people. With the advent of advanced game consoles and high bandwidth in the home, it is likely that the first commercial mainstream instances of Long-Distance Sports will be played in front of large living-room screens between family members from different cities. These games might support multiple players in each location, supported by high-resolution video and audio. Wireless bandwidth is also increasing, and therefore support for outdoor sports will be possible, for example, for joggers who will use ubiquitous devices that enable a Long-Distance Sports experience anywhere and anytime.

These instances will initially have more of a computer game than a sports character; however, with the advances of pervasive technologies, the computer aspect will step into the background and the sports aspect will dominate. Technology-open individuals will be the first to use these systems, willingly changing rules to enable them to stay in touch with distant friends. Casual sportspeople will not be bound by rules and regulations of sports bodies and are therefore free to modify their sports to allow for a long-distance experience. Long-Distance Sports will enable a new breed of sport experiences, allowing players who otherwise would not be able to participate because they are in a distant location, to join the fun.

13 Conclusion

Sports currently play an important role in the contribution to our health and our social network. However, so far, we can only exercise with people in the same geographical locations. Recent advances in networking technology and computing advances demonstrate that networked sports activities that create an increased connectedness between geographically distant players are possible: *Breakout for Two* allows remote family and friends to play together an exerting game similar to soccer. It features virtual distributed targets overlaid on a videoconference to achieve the sense of 'doing something together'. *Airhockey Over a Distance* is a casual social game in which the players hit a real, physical puck back and forth between each other. However, not so much of a sport in the traditional sense, it shows the direction of networked physical activity by demonstrating the concept of a shared space: the object of interactivity, the puck, disappears in the videoconference and comes out at the remote end. Currently supporting only a 2D surface area, the concept demonstrates a novel approach, possibly applicable for conventional sports games. Players reported a shared space experience, describing it 'as if we are playing on the same table'.

These sports games with their potential for being social interaction facilitators can support physical activity between participants that are geographically apart. Providing remote friends and families with a social sports activity can contribute to maintaining their bond, and work against the dissolution of the tie. Long-Distance Sports support people connecting with one another on a social level. Players use the universal language of sports to come together, and now they can do this with people all over the world.

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2. Modelling/Simulation

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Coaching and computer science

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Abstract

Coaching is one of the earliest areas of application of computer science in sports. It may be divided into three different activities – preparation, control and debriefing of competition. These stages create different conditions for the support of coaching by computer science with the stage of competition control being most demanding, because data acquisition, data processing and data-based interventions have to take place during and at the site of the competition.

The history of computer science and coaching was marked by continuous technological progress and growing conceptual insights into the process of coaching. Although there is considerable support in processing observational data including video data, it has to be acknowledged that central activities of coaching are not affected yet, e.g. analyses of strengths and weaknesses or the central task of strategy development and implementation. Conceptual advice for these tasks of coaching is obtained by qualitative research methodology, e.g. for assessment and intervention. Nevertheless, there are excellent perspectives for coaching and computer science. Real-time position analysis (RTPA) will allow support during competition. Analyses on more abstract levels than just positions will become possible using methods of artificial intelligence. This will result in new options with unforeseeable impact on the work of coaches.

1 Introduction

Coaching is one of the earliest areas of application of computer science in sports. Especially in game sports analysis tools from computer science were introduced very early, that means almost as soon as they were technologically available. Interestingly enough, in the 1970s parallel developments occurred in different countries dealing with the same problems without knowing about each other [1, 12, 24].

The situation has improved a lot since the founding of the International Association of Computer Science in Sport (IACSS) in 2003 that organizes biannual meetings for the exchange of knowledge and recent developments in this area. Still, applications from the area of coaching make up many of the contributions to these conferences and to the International Journal of Computer Science in Sports (IJCSS).

The reason for the attractiveness of computer science to sports coaches is simple. Imagine a football game with 22 players going on for 90 minutes. As almost any action is of relevance for coaching, acquisition and data processing of behaviour in football deal with an overwhelming number of behavioural items during a match. In fact, satisfying observational systems in many sports have only become possible through the aid of computer science.

Although pointed out already 30 years ago, some of the aims of introducing computer science into coaching are still far from being achieved. There are different reasons for this. First of all, there was too much optimism concerning the impact of computer science developments into sports practice. The willingness of practice to adopt computer science technology into their daily work, but also the capabilities of computer science in these early times were largely overestimated. The nature of the problems in the coaching process was not well understood, especially the fact that coaching comprises activities that are only to be supported by computer science if severe problems of artificial intelligence are solved. The solution of these problems has come within the reach of computer science only recently. Finally, there was large-scale failure in supporting coaching by computer science simply because one didn't know how to conduct a scientific intervention in sports practice appropriately. In some of these areas there has been much progress in recent years. Especially technological developments allow us nowadays to think about projects that are actually able to realize the 30-year-old dreams.

This chapter starts with some remarks on the process of coaching. It makes clear the requirements for giving support in this area. After that the technological standards for preparing and analysing a competition are outlined. The final paragraph glances into the future and describes the state-of-the-art and possible developments in real-time analysis of sports, which supplies coaches with tactical and strategic hints during a game.

2 Coaching

This paragraph starts with a definition of what we want to understand exactly by coaching. After this, coaching is divided into three different activities – preparation, control and debriefing of competition. These activities are analysed with respect to the demands they pose to support by computer science. As it is difficult to describe the potential impact of computer science to coaching for every sport and every group of sports, most examples used come from team sports like football, volleyball and basketball. Things may be quite different in other sports, and the arguments lined up here have to be carefully transformed to further areas of application.

2.1 Definition of coaching

Coaching comprises all activities in training that are directly related to a special competition. These activities may occur before, during or after a competition and are termed preparation, control and debriefing of competition, respectively. By *training* we mean coaching as well as all the other activities not related directly to a special competition [10].

This definition of coaching differs a little bit from its meaning in English or American, where coaching is a more comprehensive term. The advantage is that we are now able to distinguish between more long-term oriented or routine measures and those related to a special competition. To make it clear, coaching activities are considered of being a subset of training activities.

What are those activities in coaching? Because we have basically a short-term range for the measures, we find activities predominantly where we can induce changes on a short-term range. That means we are, for example, talking about cognitive aims like a game strategy. We try to build up an appropriate mental attitude towards the competition, and we have the big issue of motivation which is considered to be very essential by many people. To a lesser extent we find physical adaptations as the aim of coaching because in general this takes longer periods than available for coaching.

It is short-sighted to assume that the support by computer science contributes only to cognitive aspects of coaching, e.g. developing and implementing a winning strategy. There are good reasons to assume that a proper support in this area, an elaborate and well-founded game strategy obtained with the help of up-to-date technology strongly exhibit an influence on motivational and psychological aspects. Up to now this assumption remains hypothetical, though, unless some research is conducted to enlighten that interesting question.

2.2 A conceptual framework for coaching

Although we want to restrict the reach of the term 'coaching' to a narrower field of activities in training related to a special competition, it is useful to distinguish different stages in coaching. Especially, the role of computer science is different in those phases. This point will be discussed after a brief introduction of the three stages.

Figure 1 shows the three stages of coaching we want to distinguish. The criterion applied is simply the temporal position of the activities relative to the competition one is preparing for. Coaching activities before competition are called preparation of competition, those during a competition are termed competition control and all coaching activities after a competition belong to the stage of competition debriefing. What are the specific aims, what are the typical settings of these three stages?

The *preparation for a special competition* is the first task in coaching. The big issue in this phase is the competition strategy, i.e. an action plan based on an analysis of my own team and the opponent with the aim of maximizing success in the upcoming competition. We may distinguish two phases in this stage of coaching. The strategy has at first to be developed by the coach and then the athletes have to be trained to be able to execute it. This in turn requires a cognitive and

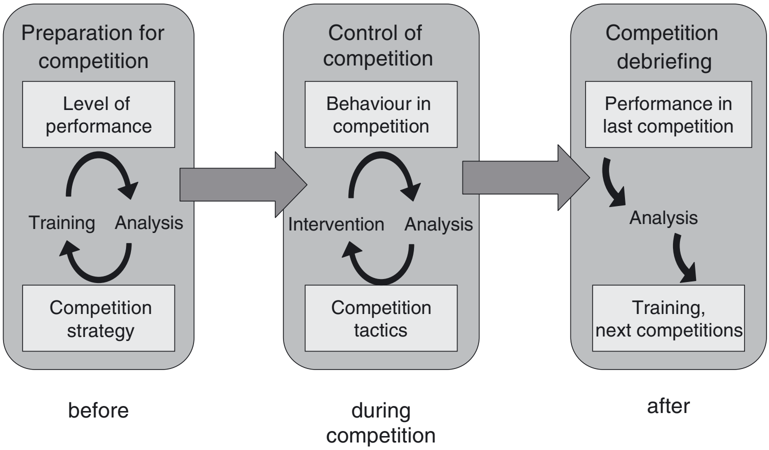

Figure 1: Stages of coaching [10].

eventually a motor learning process simulating decision behaviour in situations the competition strategy is referring to.

Of course we find deviations from the classical roles of the coach and the athlete. Especially in individual sports athletes are also engaged in strategy development and not just passively receiving the instructions of the coach. The setting in this phase is typically the regular setting of a training session. In general, there is enough time to complete the tasks of this phase, unless we have a tournament with a tight series of matches. In beach-volleyball, for example, the typical World-Cup tournaments require several matches per day, which makes it very difficult to extensively develop a strategy and to teach it thoroughly to the athletes.

Control of competition is the task of the coach during the event. The coach observes permanently the game regarding two aspects: Is our competition strategy in effect, i.e. has it become our competition tactics, and is there success or failure of my team? In case of undesired deviations from competition strategy the coach tries to re-establish it. In case of success the coach reinforces the perceived causes of success. In case of failure the measures against the perceived causes are to be taken. The longer the match lasts, the more likely deviations from the initial strategy occur.

Two basic problems arise at this stage of coaching. First, we frequently find limits of the coach's ability to realize reasons for undesired behaviour during the match. This is partly due to the fact that the observation does not cease while reasoning. Second, even if appropriate measures are identified, there are limits to a successful intervention. It is difficult to transfer the necessary information to all the players, especially if there are basic changes required.

The latter problem depends largely on the rules of a specific sport. In many sports the rules provide 'natural' opportunities for an intervention like breaks between periods of a match. Two, three, four or nine periods are some well-known examples. In some game sports the coach may take time-outs that provide, of course, excellent opportunities for changing or reinforcing the competition strategy. The replacement of players is another measure to influence the match that is controlled by the rules. Finally, the rules specify the communication between the coach and the players during a match what is of course important for the ability of the coach to exhibit control. These considerations make it clear that the conditions to exhibit control during a match are excellent in some sports, e.g. American football, and not existent in others, e.g. swimming. Here, it may be speculated that the coincidence of opportunities for coaching during a competition with opportunities for placing advertisements during its broadcasts have led to excellent conditions for coaching in the United States' big four: American football, baseball, ice-hockey and basketball.

The setting in this stage of coaching is of course the competition itself. Observation, analysis and communication are processes that run parallel to the competition and have to be performed at its location.

In *competition debriefing* the last performance is analysed in depth and reasons for success or failure are identified. Another important item of analysis on this stage is whether or not the chosen strategy was appropriate.

The results of these analyses are used as cognitive or motivational feedback for the players. They are also a valuable input for short-term planning of the next periods of training, if the analysis has detected important targets that may be addressed by a short-term training intervention. Targets for long-term training may be collected and aggregated over several analyses. The critical analysis of the chosen strategy is part of the coach's learning process on that meta-level.

The setting for the feedback is typically the next training session. Also, at this point in time the short-term consequences of the analysis for the training process have to be known. The analyses may be performed at any place available in time to meet these demands.

2.3 Conditions for support by computer science

In general, the setting of the *preparation stage* exhibits hardly any restrictions to the use of technical support for the analyses. We may work at the usual analysing facilities; we may conduct in-depth analyses of the next opponent without too much pressure of time. Results have to be present before the last few training sessions in order to teach the competition strategy to the players. Of course, it is necessary to schedule sessions between the head coach and the staff responsible for performance analysis.

It must be mentioned though, that these nearly ideal conditions cannot be met in certain settings, e.g. in tournaments of net/wall games where we typically have a high density of matches (daily or even several matches a day) and we get to know the next opponent only comparatively late. This makes it difficult to clear all the tasks of this stage in time, a fact which is not compensated by the availability of up-to-date information on our opponent.

The setting of *competition control* imposes strict limitations to support given by computer science. The aim is to give the coach some advice for his decisions of how to influence the match. As these decisions have to be ready at the intervention points, the supporting information has to be available prior to these interventions. We are forced not only to execute data acquisition and data analysis in parallel during the match but also to present these analyses in a useful fashion to the coach whenever he needs it.

Moreover, in addition to these strict temporal limitations we face the problem that support has to be organized at the location of the competition. This may cause severe problems in away matches with restricted access to the competition site. Also, making videos of sports events has become a juridical problem in the last years. The task is also to establish a reliable communication network between observers – usually several ones distributed over the location, the game analysis coach and the head coach.

In the stage of *competition debriefing* we may in general work again at our usual analysing facilities. It is important to note though, that information is needed as soon as possible after a match, because feedback should be given as early as possible to the players, ideally in the next regular training session after competition. A professional staff is required to meet these demands reliably especially when analyses are very time-consuming.

The purpose of this chapter was to introduce the different stages of coaching in order to make clear the different tasks of the respective stage and the temporal and local restrictions we may face if we want to support the coach in these stages. It has been shown that requirements differ largely among these stages. The next chapters present the state-of-the-art and perspectives of computer science to give support for the respective stages of coaching.

3 Computer science and coaching: history and state-of-the-art

Computer science and coaching is a typical interdisciplinary research area. It has been subject to considerable progress due to technological developments in computer science. On the other hand, sports science has the task of observing the technological progress and considering whether new desirable applications are accessible. If this is the case, true interdisciplinary work starts by analysing the problem and looking for a structure that allows the task to be solved with the help of new developments.

In this chapter the most important technological developments in the past are examined with regard to their impact on coaching. From the view of sports science, the structure of classical observational systems is analysed and recent insights and the state-of-the-art of the methodology of game analysis are reported.

3.1 Technological developments

One of the most outstanding characteristics of computer science is its enormous progress in hardware developments. Perl (2006) examines the last 10 years and observes increases in processing speed of about a factor of 30 and even a factor of 50 for main storage devices. These quantitative developments result in different qualities, too. User interfaces, multimedia and communication have changed dramatically in the last decade. On the other hand this was achieved by an increasing complexity of software architecture which makes software development the exclusive task of professionals.

What were the most important developments for coaching? The very first applications of computers in game analysis made only use of the data processing capabilities of computers. As still present in the French 'ordinateur' for computer, one was able to get lists sorted for many aspects basically from data gathered by hand notation. If one records for example point of time, player and action, three lists sorted by these variables provide specific analyses. Even being rather primitive, these analyses are pretty difficult without the help of a computer. So, we have a first phase of computerized observational systems in sport that is dealing with transferring hand notation systems to the computer.

The next phase is characterized by efforts to optimize the interface between observer and computer. In the eighties QWERTY-keyboards were partially replaced by digitization pads. These are electronic devices that allow to point with a digit to a spot on the pad and record the coordinates of this contact. By defining areas on the pad according to the categories of the underlying observational system, one was able to enter observational data much faster than before. New qualities of analysis were also achieved by this new technology, because it also allowed to record positions of ball and players by transferring positional observations to a pitch laid out on the digitization pad [4].

Another development aiming at the facilitation of data entry is the voice detection [26, 20, 19]. The idea is to transfer spoken comments to the categories of an observational system. Although there were some early efforts, the potential of this technology has not been exploited to its full extent. Especially considering the present progress, making it for example possible to direct traffic positioning systems by the voice of the driver, gives reason to assume that just a severe effort is lacking that makes voice detection a valuable tool for observational analyses in sports.

Another phase of development was achieved when it became possible to control video by computers [27, 6]. These early multimedia applications were most important for coaching and game analysis because video is the most common medium to document sports. Again, a hardware development – new interfaces between computers and video – allowed to introduce new solutions to problems of sports practice. Feedback given as a result of performance analysis could be presented using video, the most widespread medium in sports. Above all, the content of feedback could be selected by the medium responsible for the analyses, the computer. It has to be mentioned though, that a practical impact in a broader sense took place only with the transition from analogue to digital video in the late nineties, which is again due to the increased data processing and data storing capacities. This phase represents the state-of-the-art of common observational systems at present.

Figure 2: Information technology for game observation.

Another line of development has to be mentioned. Together with the astounding increases in capacity there was a considerable decrease in physical size of information technology. This trend is especially important to applications in coaching, because we rely on mobile, easy-to-install and physically robust devices due to the scenarios mentioned above. In addition, a considerable reduction in costs is an interesting feature of computer technology. Since the introduction of personal computers in the early eighties computer industry aims more and more to sell its products to consumers rather than to professionals. This development has of course extremely facilitated the use of information technology in a field like coaching.

Figure 2 shows the technological equipment used to support coaching of the German national beach-volleyball team at Bondi Beach during the 2000 Olympics at Sydney (bronze medal). The observer occupies just the space of a regular spectator with a video camera and a laptop. Video is stored directly at the hard disk of the computer; the observer codes the beginning and the end of rallies and may enter first comments. The costs for his equipment were about 1500€.

3.2 Observational systems

Parallel to these developments in computer science that were gradually introduced in coaching we also find developments in sports science in the search for appropriate observational systems for analysing sports. These developments were

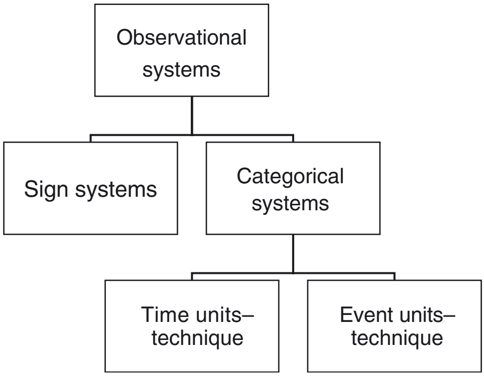

Figure 3: Strategies for designing observational systems [16].

inspired by the concept of model building which is also an important issue in computer science [3, 23].

From behavioural sciences we have learned about different strategies of how to build an observational system (see Figure 3). If we are interested in special events, we use a sign system. Here, we code every appearance of a certain, well-defined sign, e.g. a pass or a shot at goal. The result is a list with frequencies for all the signs we have specified beforehand. Alternatively, we are interested in the 'stream of behaviour'. In this case we have to specify a comprehensive categorical system with which we are able to describe the state of our behavioural system at any time. Within this strategy we have two techniques. One may structure the stream of behaviour temporarily in coding the state of a system for successive time intervals, e.g. code the state of a water polo game every five seconds [21] or one considers a game as a chain of events, e.g. service, reception, set, attack, block in volleyball. As a result of this strategy we are able to preserve the temporal structure of a match and may deal with questions relating to weak and strong phases of a game or frequent patterns of behaviour. In coaching we find very often that sign systems are preferred in practice, because this reflects much more the way a coach usually thinks about a game. The processual perspective is not so common, at least what demanded support by observational systems is concerned.

Together with the decision for an appropriate observational strategy the specification of the observational units like signs, a categorical system for time intervals or events may take place. In general we record several items per observational units, e.g. temporal and spatial items, technical and tactical descriptions and so on. The items may be continuous like positions on the pitch in metres or discrete like different service techniques in tennis or volleyball.

An early insight into the nature of observational systems was that such a system has to be considered as a model of the observed sport. Designing an observational system is very much a process of model building. This becomes evident when one looks at the reasons why we design observational systems and for which purpose they serve. We design them to represent the original, and their purpose is to draw inferences about essential properties of the sport. These are exactly the definitions of a model and model building [25].

Another insight arose only later. For some time in the past the leading opinion was that there should be one model for each sport. It was assumed that something like the observational system for tennis existed. Candidates for that universal tennis model became more and more comprehensive and sophisticated. They provided pages and pages of statistics as output for just a single game. At this stage it became obvious that observational systems have to be designed matching the purpose they serve. Different purposes, e.g. modelling the sport at an abstract level, examining a certain tactical behaviour, providing a detailed description of the game and last but not the least giving support in the coaching process, need different observational systems. An issue of model validation is not only whether the model is a good representation of the original, but also whether a model meets the purpose it was designed for.

At this point of theoretical considerations on observational systems in sports the question came into focus, what its special properties should be in order to meet the demands of coaching. The question can only be answered, if a concept of the coaching process is provided by sports science.

3.3 Coupling of competition and coaching

No matter within which stage of coaching one operates, a coupling of information between the game behaviour and the coaching process is required. The coupling of competition behaviour and coaching was proposed by Hansen and Lames [8, 15] to comprise a three-step process. Figure 4 presents this concept for the

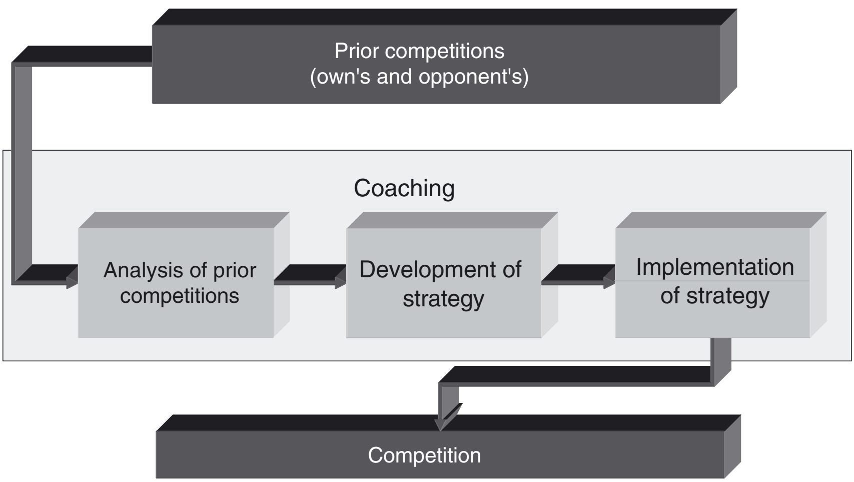

Figure 4: The three steps of coaching.

preparation of a competition. This concept holds with minor changes also for competition debriefing, when the input is our last competition and the coaching activities serve to improve our next ones. During competition the game to be analysed and affected is of course the ongoing game.

In the first step, a detailed description of prior competitions is required using an appropriate observational system. The quality of this description depends on the reliability of the observation process as defined in the narrower sense of measurement consistency. Its validity is determined by the degree it provides all the information required in the next steps of coaching.

In the second step, a strategy for the next competition has to be developed. The coach has to analyse the strengths and weaknesses of his own athletes and the skills of the opponent. The most ambitious part is to anticipate the interaction between the two sets of strengths and weaknesses. Important questions are: What is a typical behaviour of the opponent in a certain situation that might be exploited by my athlete? Which situations should be avoided, and how can this be achieved?

The third step, implementing the strategy, deals with the question of how to enable my athletes to apply my strategy in competition. The appropriate measures to be taken in training are derived from practical experiences, detailed knowledge about my athletes and the strategy to be instructed. One may not forget that strategies in sports usually do not only deal with cognitive problem solving, but perception, motor control and psychological aspects like volition and motivation are also deeply involved.

Structuring the coaching process into these three steps yields one basic insight, which is important for support intended by computer science. Coaching is by no means an algorithmic process that may be executed automatically according to a small set of simple rules operating on data from prior competitions. For example, while inferring from strengths and weaknesses of athletes one must consider many other factors such as the individual competition tactics and strategy, as well as situational aspects such as the psychological, physical and cognitive processes that occur during a game, the quality of the opponent and the level of preparation of the players. The interpretative rather than algorithmic nature of coaching becomes even clearer considering the step of strategy development. Anticipating the interaction between two opponents is highly speculative!

The consequences of these considerations are that up to now computer science has actually not been able to give much support to these central tasks of coaching. On the other hand, these tasks consist basically of cognitive, rule-driven operations. Coaches use tacit knowledge and soft rules from their experience in the domain to arrive at their decisions. It becomes evident that methods of artificial intelligence do have a big potential in this area. The development of an expert system on strategy development in coaching would pose an interesting challenge to artificial intelligence.

For the time being, the support computer science may provide is to facilitate the task of the coach. Most advanced coaching aids are designed to play their role in the three-step process cited above. Corresponding conceptual frameworks for practical performance analysis acknowledge the interpretative nature of the task.

3.4 Qualitative game analysis

The insight into the qualitative rather than algorithmic nature of coupling of competition behaviour and coaching has led some authors to apply the principles of qualitative research methodologies to this task. Qualitative research methodology exists in numerous variants, but has some features that make it well suited to practical performance analysis [5]. Such features include its applications in tackling practical problems rather than theoretical ones, its holistic and contextual approach to framing and addressing issues as opposed to the reductionist and analytic approach of quantitative methods, and its concepts of communication and intervention. Qualitative approaches adopt an interpretative and reconstructive view of social reality which is deemed appropriate for mastering the steps necessary for practical performance analysis as listed above.

To illustrate some of the characteristics of qualitative game analysis (QGA) we report in brief on an observational method that was designed to support top-level teams in beach volleyball. The details of this approach are documented in Refs. [8], [9] and [15] (see Figure 5).

The first part of QGA uses a quantitative observational system to identify the video scenes with regard to some specified items (e.g. service, reception, attack, result). This step is called quantitative pre-structuring and serves to prepare for the qualitative analysis to follow. Here, in contrast to many other purposes of observation, it has been proven to be useful to use a relatively rough grid of

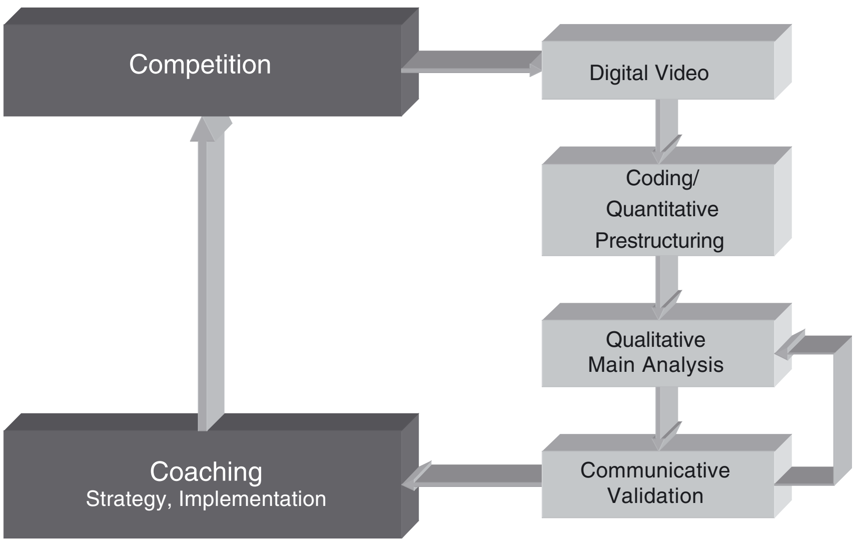

Figure 5: Steps of qualitative game analysis (QGA).

observational items. If this grid is too detailed, the search space would be unduly restricted.

In the qualitative analysis phase, the performance analyst examines the scenes selected from database retrieval using the parameters identified in the quantitative phase. These scenes may be rallies with striking features identified from a general statistical inspection (e.g. an unusual large number of service errors), or rallies containing important tactical behaviours that are looked for as a matter of routine (e.g. the service tactics of an opposing team). At the end of this step, the performance analyst will have developed a preliminary game strategy for use against the opponent just examined.

The last step of QGA is called communicative validation. In qualitative research methodology, it is typical that the scientist on one side and the participants on the other, in this instance the coaches and the players, communicate on equal terms. They enter into an iterative process, occasionally with additional support from video scenes that are displayed on demand. In the end an agreement on the final game strategy is reached.

Qualitative methodology provides advice for the central tasks of QGA. One idea is that the analysis of video scenes uses a method that is derived from content analysis, a common research method used in qualitative methodology [18]. Second, communicative validation is conceptualized as an iterative hermeneutic circle that is repeated until a common reconstruction of the findings emerges [7]. Finally, qualitative methodology provides a framework regarding how to conceptualize social interventions, which is appropriate when aiming at introducing changes in social systems.

Lames and Hansen (2001) reported a successful practical intervention with the German National Beach Volleyball teams at the 2000 Olympics at Sydney, Australia, using QGA as described. For three years one of the authors (Hansen) was involved in the preparation, the qualification and in the coaching itself during the Olympic tournament. The bronze medal was won, although the team did not finish better than 7th in the World Cup tournaments beforehand. Of course the authors do not claim that the intervention using QGA was the only cause for the German team's success.

At this point, one might ask why many examples of successful practical performance analysis worked in the past without the conceptual base of QGA. The answer is that every successful intervention has managed somehow to interpret observational data correctly, to communicate successfully with the coaches and players and to intervene efficiently in this special social context. It may be assumed that the principles of QGA were realized implicitly in these cases, a suggestion that is confirmed from talking with experienced game analysts. They report frequently that information has to be filtered prior to a presentation to the coaches, that there are long discussions with coaches on the meaning and consequences of the observational data, and that social acceptance of the information provided by the analyst to the coaches and players is paramount if it is to exhibit any influence on sports practice.

4 Computer science and coaching: perspectives

In this paragraph perspectives of future developments in the area of coaching and computer science are analysed. This is due to the fact that technology is right at the edge to allow sports and computer scientists to work with a new generation of tools to support coaching. The technology giving rise to these expectancies is RTPA. We are right at the edge to be able to track positions of players and ball, runners, drivers in real time, allowing for the first time in many sports to conduct supporting analyses during the event, a necessary condition to support coaching at the stage of competition control.

First, some technologies of RTPA are introduced and discussed. After this, the long way from automated position detection to coaching is described stressing the challenges for computer science that still remain. Finally, it is pointed out that such a system would immediately offer unprecedented options for performance analysis with unforeseeable impacts on coaching.

4.1 Real-time technologies

At present, RTPA is one of the hot spots of computer science in sports. There have been efforts using different technologies:

- *GPS*: This satellite-based technology uses radio waves and is very common in traffic-guiding in cars and trucks. The necessary spatial resolutions for sports purposes may only be achieved with additional equipment, though. Moreover, there must be a permanent visual contact between emitting and receiving stations, and the tracked objects have to wear small antennas. The technology is very well applicable in sports where athletes wear helmets and pursue rather simple trajectories in space such as cross-country and alpine-skiing or ski-jumping [13]. Although there was some disappointment in recent applications where the robustness of the measurements is concerned there are new promising fields of application such as rowing.
- *Radar*: RTPA-applications on the base of radar waves have demonstrated to be successful in motor sports [17]. There is almost no limitation on the number of tracked objects, the sampling frequency and the area to be covered. Systems are commercially available and have been successfully used to analyse for example the trajectory in speed skating even on indoor tracks. Radar technology requires the tracked objects to be equipped by active tags.
- *Microwaves*: Specialized on the demands of soccer, a research group has recently demonstrated the necessary basic capabilities of microwave technology for the purpose of real-time position tracking [11]. Practical tests in football were devoted to the control of the goal line to provide objective decisions on goal/no goal. The achieved precision was not fully satisfactory for this aim. Nevertheless this remains a promising technology, because for scientific purposes or for coaching a much lower precision may be tolerated. Microwave technology requires active tags for players and ball, too.

- *Image processing*: An unchallenged feature of RTPA by image processing is that the players and the ball need not to be equipped by any tags, which is a great advantage in terms of the necessary compliance of clubs and associations. Along with nowadays ubiquitous digital video, position detection by image processing came into the reach of users outside of computer science. In football, semi-automatic position tracking is commercially available and run regularly by leading European clubs.

As pointed out, the most promising technology for RTPA is image processing. Because either the rules have to be changed or the opponents have to show compliance, any technology requiring tags face severe problems of being installed in practice. Therefore, position detection by image processing is explained in greater detail.

In a first step the system is provided with some prior information, e.g. the coordinates of visible items in the field like the lines on a soccer pitch. Also, the system has to be trained to detect the colours of the teams and of the pitch. Position detection of an object consists of three steps:

1. In each frame, the projection of the 'world' into the pixel map is calculated by fitting its known coordinates to their pixel representation.
2. Pixel positions of players and ball are detected by image-processing techniques.
3. Applying the inverse of the projection of the world into the pixel map from step #1 to pixel positions of tracked objects yields the positions of these objects on the pitch.

Problems still persisting in the first step arise from the quality of video images. Unless there is a large number of fixed cameras covering all parts of the pitch we have to make sure that pixel resolutions of tracked objects are large enough, that swaying cameras do not cause too much blur in the colours, and that optical bias in the pixels by violations of linearity by camera lenses or curvature of pitch do not result in imprecise estimations of world's positions in the pixel plane. In the second step the length of the tracks of objects identified automatically depends on the 'cleverness' of the tracking algorithms. Simple colour matching hardly yields good results, especially in football, where we face frequently overlaying objects that make up 'blobs' consisting of two or more tracked objects. The last step is basically an algorithmic one and yields precise estimates for the pitch positions (error < 25 cm) if the prior steps worked reasonably well [2].

4.2 From position detection to coaching

This paragraph is intended to analyse the new offerings of RTPA with respect to the needs of coaching. In other words the question addressed is how much support may be expected by RTPA. The answer will be that coaches will of course profit from RTPA, but the most promising perspectives for coaching are only achievable, if inferences from the positional data are drawn on 'higher' e.g. more abstract levels like tactical behaviour, quality of actions and so on. This, in turn, poses additional challenges to computer science, especially in the area of artificial intelligence.

Let's first have a look at information made available to the coach by 'pure' RTPA, i.e. just by presenting positional data. We may just record the position of players and ball and depict it as a 'heatmap' like it is shown in Figure 6. Here the positions of two players of the German national women's football team are shown for the first half of the game. Immediately one gets an impression of the regular areas of operation of the players and special tasks like free kicks and corners. A very interesting option is to present the heatmaps dynamically, e.g. a heatmap-movie showing a 10 minute window over the match [14]. Heatmaps have of course been available for a long time, but only hours or days after the match. With RTPA the coach may inspect heatmaps continuously during the match and draw inferences for tactical changes from it.

Another option that may be realized immediately on the basis of positional data is to collect distances run and running intensities. Figure 7 compares Garefrekes and Lingor for their respective distribution of running intensities. One may notice considerable differences between the playmaker and the winger which are somewhat surprising. Having this information at hand any time during a match allows the coach to make assumptions on fatigue-levels of his players. Again, he can evaluate how their movement profile changed over the match. This gives important hints, for example, for the main coaching decision in football which players to replace. Moreover, as these profiles are available for the opponent's players also, this provides valuable information for tactical planning during a match.

Although these options promise great progress in the support of coaching, one still has to admit that they do not support the central tasks of it as pointed out in Figure 4. They do not help in identifying strengths and weaknesses of players; they do not supply suggestions for a game strategy. Intelligent processing of

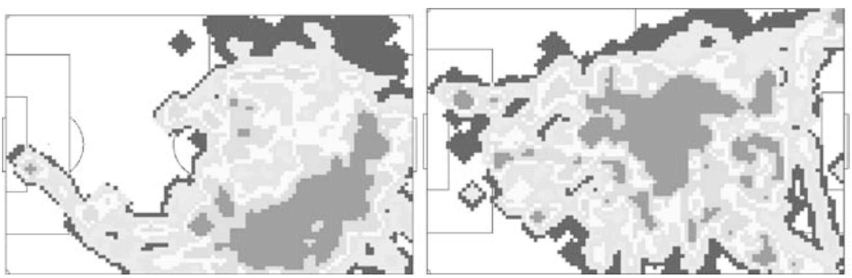

Figure 6: Heatmaps (distributions and frequencies of positions on pitch) for Garefrekes (left, forward mid-fielder/winger of German women's football national team) and Lingor (right, play maker, specialist for free kicks and corners) from a world-championships qualifying match against Switzerland in November 2005.

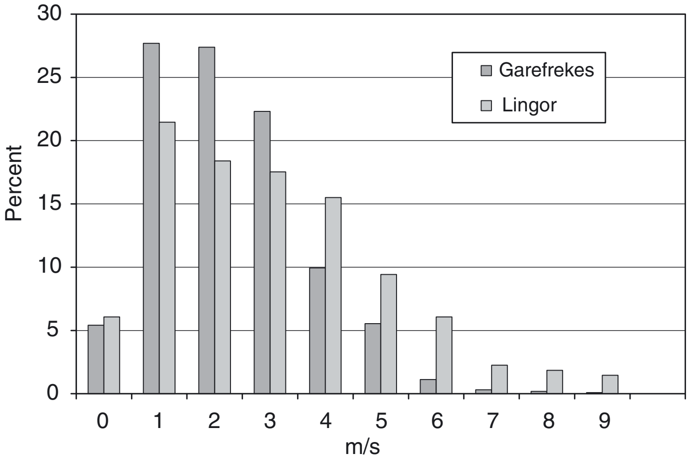

Figure 7: Comparison of distribution of running speed between Garefrekes and Lingor.

Figure 8: Levels of computerized analysis of a football match.

positional data alone does not at all exploit the potential of computer science to its full extent. We need inferences on higher levels than just the level of positional data. We should use techniques not only from image detection but from image understanding to proceed to analyses on higher levels (Figure 8).

First, positional data of players and ball could be used to identify actions on the pitch. Important concepts like ball possession, pass, dribbling or shot have to be detected by these means giving an overview of action profiles of players. Analyses on the level of actions are also valuable to estimate load and strain of players. For example, research has shown that energy expenditure is higher when moving with ball than without ball at the same velocity. A dribbling against a dogged defender consumes for sure more energy than walking with the same speed. These well-known facts mean that an estimation of the strain of players has to combine data from the positional and the action level.

With the actions on the pitch given one may infer on situations. These are tactical configurations like fast break, position play, screen pass or counter attack. But not only an analysis of the behaviour in the field according to a general classification may be obtained, but also individual analyses of situations may be given. That means for example the degree at which a situation poses a threat to the goal or an assessment of the value of different options to pass may be obtained at that level. This allows to evaluate the quality of tactical decisions of players during the match and maybe gives rise to corrections of the game strategy.

At still a higher level, tactical behaviour is analysed. This integrates in a way information about behaviour in certain situations and gives a comprehensive overview on the degree a player obeys to his tactical duties. Analyses are conducted that aim at revealing the opponent's tactical system in offence and defence. One may control the tactical discipline of players of one's own team.

Above all there is a level of assessment where comprehensive evaluations are realized operating directly on issues interesting to coaching. For example strengths and weaknesses of players in physical, technical and tactical sense, preferred operations of players and team, agreement between game strategy and behaviour of own team and opponent, changes in tactics after critical events in game such as disqualification of a player, change of players or goals marked.

So, there is no doubt that computer science has the potential to support coaching in a much broader and deeper sense than is realized uptil now. On the other hand, most of the above cited items require extensive research in the most challenging areas of AI: multi-agent systems, detection intention, image understanding and others. It is an important point to note that RTPA will unfold its full benefit for coaching, only if one proceeds to the higher levels of analysis cited above, because this is where the important decisions in coaching take place.

On the other hand, coaching provides to computer science an excellent opportunity to develop its capabilities in an area with a large public attention, a widespread knowledge of domain and a large number of people familiar with problems in the domain. This type of cooperation may become typical for interdisciplinary contacts between sports science and computer science.

4.3 Future perspectives

In this last paragraph three big issues are discussed that will most probably be the main concerns in the area of computer science and coaching in the near future. These issues constitute demanding challenges for both disciplines, for computer science as well as for sports science. They will account for much of the legitimation the interdisciplinary research area computer science in sports will be founded on.

Pervasive computing and real-time analyses: It is not implausible at all to expect great progress in the area of pervasive computing and, closely associated to that, real-time analyses in sports. Sensor technology, signal detection and evaluation software will allow for unprecedented developments in this area. Performance monitoring in sports will become ubiquitous. Maybe the main drive in this direction will not come from coaching but media is already and will even be more engaged in a race for the most spectacular presentation of sports.

The task for researchers in the area of computer science and coaching will not only be to realize the systems of information technology that realise technological innovations in the area of sports. They will also have to provide ideas and concepts of how to work in practice with these new tools. The new informational base and its unlimited availability will for sure make the practical work of coaches different from what it is today. The readiness and efficiency in introducing these changes will create differences among competitors in future with dramatic consequences for all stakeholders in that area.

High-level inferences: As has been pointed out throughout this paper the real challenges for a coach are inferences on more abstract levels than just observations of positions and actions. If the aim is to generate an efficient game strategy, more abstract inferences are to be drawn, e.g. consisting of only weakly defined terms, with a considerable amount of uncertainty, using soft rules or intuition.

Although this sounds pretty demanding, the situation is not desperate at all for coaching and computer science. The problems mentioned constitute areas in computer science with main focuses in research. For example reconstructing intentions from behavioural data is an important topic as well as reasoning in multi-agent systems. Again, the task for researchers in computer science and coaching will be to direct attention to their interesting field of application and to benefit in this way from technological progress.

New impulses for sports science: Some of the developments cited above bear the potential of extraordinary innovations in sports science. If it is possible, for example, to assess the threat a certain positional constellation poses to the opponent's goal in real time, this may be done before and after an action of a certain player, providing a figure for the quality of this action. Adding up these figures we arrive at an objective, quantitative method of assessing the individual performance of a player in team sports, a problem that has seen no viable solution so far. With the same tool of situation assessment it is possible to compare the values of possible alternative actions with the actually chosen one, measuring the efficiency of tactical decisions of players in team sports.

For the area of exercise physiology the future capability of monitoring positions, actions and situations in real time during a game will allow inferences on the state of fatigue of every player at every moment of the game. This should become possible by establishing the individual reactions of players to physical strains which may be found out with some extra investigations under field conditions. Applying these findings for the individual players to their movement profile at a certain point in a match should result in a good estimate of his momentary state of fatigue. Of course, this option is not only of interest for exercise physiologists, but also for coaches. The fatigue level of my own players is an important information for tactical interventions during a match, but estimates for the fatigue levels of the opponent players may be even more valuable for coaching purposes.

New theoretical approaches: Finally, with the new quality of future data theoretical progress may be expected. From a dynamic systems perspective monitoring the stream of positions, actions and situations allows for the development of completely new models to describe and understand complex sports. For example, one may become able to describe transient and attractive states of a game, perhaps the idea of a field theory of sports may be realized with the help of these data. There is hardly a limit to perceive what is the potential of computer science and coaching in the near future. It will be decisive, though, whether one will arrive at interdisciplinary projects bringing together the practical questions and demands of coaching with the innovative power of computer scientists.

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Modelling

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Abstract

Modelling not only means mapping a system for calculating its state or predicting its future behaviour. The procedure of modelling itself helps for a better understanding of the system's structure, dynamics and behaviour. However, most of the real-world systems are so complex that a satisfying modelling seems extremely difficult if not impossible. One typical consequence is that the complexity is decreased by reducing the part of the system to be modelled. For example, the complex dynamic system 'game' is reduced to numbers, frequencies and distributions of events or actions – often neglecting, however, determining factors like interaction and time-depending dynamics. Although it can be helpful, of course, to know what the success rate of a player was: more informative is *why* it was so low or high, i.e. what particular behaviour, interactions and tactical processes were the reasons for the particular performance. The presented contribution tries to give some ideas and approaches to how to deal with these problems.

Keywords: modelling, simulation, soft-computing, artificial neural network, adaptation, process, game, training

1 Introduction

Modelling is an implicit part of nearly all human activities: Analysing the situational context of a planned action means mapping the huge amount of sensorial input to an abstract model consisting of information patterns. In turn, the situation-oriented adequateness of a possible action is measured using behavioural models based on experience.

Therefore, it is not surprising that modelling on the one hand plays an important role particularly in the area of sport, where precise recognition of the situations and selection of adequate actions often decide on win or loss. On the other hand, there are a huge number of concepts and methods, approaches and applications in modelling, which makes it a problem to select a small number of representative ones. Furthermore, the areas of biomechanical and stochastic quantitative modelling are quite well presented in literature. A lot of open questions and problems are left, however, in the areas of qualitative and behavioural modelling of dynamic systems.

Hence, the idea was to focus the contribution on three major areas of modelling in sport – namely advanced aspects of modelling, modelling of adaptive systems and process-oriented modelling.

Section 2 deals with basic problems and corresponding basic ideas how to handle them. Some paradigms and concepts of modelling are discussed particularly considering their usefulness for application in sport. In particular, the difference between data and information and the importance of soft computing are focused on.

Adaptation as a basis of physiological training and learning processes is dealt with in Section 3. One central problem is that of understanding the dynamics of adaptation. An approach is introduced, which – on the basis of antagonism – allows for simulating the dynamics of adaptation processes over a wide range of applications.

Section 4 focuses on processes. In particular, games and learning dynamics are dealt with. A main emphasis is put on artificial neural networks, which are able to recognize patterns and therefore can be used for recognition of striking features and structures in processes.

The aim of the contribution is to give a brief overview of what the ideas and concepts of modelling are, how models can be developed, and how they can be used in a fruitful way.

2 Modelling and simulation in sport

2.1 Paradigms and types of modelling

Modelling is one of the most basic working areas in different disciplines, not only in computer science and sport science. Whenever complex system behaviour has to be analysed – in the case of technical as well as biological systems – the main problem is that of modelling its structure and the interaction of its components. A reduction to just comparing input data to output data is not sufficient neither for qualitative nor for quantitative analyses. Only if the system's dynamics is transparent and well understood, there is a chance of predicting the future system behaviour based on its present state and the planned activities. Modelling and simulation can help for a better understanding of system behaviour in general and additionally allows for finding and optimizing schedules or strategies without troubling the athlete.

According to the development of computer science, sport science can take advantages in recording, analysing and handling data as well as in modelling and simulation. The improvement does not just mean 'more' and 'faster'. In addition, the improved quality of data handling allows for overtaking or developing new concepts and methods as soft computing (which is briefly dealt with in Section 2.4) and process orientation.

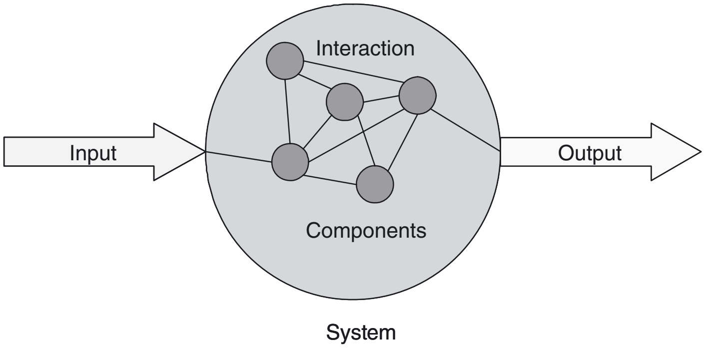

Figure 1: Dynamic system with external input and output, and internal components and interaction.

Process orientation means that not just one isolated activity causes an isolated change of a state, but sequences of activities or events cause sequences of states, where in particular buffers and transfers play an important role for delayed effects. It is of particular importance that such delay effects are driven by internal system dynamics and therefore very often cannot properly be measured by statistical methods.

Therefore, modelling a dynamic system means mapping not only its components and input–output behaviour but – depending on the demand on precision – also and in particular its components interaction (see Figure 1). The reason is that, as mentioned above, dynamic interaction of system components is characterized by buffers and delays. This means that a system input – depending on the respective internal status – can cause quite different outputs, which makes it extremely difficult to predict the system behaviour by only taking static pairs of input and output values into consideration. Accordingly, stochastic analysis methods like correlation or trend analysis based on past values in the case of dynamic systems are normally neither sufficient nor adequate for an acceptable prediction. This is quite obvious in cases like game analysis or rehabilitation but holds also for motor analysis and training and performance analysis.

2.2 Simulation and prediction

As an example for demonstrating the problem of prediction, the case of performance adaptation is discussed.

'More and better training causes increased performances' on the one hand seems to be a convincing approach – since it seems to meet most of our experiences from short-term as well as long-term training. On the other hand, too much of training can reduce performance. Therefore, of course, it is quite clear that simple rules like that described above only can give a first orientation. Due to the fact that an athlete is a complex system with limited capacities and feasibilities, which moreover is embedded in a complex interaction of external impacts, his or her reaction on training can be complicated and, at least in details, unpredictable. So, the problem of predictability is a central one in particular in the field of adaptation, where the proband forms a dynamic system with time-dependent dynamic states. Therefore in sport, particularly in training and motor learning to optimize training and learning strategies and schedules, the problem is not only to evaluate the status of an athlete but also to understand his/her specific dynamics.

This obviously can hardly be done by sporadically and unsystematically recording isolated values, but only by systematic recording of complete time series.

Even more complicated is the situation in case of games if one tries to predict the result of a future game based only on past results or other statistical data and without taking dynamic state fluctuations of the teams into consideration. In a similar way, most of the so-called performance models of players as well as of teams are useless if they are based only on past values. These values of course are necessary, but they are helpful for a workable prediction only if they are used on the basis of an adequate model with which the data are compatible. Often prediction fails because there is no model at all or the recorded data do not meet the requirements of the model. Some examples are given in Sections 3.2, 3.4, 4.2 and 4.3.2.

2.3 Data vs. information

Often a confusion regarding data and information can be found: Data that can be recorded (even automatically) from the athletes' activities are taken as information and stored – the more the better – in a database. However, as the following examples may clarify, depending on the type of analysis, the data can be relevant or they can be highly redundant or in strong correlations to each other.

As a first example, motion data of an athlete can be recorded automatically, one hundred times a second, containing positions, angles, speed of articulations and much more. On the one hand, these data are useful for the biomechanist to find out specific striking features of a single articulation over time. On the other hand, if the process of moving as a whole is of interest, many of the data and also their precision are of minor meaning because they are strongly correlated to a complex pattern of moving. That is, the information connected to the data can be quite different and obviously depends on the aim of investigation (also see Section 4.1).

The second example deals with picture recognition: By looking at a pixel picture of a game, we can recognize lines, players and the ball and even have the impression of motion and dynamism, while the computer can 'see' only coloured pixels. To make the computer understand the picture, i.e. interpret it semantically, it needs to be fed with all the experience we have learned in transforming data to information.

Surprisingly enough, even fly brains have no problem in dealing with huge amounts of data, recognizing patterns and situations and transforming data to useful information. These abilities, and moreover even human intelligence, have been the aim of investigation and a challenge since the early days of computer science activities.

2.4 Artificial intelligence and soft computing

Since the 1950s, artificial intelligence has been one of the most challenging areas of computer science. The aim was to understand and model human thinking by means of computers. Finally, in the 1980s, it became clear that neither could human thinking be understood in a simple algorithmic way nor were the computers powerful enough for an appropriate simulation of complex neural systems.

Soft computing, as an important new area of computer science, is developing the ideas of Artificial Intelligence in a modern and more pragmatic way. It is dealing with new approaches and concepts of handling complex dynamic systems, which means a change of paradigms according to biological systems where determinism is replaced by randomness, precision by fuzziness and completeness by flexibility and adaptability. This way, patterns of motions or tactical patterns in games can be analysed and compared more easily by means of artificial neural networks; interaction and communication in games can better be described by means of fuzzy modelling; solutions in high-dimensional problem spaces like optimal tracks of motions can be found much faster by means of evolutionary algorithms.

Not least, soft computing and new paradigms allow for a more holistic view and understanding of complex systems and their interactions. (Regarding the problems of modelling complex systems see Ref. [1].)

In particular, in the case of processes, i.e. the time-dependent event-based change of systems' states, analyses must not be restricted to single states or events but have to take into consideration present states and changing events as well as past ones. Future behaviour cannot be predicted without understanding the past, and therefore cannot be calculated by means of statistical probabilities only.

Moreover, if dealing with human behaviour and interacting like in sport games, a certain contradiction between rule-based behaviour (tactics, strategies) and spontaneous, situation-based human decisions has to be taken into consideration.

Four examples in Sections 2.4.1–2.4.4, one in each section, may briefly demonstrate how the major approaches of soft computing can work in practice.

2.4.1 Fuzzy modelling

A fuzzy approach was used in a first attempt of modelling these types of behavioural processes in handball. The idea was to complete the positions of the players by a fuzzy area of possible positions, which diverges at the beginning of an action and converges at its end. The results were fuzzy process patterns that modelled typical behaviour much better than time series of positions with more or less arbitrary coordinates (see Figure 2, also compare Ref. [2]).

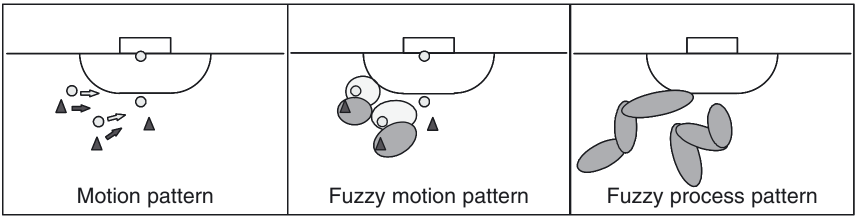

Figure 2: Motion patterns of attack (dark grey) and defence (light grey) in handball. First graphic: position oriented; second graphic: positions completed by fuzzy areas; third graphic: process consisting of fuzzy motion patterns.

More information about modelling of handball can be found in Refs. [3–5] and in Section 3.3.2. An approach dealing with artificial neural networks is introduced in Section 4.2. An approach of fuzzy modelling in soccer is given by Wiemeyer [6], who answers the question how the assignment of positions and players in a team can be optimized.

The idea of reducing precision in order to obtain more information has been discussed in Section 2.3 and appears in a lot of approaches where not the single events but the event interactions during a dynamic process are of major interest. One very important example is given by communication, where only the fuzziness of the transfer objects (like words or pictures) enables interpretation and understanding of the semantics of communication patterns. This concept of fuzziness is used in different ways in the approaches described in Sections 2.4.2–2.4.4 as well.

2.4.2 Evolutionary algorithms

Different from playing behaviour in a game, finding an optimal track for instance in Alpine skiing seems to be a problem that has to be solved by means of mathematical equations only.

On the one hand, this is correct because one of course needs these equations for an appropriate model. On the other hand, there are a huge number of more or less optimal solutions that differ only in tiny little bits, and it would make tremendous effort to calculate the very best one. Moreover, in the end the athlete would not have a chance to follow exactly this best track anyway.

In nature, the problems of best fitting have been solved by means of evolution and survival of the fittest, which is successfully simulated by evolutionary algorithm. Such algorithms not always result in just one best solution. Instead, they offer a collection of solutions very close to the optimum, which gives an idea of possible variations and therefore allows for individual adaptation (see Figure 3).

More examples of the usability of evolutionary algorithms in sports are the optimization of bows [7] and the analysis and optimization of strategies in tennis [8].

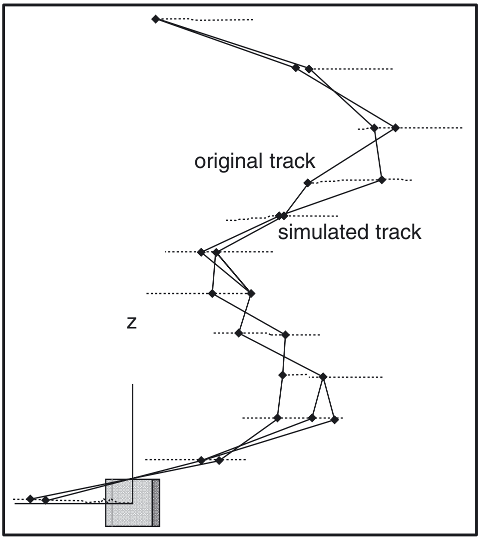

Figure 3: An original track in Alpine skiing compared to a simulated one (with some minor variations) that is calculated by means of an evolutionary algorithm. Although the original and the simulated tracks defer a lot, the time needed is rather the same, where the simulated track is a bit better. Modified from Ref. [9].

Completing or even replacing quantitative modelling, focussing on numbers, by qualitative modelling, focussing on patterns and types, can be done using artificial neural networks.

2.4.3 Artificial neural networks and pattern analysis

Patterns in sport can be taken as tactical patterns from a game (see Figure 4), as motor patterns from movements or as training or performance patterns in training analysis. As is demonstrated in the following examples, such patterns reduce the complex original information to the most relevant parts, e.g. trajectories of a time-dependent process, and so help for easier analyses [10].

Also movements can be classified and represented using networks if the neurons that belong to the process are connected to trajectories. This is demonstrated in Figure 5, where the trajectories of rower A and rower B can be compared under the aspect of intra-individual stability or inter-individual similarity. It can easily be seen that all the trajectories are rather similar to each other, but the rowing of A is more stable than that of B. A closer look, however, shows that there are specific differences in some parts of the trajectories, which can be the reason for a deeper analysis of the corresponding video frames [11, 12]. Neural networks are dealt with in more detail in Section 4.

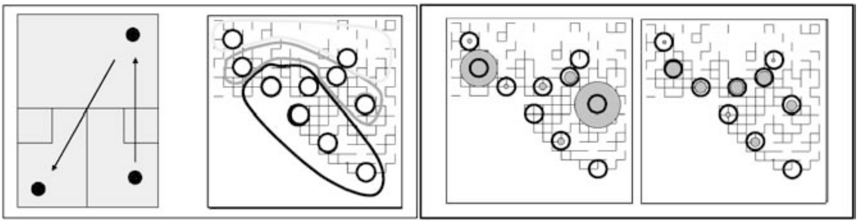

Figure 4: Left graphic: a sequence of striking positions on a squash court. Second left graphic: A neural network with some of its neurons marked by black circles, which represent characteristic rallies of squash. Areas of major types of rallies like 'long line' or 'cross' are marked by black and grey lines. A player's tactical pattern is represented by the frequencies (i.e. diameters of the neurons) with which those neurons are activated by the player's action data (two graphics on the right hand side).

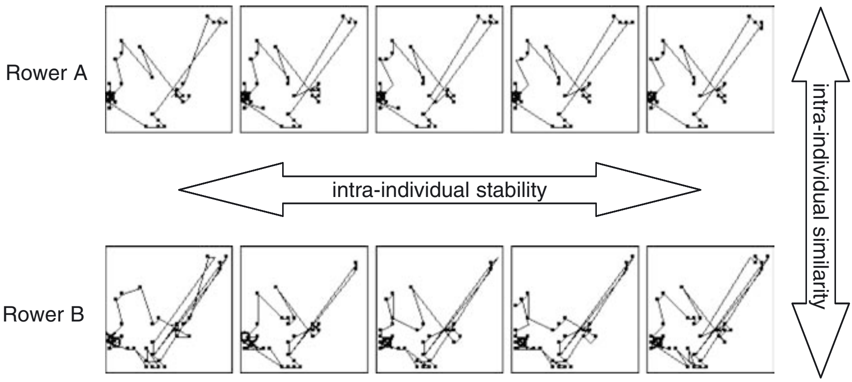

Figure 5: Net-based trajectories of ergometer rowing: Each node represents the two-dimensional mapping of the corresponding high-dimensional vector of biomechanical attribute values like articulation position, angle, speed or force at one point in time.

2.4.4 Antagonistic dynamics

The last example of modelling and dynamic patterns deals with the problem of scheduling appropriate training plans.

Scheduling needs prediction of behaviour and therefore requires an understanding of the dynamics of the complex system 'athlete' under the view of load–performance interaction. If at least the trends of that interaction can be simulated (as is done in Figure 6), this helps a lot for scheduling better training plans, avoiding too much overload and contra-productive training units. The model used in Figure 6 is based on the antagonism of training load, which on

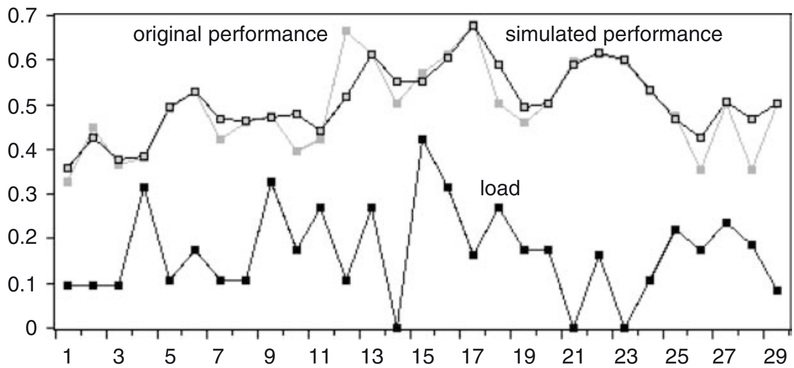

Figure 6: Training load per day (black dotted line: hours of training) results in a delayed performance output (light-grey dotted line: haemoglobin concentration). The interaction of load and performance depends on a complex internal dynamics, which can be simulated by means of an antagonistic model (dark-grey dotted line: simulated performance output).

the one hand reduces performance but on the other is necessary as a stimulus for improving performance.

More details regarding the model, the term 'antagonistic dynamics', and in particular prediction of performance and scheduling of training load are given in the following section (also see Ref. [13]).

3 Adaptation models

3.1 Antagonistic meta-model PerPot

The *Per*formance *Pot*ential meta-model *PerPot* simulates the interaction between load and performance in adaptive physiological processes like training in sport by means of antagonistic dynamics.

The term 'antagonistic dynamics' means that the same load input has two contradictory effects, namely the performance-increasing response flow and the performance-decreasing strain flow. Depending on the delays with which these flows become effective, the training can cause positive or negative temporary results [14, 15].

An input like a load rate feeds two internal buffers, which can be interpreted as system components that produce or transfer substances or effects with specific delays.

In the case of PerPot, the strain potential together with a performance-reducing flow models the negative effects of training load, while the positive effects of training load are modelled by the response potential and the

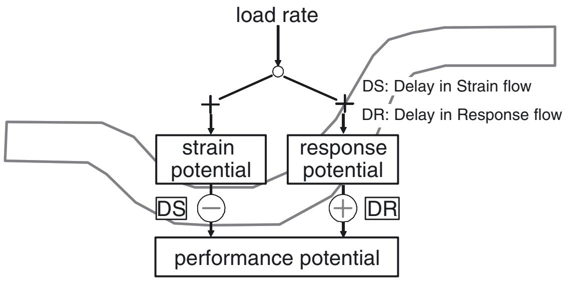

Figure 7: Basic antagonistic structure of PerPot, with DS and DR the characteristic delays.

performance-improving flow. After an appropriate calibration, the pair of flow delays, DS and DR, determines the characteristic behaviour of the model and so, like a fingerprint, encodes the characteristics of the modelled systems (e.g. the athlete together with his discipline) (see Figure 7).

Depending on the relation between strain delay (DS) and response delay (DR), specific standard behaviours are determined. If the DR is greater than the DS, then strain works faster than response and so (as is shown in Figure 7) causes the well-known supercompensation effect. If in contrast DR is smaller than DS, then the response is faster, causing a smooth balancing out.

Because of an internal normalization, PerPot is independent of the scales of load and performance. Also, the timescale does not play any role because the time units are embedded in the delays. Therefore, PerPot can be used for modelling arbitrary types of load–performance interaction.

3.2 Applications and approaches

3.2.1 Performance prediction and delay analysis

As has been mentioned above, calibration (besides others) is able to deduce the delay values from the load and performance profiles. Consequently, it can be asked how much ‘current’ data sets are necessary to calculate delay parameters, which allow for simulating not only the current but also the future performance values.

Figure 8 demonstrates that 5 data sets seem not to be sufficient for a proper prediction, while 25 data sets seem to fit rather well. The typical dynamic changes, e.g. from low to high and/or from high to low load, are necessary to give the model enough information about the characteristic adaptation behaviour. Moreover, this method of prediction can be used for online adaptation, where every new pair of load and performance values can be used for adapting the delay values to the changing situation respectively to the changing status of the athlete.

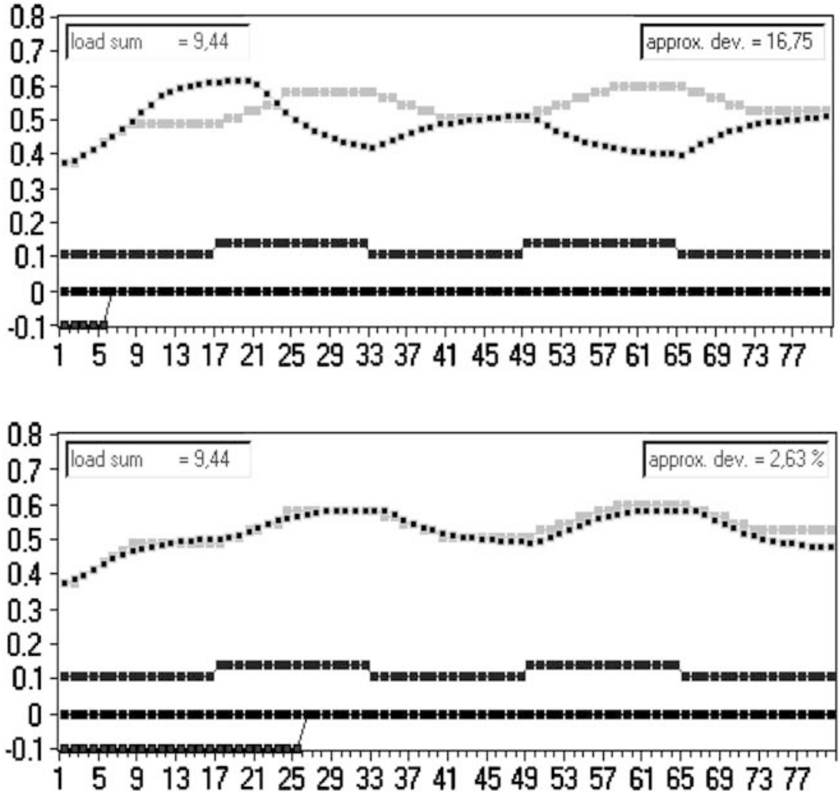

Figure 8: Precision of prediction depending on the load dynamics and/or the number of data used for delay calculation (the dark dots on the time axis mark the interval of used data sets; profiles on top: light grey – original performance, grey – simulated performance; profile on bottom: dark grey – oscillating load).

3.2.2 Load and performance scheduling

Last but not the least, it seems interesting to know how to plan the load profile in order to optimally meet a given performance profile, and how the performance output changes if the load profile is changed. Doing this by means of simulation saves time and is beneficial for the athlete. In the upper graphic of Figure 9, the original haemoglobin profiles are shown with a load sum of 4.90 and a maximum load value of 0.42 (note that these values are normalized from the original ones to a scale from 0 to 1). A PerPot-based optimization of the load profile reduces the load sum to 4.75 and improves the simulation deviation from 10.78 to 6.95%, even if the maximally allowed load value is reduced to 0.30 (Figure 9, lower graphic).

In Figure 10, the first graphic shows a part of a performance profile, which was designed using the PerPot scheduling component. The load values then were

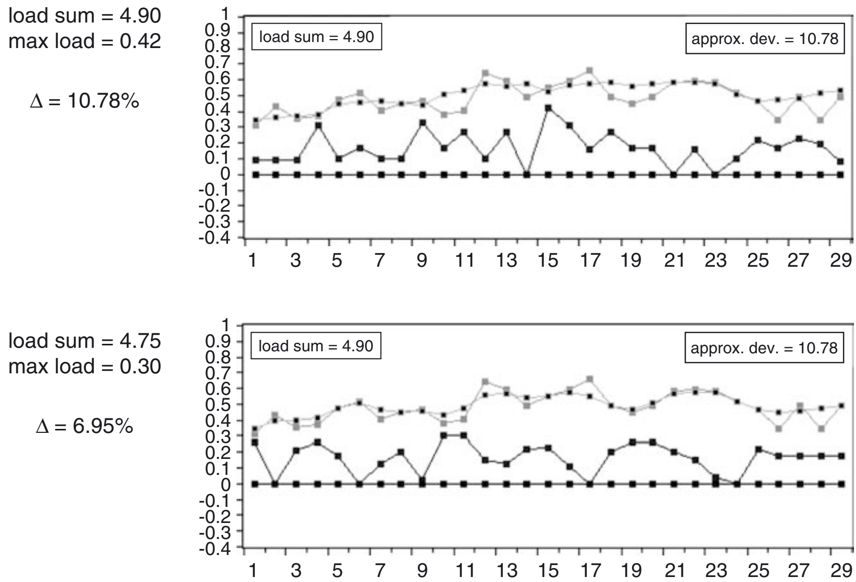

Figure 9: PerPot-based optimization of the load profile. The grey and light-grey profiles on top present the original and simulated performances, respectively; the dark grey profiles on bottom present the load.

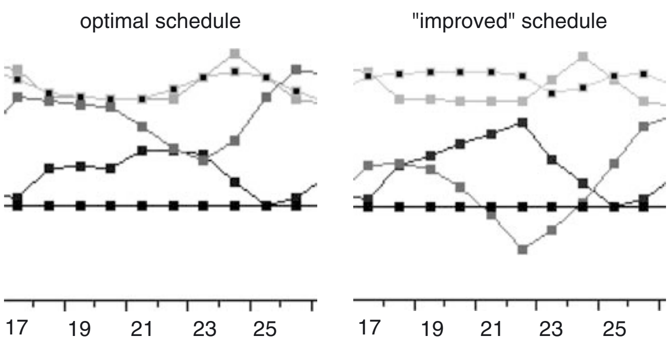

Figure 10: Detail of the effects of optimal load profile compared to that of the ‘improved’ one (regarding the legend compare Figure 9; a medium-grey profile is added that indicates the performance reserve that should not decrease below zero, but it does in the ‘improved’ schedule).

generated correspondingly in order to optimize the load profile. As can be seen, the plateaus as well as the singular event are met in a satisfying way.

Coaches or athletes might have the idea to even improve a proper training schedule by increasing the training load. This attempt was simulated, and the result is shown in the second graphic, demonstrating that too much load is contra-productive and can cause effects that are in contradiction to the planned ones. For more information about modelling and applications, see Refs. [15–17].

3.3 Modifications and extensions

3.3.1 Two-level model of long-term training efficiency and lifelong training

One reason for a changing status of an athlete can be a worse condition, and should influence the delay values. In turn, as is demonstrated in Figure 11, changing delay parameters influence the performance that can be reached maximally: While in the left graphic a fast effect of strain (DS = 2) reduces the maximum performance to 0.22, a slow effect of strain (DS = 5) increases the maximum performance to 0.54. This means that a long-term improvement of efficiency (i.e. increase in maximum performance) can be achieved by changing the delay values, which reflects physiological phenomena of training like improving the adaptability of organic components.

The dynamics of those long-term effects can be modelled using two exemplars of PerPot, where the performance output of the internal long-term model modifies the delay values of the external short-term model.

As can be seen in Figure 12, the same load rate controls the internal model as well, affecting the delay parameters of the external model, and the external model itself, affecting its temporary performance. (For more details see Ref. [18].) Some examples of the basic dynamics of that approach in the case of constant load are given in Figure 13 and discussed below.

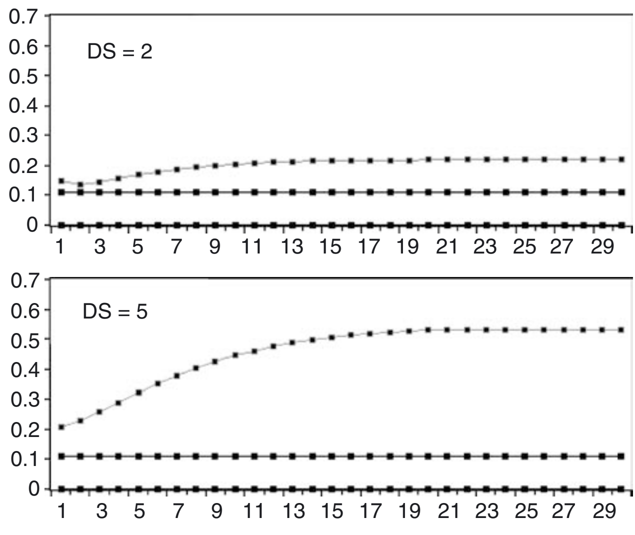

Figure 11: Correspondence between DS values and performance maxima.

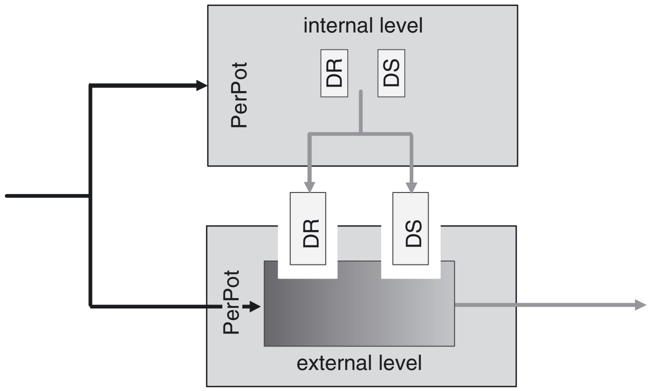

Figure 12: Load rate controlling the internal and the external model of two-level PerPot.

Comparison of the first and the last row shows that with increasing level of load, the maximum obtainable external performance increases as well (take the horizontal line as orientation). The third row shows that smaller values of the DR (with the interpretation of improved internal condition) are the reason for this effect.

Changing DR behaviour is the result of affecting the internal model by the load, as can be seen from the second row: With increasing load, the internal performance profile also increases to its maximum, but decreases the length of that maximum phase.

The DR profile of the external model is more or less the mirrored performance profile of the internal model. So, higher load causes a higher but shorter maximum phase of internal performance. In turn, it causes a lower but shorter minimum phase of the external DR profile, and this finally causes a much higher but much shorter maximum phase of the external performance, even including the danger of a sudden collapse (Figure 13, row 4, column 3).

Interpreting the timescale as lifetime, the result means that an intensive training in the youth not only can increase the performance extremely, but can also imply the hidden danger of an unexpected breakdown a long time later.

The problem is how to optimize the long-term training load in order to stabilize long-term performance and avoid breakdowns. Figure 14 demonstrates how two-level PerPot may give an answer.

The left column shows one very common scenario: During a period in the youth, the load values are very high, causing a high (but not necessarily constant) performance. Stopping training completely then leads to a reduction of the stable performance on a low level.

The middle column shows what happens (in the model) if training is not stopped but continued, maybe with even increased load: The internal system becomes ‘empty’ (i.e. there is no organic reserve any more) and the external

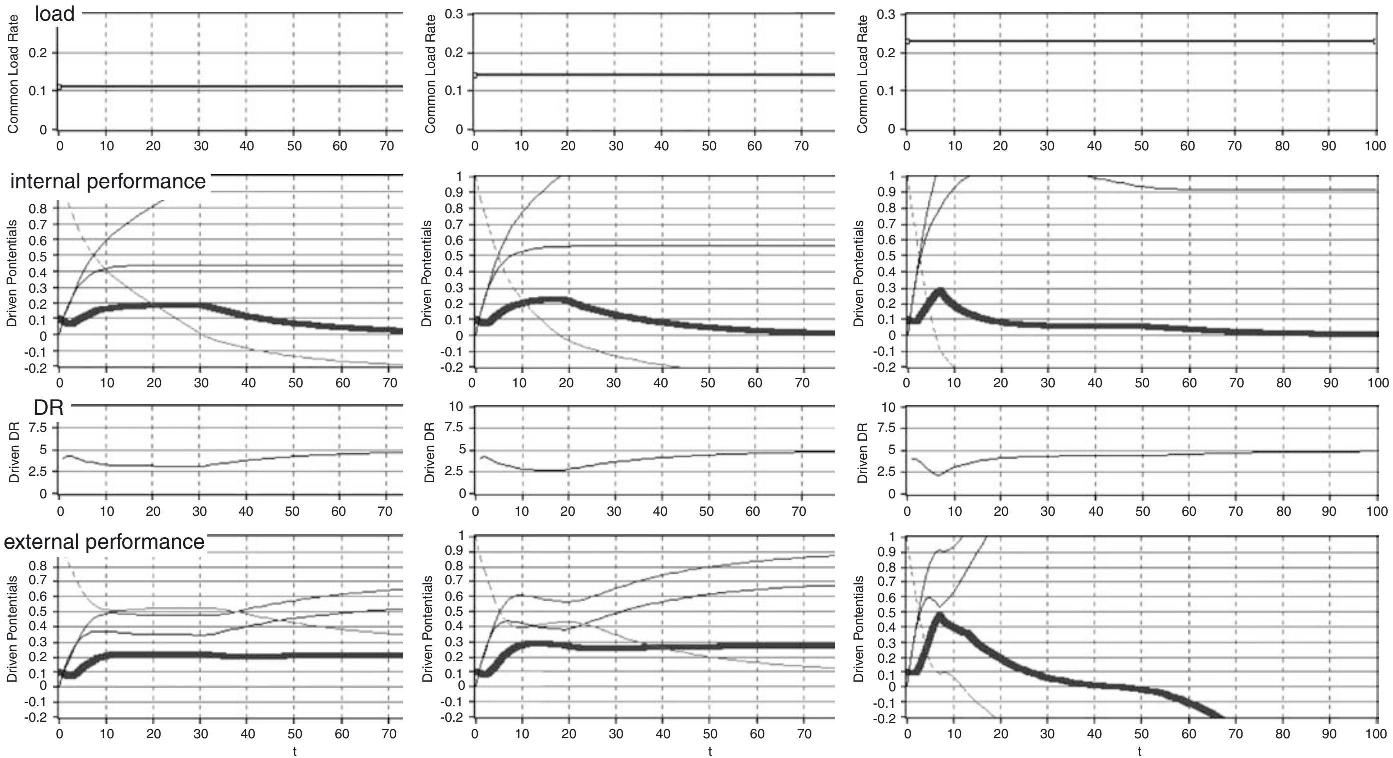

Figure 13: Basic dynamics of two-level PerPot in the case of different types of constant load.

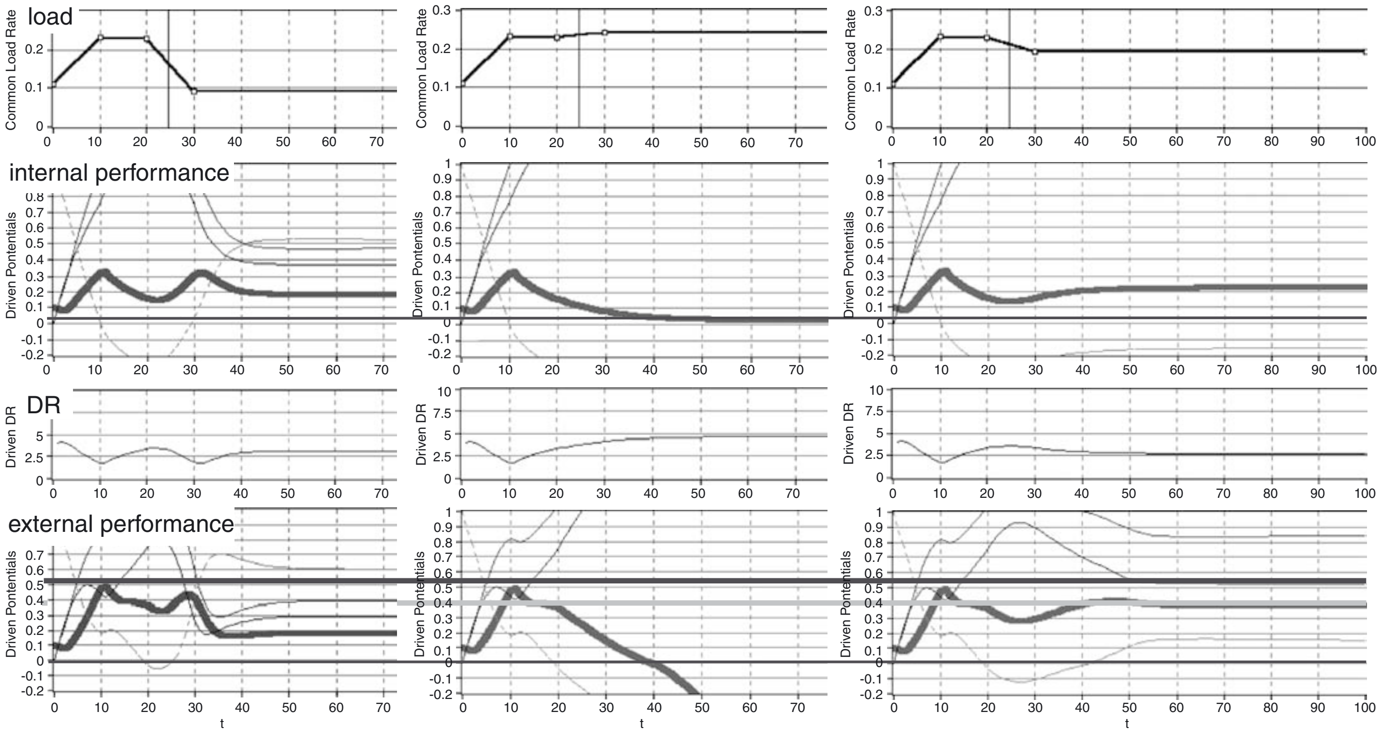

Figure 14: Optimizing long-term training to stabilize long-term performance.

system collapses. In the special case demonstrated here, this happens without improving the performance at any time.

Finally, the right column demonstrates that already a small reduction in the load level can stabilize the performance on a very high level (horizontal line) without reducing the maximum performance (horizontal bold line).

Currently, projects are in preparation, which use the presented approach for scheduling long-term training plans and predicting corresponding performance profiles.

3.3.2 Two-component model of symmetric interaction in sport games

The dynamics of team behaviour in games shows rather inhomogeneous distributions of the levels of activity and effectiveness, where phases of great effort are followed by phases of reduced activities, which are used by the opponent team for increasing its pressure.

Lames [19] measured the scoring effectiveness depending on the probabilities of score at ball possession. The results were diagrams like that in Figure 15, where high and low performance intervals of both of the teams can alternate, follow and overlap each other or even can appear concurrently, as is marked by the segments A to E.

On the basis of the interpretation that the subsequent effectiveness of one team is a kind of performance, which in a delayed way is caused by the past and

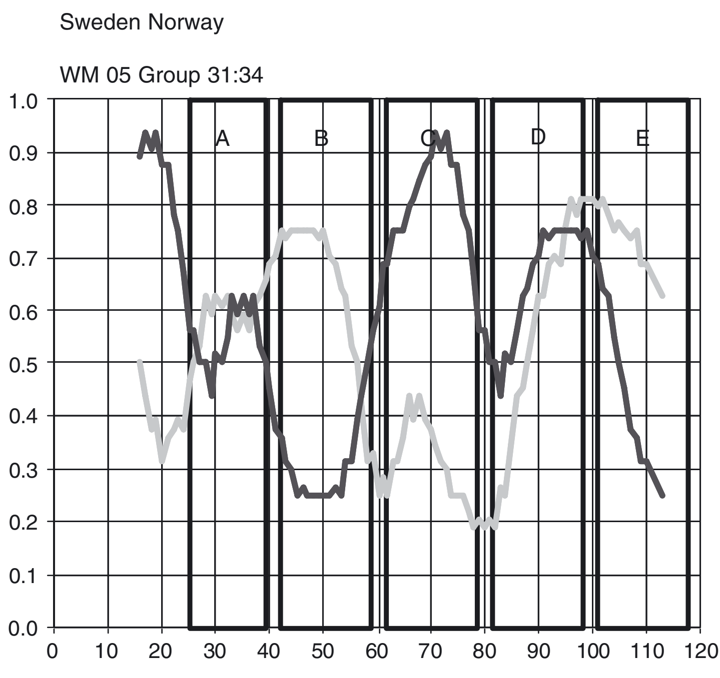

Figure 15: Time-dependent performance interaction in handball.

present pressure or load from the opponent team, i.e. its activities and scoring, the game can be understood as a symmetric process of load—performance interaction. Such symmetric feedback systems very often show an oscillating circuit behaviour, where both components show oscillations that are in anti-phase to each other (see segment B in Figure 15).

Therefore, a white-box approach has been used for modelling, where two exemplars of PerPot (see Refs. [20, 21]) model the respective dynamics of each team.

On the internal level, the team-specific dynamics of performance depending on fatigue and recovery have to be modelled. On the level of interactive feedback, the output of the one team serves as input for the other team. Here, for example, scoring or pressure can cause positive effects like motivation and increased effort or negative effects like frustration and giving up. On the level of external control, tactical or strategic aspects can determine, influence or modify local as well as global behaviour.

Distinct from standard PerPot, the modified ‘team-PerPot’, which is used here, contains connections between internal potentials SP and RP and the corresponding delays DS and DR. In particular in the case of RP and DR, this means: increasing response potential indicates improving recovery and therefore reduces the delay for sped-up reaction.

The feedback connection of two exemplars of that team-PerPot (each one representing one of the teams, see Figure 16) immediately results in a remarkable behaviour: After a small initial phase of balancing in, the performance profiles of the two connected team-PerPots oscillate in a rather perfect periodicity, without any external impact, and just depending on different team-specific start parameters that determine the minimum values (Figure 17, left graphic).

In terms of dynamics and control, this result means that under constant conditions, i.e. without external impact, the oscillation will continue unlimited. Those external impacts can come from the trainer or from the players and can consist of decisions like ‘go slow and recover’ or ‘stop recovery and start to react’. These effects can be understood as slow down or speed up of the mechanism described

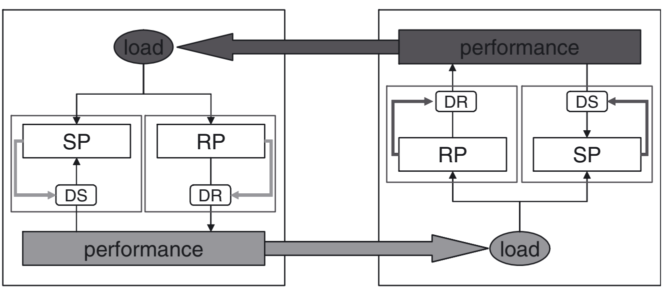

Figure 16: Two exemplars of PerPot with internal potential delay control, connected by feedback flows, where the performance output of the one model builds the load input of the other model.

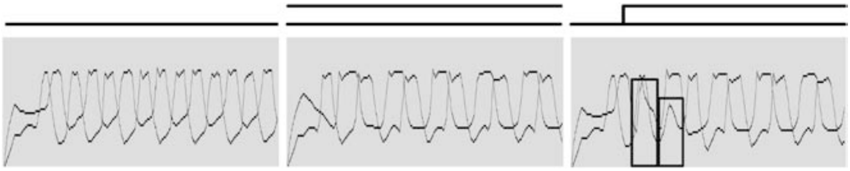

Figure 17: Oscillations depending on the respective values of the external delays of reaction (bold lines on top).

above, and therefore can be modelled by delays that can be briefly described as ‘gradually closing the valve’ or ‘gradually opening the valve’. In the following paragraphs, these external impacts are called ‘external delay of reaction’.

Figure 17 shows the impact of external delays of reaction on the type of oscillation. The left graphic of Figure 17 shows the identical constant external delays of reaction and periodical oscillation. In the second graphic the one team has a still constant but greater external delay, resulting in a reduced frequency for both teams. This is because a delayed reaction of the one team in turn shifts the reaction of the other team. Finally, in the right graphic, the effect of changing the external delay is shown: The periodicity becomes disturbed but after a while is restored again. Moreover, also the amplitudes are changed.

This concept allows for simulating given behaviours as well as for scheduling desired ones by just modifying the profiles of external delays of reaction. Therefore, it has to be understood how a change of external delays can change frequencies and amplitudes of the resulting performance profiles: A small external delay of reaction means a short recovery phase. The internal response potential is not optimally filled, and therefore the transfer to performance yields only rather small amplitude, i.e. small external delays can cause higher frequencies together with smaller amplitudes. In turn, large external delays can cause lower frequencies together with greater amplitudes.

In Figure 18, two games of Germany are analysed exemplarily: In the first game against Denmark, the German team shows two long phases of large delay of reaction with corresponding maxima of performance. In contrast, the Danish team shows smaller delays that cause comparably small fluctuations of performance. So far, this example confirms the ideas developed above. In the second game, the Croatian team plays more or less the role of Germany from the first example: Large external delays cause comparably high performance. In contrast, the German team shows smaller delay values, which however are not as small as those of Denmark. The result is a German performance profile, which lies between those of Denmark and Croatia, and the frequency of which is smaller than that of Denmark.

One aim of the presented approach could be to analyse profiles of reaction under the views of inter-individual and intra-individual stability and similarity, i.e. if there are opponent-independent patterns (invariants) or opponent-specific patterns (tactical variability or strategic concepts).

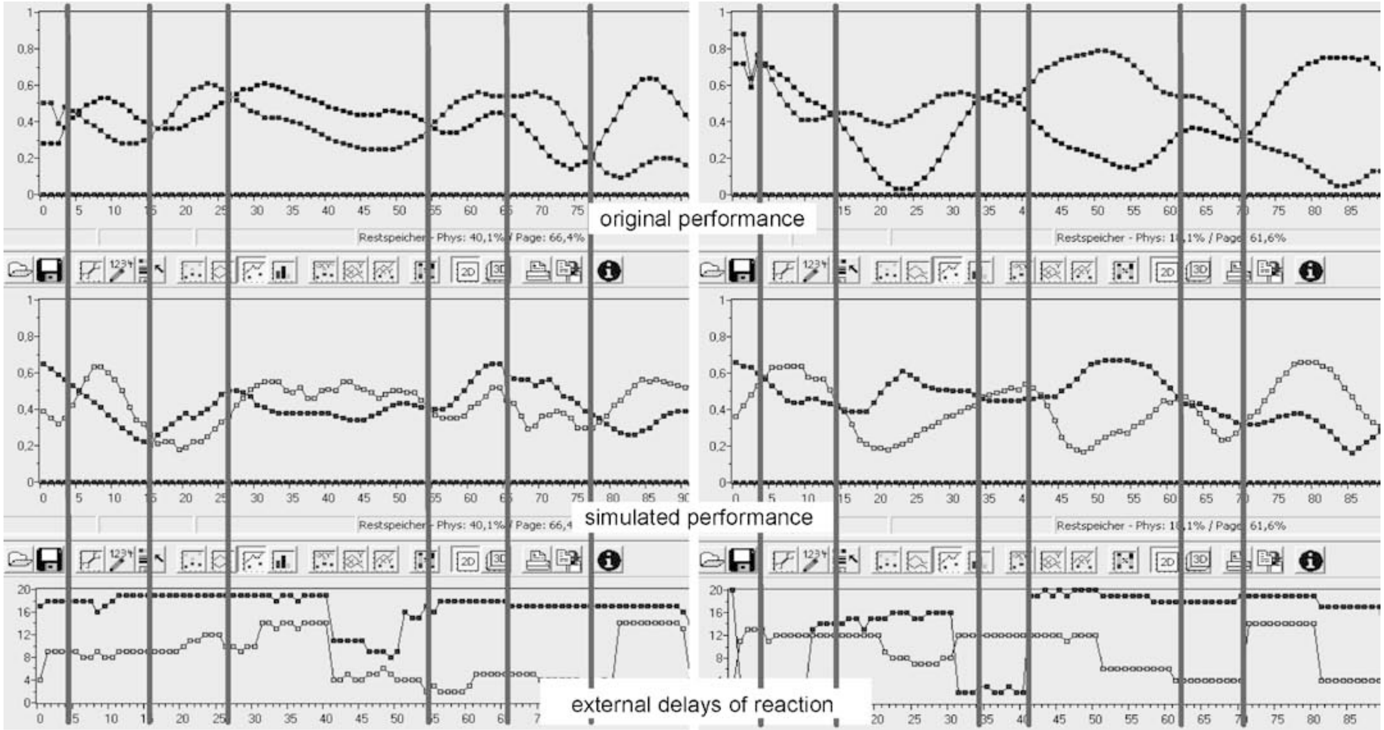

Figure 18: Left: Germany (dark grey) vs. Denmark (light grey) (22:20). Right: Germany (light grey) vs. Croatia (dark grey) (23:23).

3.4 PerPot as scheduling tool for endurance sports

Scheduling of training and contests in outdoor endurance sports, e.g. running, biking, or skiing, is difficult through course contexts (ground condition, slopes, etc.) and delayed physiological reaction on load changes. In the following paragraphs, some of these impacts are exemplarily discussed for the case of running (also see Refs. [22, 23]).

Figure 19 shows the effect of delayed reaction on periodically changed speed on plain ground: From bottom to top, the first line contains the speed values (6.5 and 8.0 km/h), which are graphically reproduced as profile, followed by the corresponding heart rate profile and the heart rate maximum values in the top line.

The marked delay intervals exemplarily indicate the time needed until stabilizing after a speed change. The figure shows the standard case that the recovery delay is larger than the load delay.

It is, however, to expect that the slope-caused load can affect the heart rate profile (graphic in the middle) at least as much as the speed-caused load does (graphic on top). To model that impact, additional parameters are taken from the course profile, in particular from the positive and negative slopes.

Depending on the original speed v_0 and the original slope S, a transformation $v_R = \lambda(S,v_0) \times v_0$ calculates a (virtual) reference speed v_R that represents the load effect regarding the resulting heart rate output. Each v_0 defines a characteristic λ-function, which looks like a piece of a parabola, and the values of which have to be taken from experiments (see Figure 20, right graphic).

To this aim, the course is recorded and measured by means of GPS and altimetry, and then departed into segments of (more or less) constant slope. For each segment, the λ-transformation can be done in the way described above.

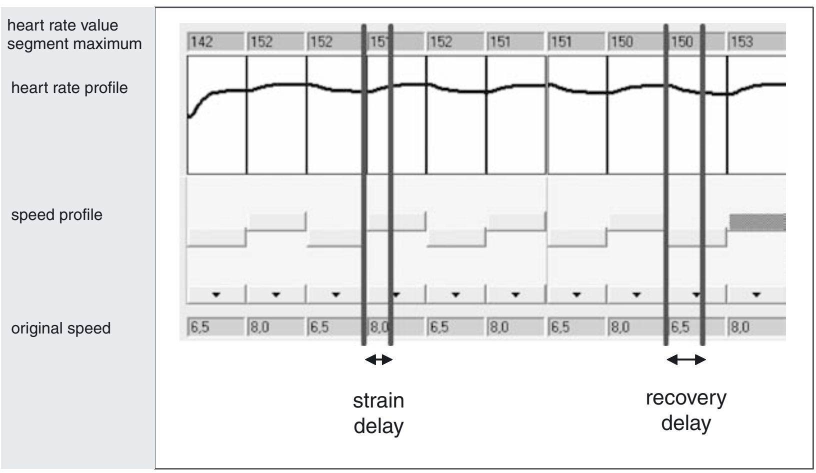

Figure 19: Delayed influence of strain and recovery in the case of speed changes (also see explanations in the text).

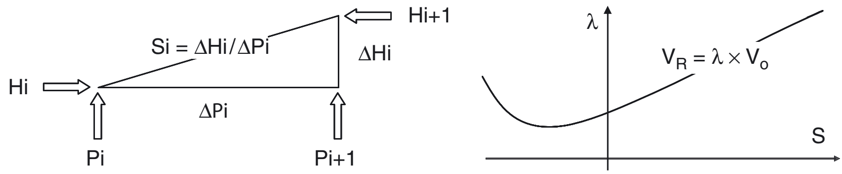

Figure 20: Calculation of the slope S of a course segment using position and altitude data (graphic left), and transformation from original to reference speed depending on the slope (graphic right) (also see explanations in the text).

The left graphic in Figure 20 shows how the GPS position data P and the altitude data H are used to calculate the slope S, while the right graphic shows how S and v_0 define $\lambda(S,v_0)$, which then is used to calculate v_R [24]. After calibrating the λ-transformation to the athlete, the course-specific load profile can be scheduled and optimized.

Finally, it has to be taken into consideration that (besides others) age and fitness have impacts on the delay values that in turn characterize the heart rate reaction on speed input. For example, the recovery delay (=response delay) DR will increase by fatigue, which depends on age and fitness as well as on the time already used on the run.

Figure 21 demonstrates the output of a SpeEdi Run analysis. The lower graphic shows the altitude profile with segments and corresponding slope values. The table between the graphics shows the original speed values and the reference speed values of each segment. The upper graphic shows the heart rate profile and corresponding segment maxima, which are calculated from the reference speeds by means of SpeEdi Run.

In the same way, the optimal speed profile can be calculated given a heart rate profile as objective function, which can help for improving the runner's performance and saving his health. In Figure 21, the objective heart rate profile was defined by '≤150'. The bold line shows the optimized speed profile, where the lowest speeds, as expected, are calculated for the two segments of largest positive slopes, while the highest speed is found only for one of the segments with the largest negative slope. The reason is that an increase in the speed in the fourth segment would cause a delayed increase in the heart rate in the sixth segment to '151'.

In turn, the correspondence between speed and heart rate can be used for controlling the run by just watching the heart rate, i.e. optimizing the speed by matching the intended heart rate. This approach exemplarily was applied successfully in a test where one of the authors of [23] (Stefan Endler) in his first hill marathon missed the scheduled time of 3:00 hours by only 10 minutes or 5.6% – using a heart rate meter as only control instrument.

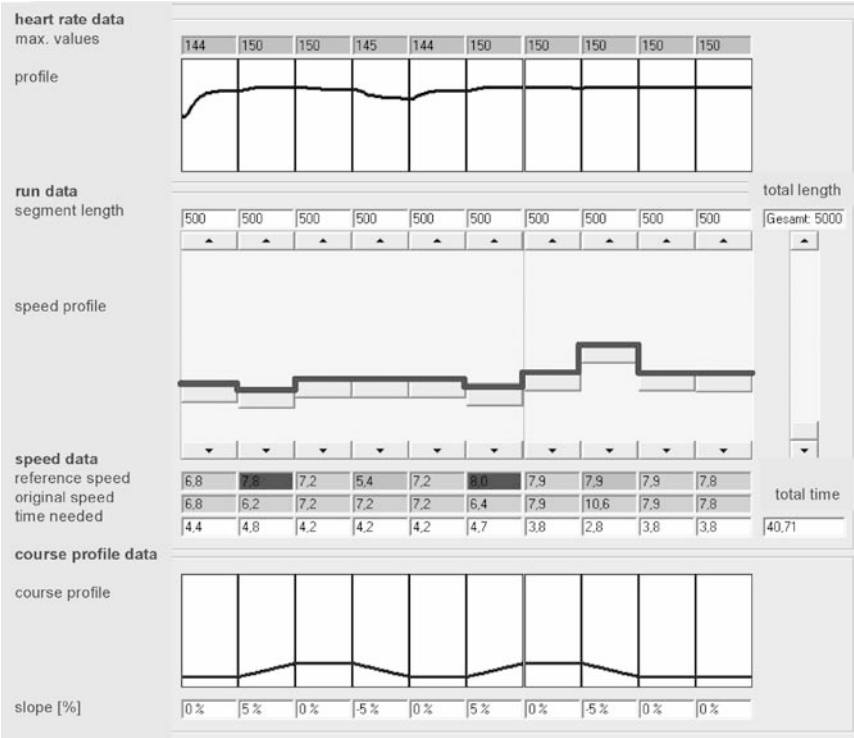

Figure 21: Speed profile optimized under the objection of not exceeding a heart rate of 150 (also see explanations in the text).

4 Analysis and simulation of processes

Processes in sport can be described as time series of patterns, which can as well characterize situations (e.g. positions on the playground or angles of articulations) as activities (e.g. moving of players or angle speeds).

Patterns can be learned and recognized by means of ‘self-organizing maps’, where in the following the term ‘learning’ is used to describe the effect of net training, which is measured by the presence of patterns that represent training contents.

4.1 Artificial neural networks

4.1.1 Introduction

In the field of ‘unconventional’ approaches, artificial neural networks play an important role in learning and recognizing patterns, which in particular is of high relevance under the aspect of behavioural processes (see Refs. [25–27]).

Briefly spoken, a behavioural process is a series of actions, which consist of a phase of state recognition followed by a phase of activity selection. Both phases need a specific type of learning. State recognition is based on similarities of situation patterns, while activity selection is (mainly) based on success. Accordingly, learning of situation patterns means generalizing pattern characteristics, i.e. clustering the set of possible patterns into classes of similar ones, which can be done without explicit supervising. In comparison to this, learning what the best activity in a recognized situation is has to be supervised in order to reduce bad decisions and reinforce good ones. These two types of learning use two different types of network:

1. Supervised learning can be done by means of networks that can be found under the denotations 'feed forward' or 'back propagation', which is due to their specific organization techniques.
2. Unsupervised pattern recognition, which is dealt with in Section 4.1.2, can be done by means of 'self-organizing maps', the most famous type of which is that of Kohonen Feature Map (KFM) (see Refs. [28–30]).

4.1.2 Kohonen Feature Map

A KFM consists of a grid or matrix of neurons. The dimension of this neuron matrix determines the dimension of the network, which is usually 2. The neurons of a KFMs are connected by a topologic relation that defines neighbourhoods: A neuron is neighboured to every neuron to which it is topologically related. By transitivity, levels of neighbourhood can be defined, which form shells of decreasing proximity: The direct neighbours of a neuron form its first-level neighbourhood; the neighbours of the neighbours (if not caught already) form the second level and so on.

Input data and neuron entries of a KFM belong to the same metric data model, i.e. their values are comparable and in particular have a distance between each other.

During the learning phase, an input affects the particular neuron, which is closest or most similar (and thus is called 'winner neuron'), by moving it towards the input. Also, the neurons of a number of neighbourhood shells are moved in the same direction, with decreasing intensity at increasing distance.

The moving intensity ('learning rate') as well as the number of considered neighbourhood shells ('radius of activation') determines the learning behaviour and, for strategic reasons, has to be adjusted during the learning process.

Because of the similarity-controlled neuron movements, the input values eventually effect a distribution of the neurons, which is topologically similar to the distribution of the input values. In particular, classes of input values are mapped to clusters of neurons.

After the learning phase, input values can be classified as belonging to specific clusters, and in general, hidden structures of the input data set can be detected, which is very helpful particularly if the dimension of the input space is large (e.g. high-dimensional attribute vectors of motions).

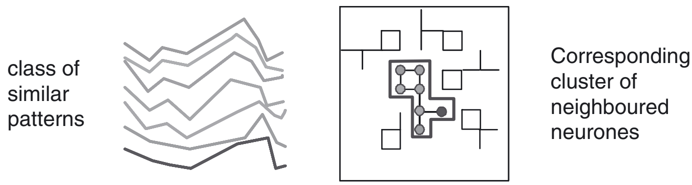

Figure 22: Unsupervised learning: Patterns (e.g. from motions) are inputs to a KFM, which then form clusters and the neurons of these clusters correspond to the patterns.

Moreover, by mapping the high-dimensional attribute vectors to neurons, which are two-dimensional regarding their grid – coordinates, the complexity of the input space is reduced to a two-dimensional geometric structure, which in particular helps for representing time-dependent processes by the trajectories of the corresponding neurons and therefore allows for much easier analyses.

Figure 22 demonstrates the net clustering and the correspondence between pattern classes and clusters. Here ‘pattern’ means any time series of values (e.g. from a motion process) that can be taken as one high-dimensional input.

4.2 Approaches and applications

The importance of artificial neural networks in sports can be seen from the wide variety of applications in different areas, as for instance are individual sports [31–33], team sports [10, 34, 35], biomechanics [36–38] and rehabilitation [39].

A number of applications of KFMs in sport, which stretch from game analysis over biomechanics to rehabilitation, can be taken from Ref. [40]. The most complex challenge regarding process analysis and pattern recognition in sport can obviously be found in games. Therefore, two examples of how KFMs can support such analyses are dealt with in Section 4.2.1.

4.2.1 Handball

In the example in Figure 23, a KFM is used in order to analyse types of tactical structures in team handball. Therefore, a process-oriented observation model of the offensive play was developed on the basis of offensive attempts. Fifteen matches (12 teams) of the Women’s Junior World Championship 2001 were observed. Afterwards a prepared neural network was trained with 2900 offensive attempts (processes) from all teams to coin offensive attempt patterns. In the contribution, it is shown that the neural network can be used in order to identify typical tactics of different teams [41].

Some selected results are presented below to indicate the kind of conclusions about the tactical structure in team handball which can be provided by the net. Figure 23 illustrates the trained network, where the marked surfaces represent those patterns of offensive attempts which exhibit a similar tactical structure.

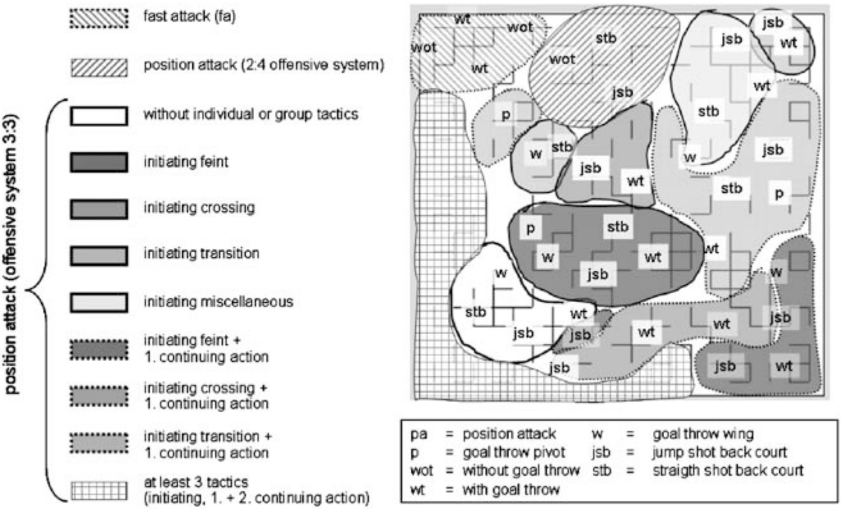

Figure 23: Type-pattern of the offensive attempts (Women's Junior World Championship 2001). For more information see Ref. [41].

In the upper-left corner of the network, offensive attempts are identified, which are formed in fast attacks (solid dashed line). Those attempts in the position attack with the system 4:2 are classified by the network on the top within the middle area (striped area). The remaining network represents attempts in the position attack 3:3. Within this area, clusters of neighbouring neurons are identified, which are connected by edges indicating similarity.

In a next step, the neurons and clusters identified by the network architecture can be specified and analysed with regard to the tactical behaviour (Figure 24). In particular, teams can be analysed and compared regarding the similarity in their tactical behaviour. As an example, the offensive attempts of the three best teams were isolated from the training data and tested afterwards with the network. A network pattern for each team, in which the quantity of an offensive attempt type is represented by the circle diameter, is shown in Figure 24. For better illustration, the frequently occupied areas, i.e. dominant types of attempts, are marked by additional lines.

As can easily be seen, the basic structural frame is identical for the three teams, while the individual areas of major importance and frequency are quite different. As is analysed in more detail in Ref. [41], the tactical behaviour of Hungary, Russia and Germany can briefly be characterized as follows: The activities of type 'fast attack' are represented by the upper-left corner of the net. They are not identical but rather similar for the three teams. In contrast, the activities of type 'position attack' differ a lot. The tactical concept of Hungary is dominated by the formation '3:3' and individual actions (large central cluster), while the Russian team additionally shows the formation '2:4', transitions and other

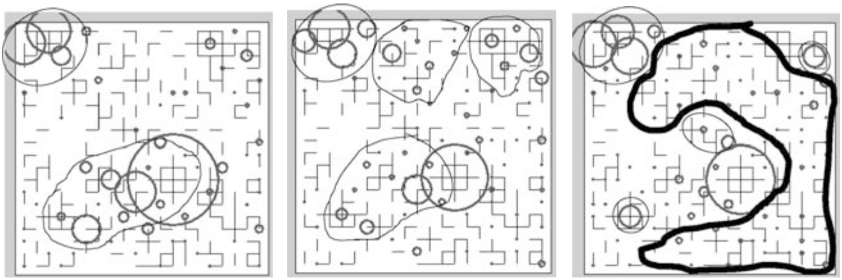

Figure 24: Type-patterns of offensive attempts (oa) of Hungary, Russia and Germany as the best three teams of the tournament.

actions (two additional clusters on top). In the German tactical concept, dominating tactical types can hardly be identified. The offensive attempts are distributed over the entire network area, indicating a diversified tactical behaviour (marked large area without clusters). A similar approach was developed by Leser [42], who focuses on processes as sequences of tactical events in soccer (also compare Ref. [25] for volleyball).

The next example deals with the question whether positioning movements of players in a game can be recognized as tactical elements.

4.2.2 Volleyball

The aim of the approach was to identify the tactical concepts of the teams by means of a net-based analysis of the teams' configurations, where the term *configuration* means the set of positions of every athlete of a team on the playing ground.

The analysis of team configurations with self-organizing artificial neural networks allows for detecting patterns as well as their changes and variability. This has a strong practical relevance since variable attack and defence configurations are supposed to be necessary for successful teams [43]. The analysis of these aspects by means of networks is done by mapping the time-dependent sequences of configurations onto the two-dimensional grid of the net neurons. This reduction of the complex information helps to understand the structural as well as dynamical properties of the processes: As Figure 25 demonstrates in the left graphic, structural aspects can be identified as clusters of neurons (i.e. types of specific configurations), while dynamical aspects can be studied by connecting subsequent configuration neurons to trajectories (right graphic, representing time-depending changes of configurations). Thus, net-based analysis of players' configurations seem to be helpful for:

- Identifying typical patterns in game situations.
- Determining differences in tactical concepts.
- Evaluating the variability in a team's action regarding tactical arrangements.

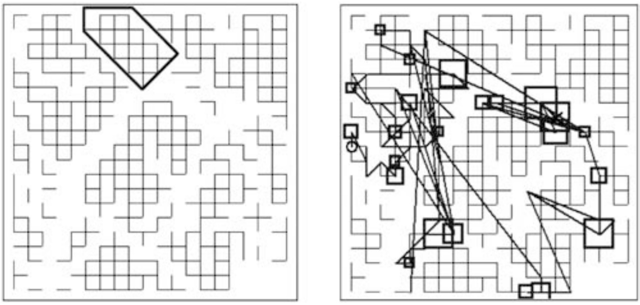

Figure 25: A KFM after training with constellation patterns: The left graphic shows a typical cluster structure of neurons, which represent types or classes of similar constellations. One cluster is marked by a polygon. The right graphic shows the same net with a trajectory connecting single neurons in the order they correspond with the constellations of the regarding preparation process.

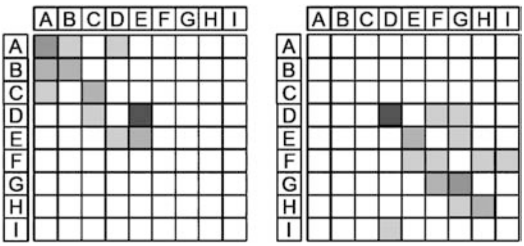

Figure 26: Transitions in configurations from Germany (left) and Italy (right).

Figure 26 demonstrates on a very abstract level what kind of information can be taken from net-based analysis: With 'A' to 'I' denoting the most frequent clusters or types of constellations, the matrices show the moves between those types in a phase of preparation before acting. As can obviously be seen, the move patterns of Germany (left) and Italy (right) are quite different, thereby characterizing quite different tactical concepts.

There are several different approaches of analysing players' positions in games, as for instance:

- By means of artificial neural networks, recognizing patterns in the interaction of squash players [10].
- By means of a hierarchical cluster analysis, identifying volleyball teams [44] or studying opponent specific defence patterns [45].
- From a dynamic systems perspective, analysing stable and unstable phases in the positions of two squash players [46].

More information about modelling and net-based analysis of team games can be found in Refs. [47–50].

4.3 Modelling of learning processes

Although neural networks of type KFM are very helpful for analysing data by just learning them, they are rather useless if learning itself is the process to be analysed: Due to the fact that a KFM learning process is controlled by an external algorithm using parameters that run down to final values and so eventually cause the end of the learning process (see Section 4.1.2), a once trained KFM cannot be reactivated. Therefore, additional or continuous learning can be done only by repetitions of the learning process using appropriate mixtures of data from the different phases of the learning process, which is uncomfortable as well as methodologically not satisfying. To handle this problem, the concept of Dynamically Controlled Network (DyCoN) has been developed.

4.3.1 Dynamically controlled networks

DyCoN is a neural network approach, which particularly has been developed for analysis of dynamical adaptation. A DyCoN network is able to learn and recognize types, frequencies and distributions as well as time-dependent changes of patterns. The pattern itself can be either a static structure of item values (e.g. in the case of medical diagnosis or fraud detection) or a dynamic time series of item values (e.g. in the case of strategic behaviour in sport or in rehabilitation processes). Items primarily mean scalar numeric attributes, but also non-numeric attributes can be used as items.

Because of its ability of identifying patterns and recognizing suspicious features in complex data sets, DyCoN is used for supporting data-based decisions, meanwhile ranging over a wide area from sport and medicine to fraud detection.

The DyCoN approach is basically following the above-described concepts of KFMs. The new idea of DyCoN is that each neuron learns and offers information individually and continuously without using external control functions [10, 51]. This way, the network can be trained in different phases, depending on the respective training success, and so can be optimized with regard to available data on the one hand and required precision on the other. In particular, besides the original data, synthetic data can also be used for net training if properly generated from the original ones (e.g. by means of Monte Carlo methods). Using these artificially generated surrogate data, the amount of original data necessary for training can be reduced drastically.

Moreover, continuous learning allows DyCoN for completing already learned patterns and trends by new information that was not available during the initial learning phase. This enables for using DyCoN as a tool for the analysis of learning processes. A current project (see Refs. [52, 53]) deals with children's learning of creativity in sport games and promises a lot of qualitative information that could not be obtained from quantitative statistical analyses.

4.3.2 Net-based analysis of learning behaviour

In the first phase of the above-mentioned project, the learning progress of the children was evaluated three times by six raters each: first time at the beginning, a second time at the end of the six weeks training and a third time nine more weeks after the training. The expectation was that there was an improvement from the start to the end of the training phase, followed by a certain stabilization. The result, however, was different.

In a first step, the network was trained with the six-dimensional rating data, resulting in a net the neurons of which were separated in areas of similar learning success (see Figure 27).

The three-step training process of each child could be mapped to a time-dependent sequence of three neurons, i.e. the trajectory that mapped the training process to a geometric pattern (see Figure 28).

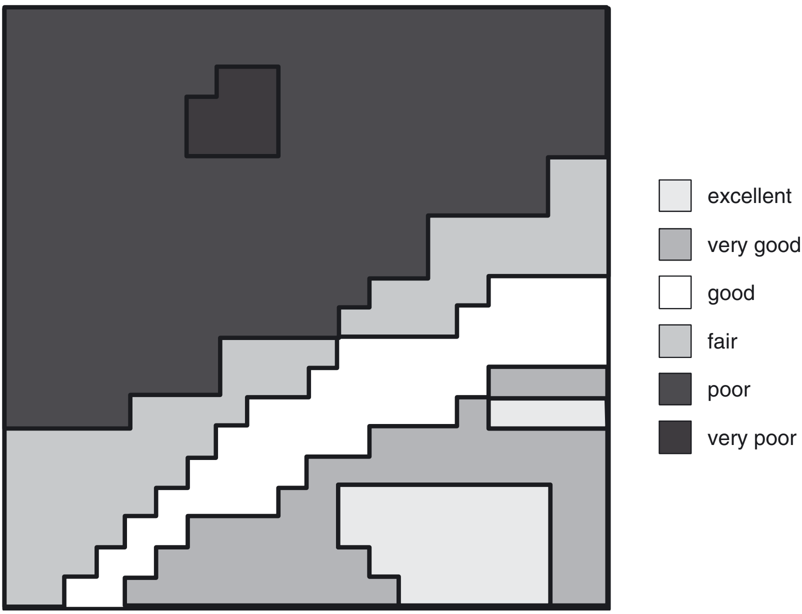

Figure 27: Trained neural network with areas of learning success.

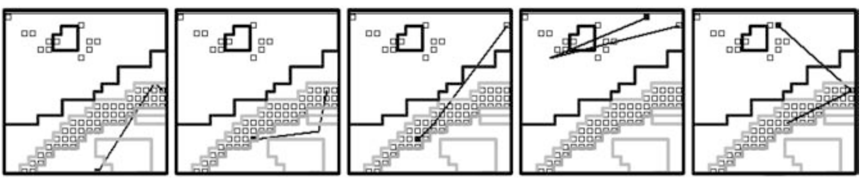

Figure 28: Examples of neuron trajectories of learning processes.

As can easily be seen, the trajectories form quite different patterns, reflecting all combinations of good and bad success and therefore suggesting quite different individual types of learning behaviour. The question was whether a network like DyCoN was able to reproduce such learning dynamics. First positive results were available from a study dealing with the learning dynamics of DyCoN (see Section 4.3.3). The major problem, however, was how aspects of creativity, namely associative links, originality and flexibility, could be modelled with such net approaches. Section 4.3.4 gives some brief introduction to the way the problems have been dealt with.

4.3.3 Dynamic learning and forgetting

One major consequence of the DyCoN concept is that its neurons not only can learn but also can forget information and so enable for replacing one pattern by another in a replacing learning process (see Figure 29).

These examples represent a typical conflict situation in learning processes. Sometimes one already learned pattern has to be completed by another one (e.g. if the backhand technique is added to an already available forehand technique) and sometimes an already learned pattern has to be replaced by another one (e.g. if a wrong technique has to be improved). Obviously, appropriate learning schedules are necessary to meet the respective intentions. The questions are whether such schedules can be found and seem to be reasonably transferable to human learning and could help for optimizing learning and training strategies, e.g. in the areas of motor learning or tactical game analysis.

A first systematic study was run by Weber [54], where a genetic algorithm (GA) was used for calculating best-fitting learning schedules to given objectives. The number of possible schedules is enormous, and as long as there is no idea what a successful training profile could be it seems to be hopeless to find an optimal schedule. However, as is well known from similar problems of this type, GAs can be helpful due to their ability of selecting, modifying and combining parts of temporary solutions.

In the study of Weber [54], the GA had to arrange the training of two different patterns, where the one objective was superposing learning in the sense of

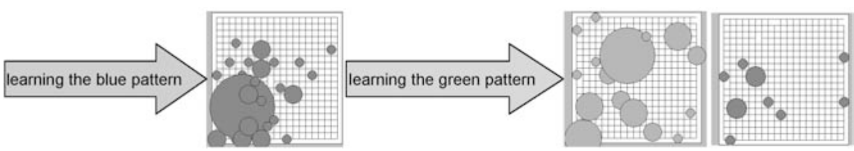

Figure 29: First learning the dark-grey pattern results in a high degree of presence that is represented by the number and the diameters of the respective circles. A following training with the light-grey pattern establishes its presence and reduces the dark grey one.

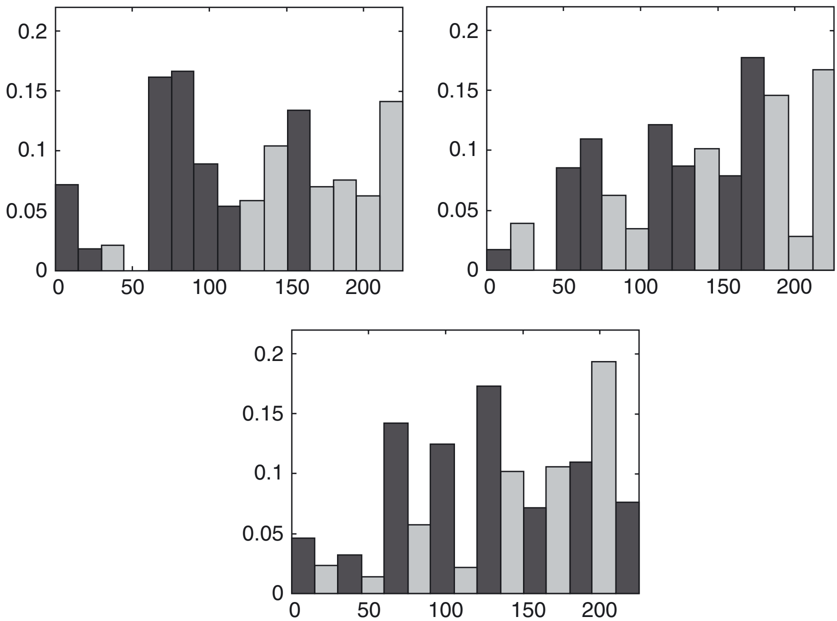

Figure 30: Three characteristic types of optimal schedules in the case of superposing learning (dark-grey and light-grey the learning intensities of the respective patterns). In the right graphic, the alternating learning rhythm was fixed, while the learning intensities were optimized.

establishing two patterns with equal degrees of presence, and the other objective was replacing learning. The structure of the schedules was given as an equidistant scheme of time-slots. The GA had to select one of the two patterns as well as the regarding learning intensity for each time slot.

Briefly spoken, the results are as follows: In the case of superposing, learning the optimal schedules are of the types shown in Figure 30, meaning that alternating learning phases with moderate learning intensities fit best for a balanced presence of two patterns.

In the case of replacing learning, the first result (Figure 31, left graphic) met the expectations: The replacing pattern had to be learned with a rather high sum of intensity. Additional tests, however, showed that an even better result could be reached by first 'attacking' the net with an erasing third pattern (Figure 4, right graphic) – which can be interpreted as 'brain washing'.

The major result from this first study was that the DyCoN approach with its complex internal dynamics, where each neuron has its individual memory, can be useful for the simulation of learning processes. This simulation, however, is limited to quantitative and rule-oriented aspects of learning where frequencies and precise mappings play the important role. If, as in the case of creativity, the

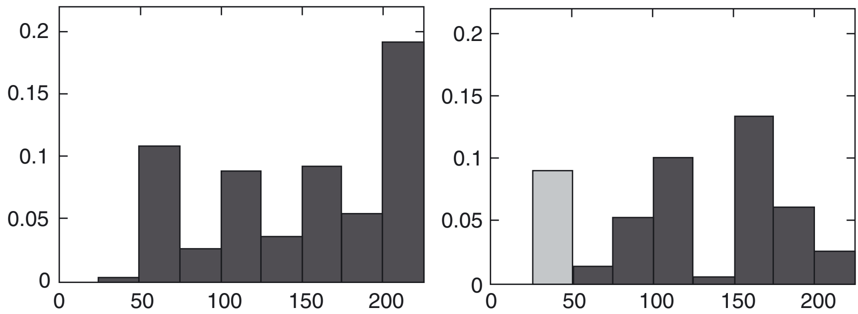

Figure 31: Left graphic: Typical learning schedule in the case of replacing learning (dark-grey columns: learning intensities of replacing patterns). Right graphic: Learning with additional erasing pattern (light-grey column).

focus is on qualitative learning and flexible adaptation, the concept has to be completed accordingly.

4.3.4 Net-based modelling of creative and associative behaviour

One way of completing the DyCoN concept is to dynamically adapt the capacity of the network to the requirements of the learning process; this can be done by integrating the concept of Growing Neural Gas (GNG: Refs. [55, 56]). Another aspect is to take care of seldom events of high relevance – as creative activities are – which are neglected by all known net approaches. The result is the Dynamically Controlled Neural Gas (DyCoNG: Refs. [57, 58]), the concept of which completes the combination of DyCoN and GNG by quality neurons that reflect the quality of information and therefore can measure the creativity of a recorded activity.

Finally, the clusters that are built during a training process are unambiguous, i.e. an accepted test stimulus is always recognized as corresponding to exactly one neuron. In contrast, modelling associative behaviour would mean to implement 'bridges' between clusters or from clusters to single neurons, as is demonstrated in Figure 32: The idea is to allow drifts from the primarily recognized neuron to similar or neighboured ones using stochastic-based decision rules. Current projects are dealing with getting that concept to work.

The DyCoNG approach was tested in a creativity-learning project that was the continuation of the project mentioned in Section 4.3.2. Some first results from DyCoNG-based simulation show that the network is able to reproduce recorded learning processes and separate main process types.

To analyse creativity learning in games, the behaviour of 42 children in standardized game situations was tested. The task was to recognize gaps in a defence line for passing the ball. Over a period of 6 months, every two weeks the children's actions were video-recorded, and the player positions were extracted from the video frames. Subsequently, the actions were rated regarding originality

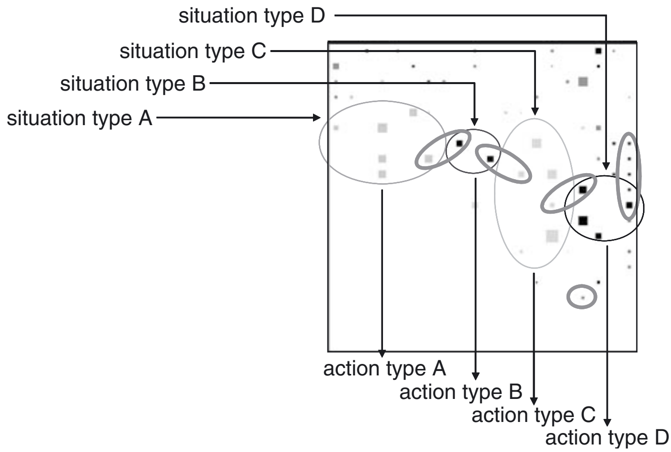

Figure 32: As a result of convergent learning, actions are strongly connected to corresponding situations – i.e. situation types define action types via specific net clusters. Divergent learning enables drifting between those clusters (centre), expanding clusters (right) and even defining new clusters (bottom right). Convergent clusters: light grey; divergent clusters: dark grey.

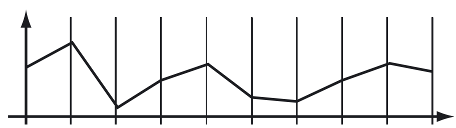

Figure 33: Example of a learning profile, i.e. a time series of creativity values.

and flexibility using the original frames (including context information from the game) as well as standardized computer-simulated frames. A typical learning profile is shown in Figure 33.

An action in a specific situation is called creative or of high originality if it is a seldom event in that situation. In terms of networks, the regarding stimulus has a great distance to all stimuli the network has already learned, and therefore, from the information-theoretic point of view, has a high relevance. Conventional KFMs, however, do not care about great or small distances but melt the new stimulus to the best fitting neuron, therefore neglecting the particularity of that specific information. In contrast, DyCoNG embeds every neuron in a sphere that limits its area of attraction. New stimuli outside the spheres of all available neurons are categorized as ‘strange’ and then define new (quality) neurons of high relevance. This specific quality of information-theoretic relevance can fade out if the same stimulus is fed more frequently to the net, resulting in a slow opening for different stimuli and therefore eventually merging into different neurons and clusters. If in turn a neuron is less frequently contacted compared to its neighbourhood, it again can become an isolated quality neuron with high relevance.

The main idea was that the originality or creativity of an action can be described by the quality of the representing neuron: high creativity goes with low frequency and high neuron quality values and vice versa.

The learning profiles resulting from DyCoNG training were compared to the regarding rater evaluations as well as to the learning types obtained from the children's profile analysis.

In order to check whether the net-based neuron quality meets the measured action originality, the time-specific data sets of the children (i.e. the training stimuli for the net) were classified into three classes: The class of high originality (values 6 and 5), the class of medium originality (values 4 and 3) and the class of low originality (values 2 and 1). Training the net with stimuli from the respective classes and taking the mean quality values of the corresponding neurons result in specific time series representing the learning behaviour of the net with regard to the particular class. As can be seen from Figure 34 (left graphic), the plotted profiles are not only similar to those from children's learning but are also separated regarding the levels of originality. Moreover, there seems to be a certain qualitative correspondence between the simulated and the original profiles (Figure 34, right graphic), which however has to be taken with care because of significant differences regarding the quantitative aspects and the need for deeper analyses and interpretations.

Nevertheless, the already obtained results and experiences regarding modelling and simulation of learning processes encourage for further investigation to support scheduling and optimizing those processes individually.

5 Conclusion and outlook

As has been demonstrated by examples of concepts, approaches and projects, modelling plays an important role in the area of sport science. It not only supports problem solving but also helps for a better understanding of those problems and the corresponding complex systems behaviour.

In order to get models to work, e.g. in order to simulate future behaviour or development, it is most helpful to use methods and techniques from computer science that enable handling complex data, calculating difficult algorithms and making complex structures and dynamics transparent by simulation and animation. Moreover, methods from computer science can improve approaches conceptually, as has been done with the paradigms of soft-computing. Finally, those approaches can improve process orientation in sport science, which is of central importance if understanding of complex dynamics is of interest.

Therefore, cooperation of structural systems analysis, process-oriented modelling and computer-based simulation seems to be the future way of adequate problem analysis and solving.

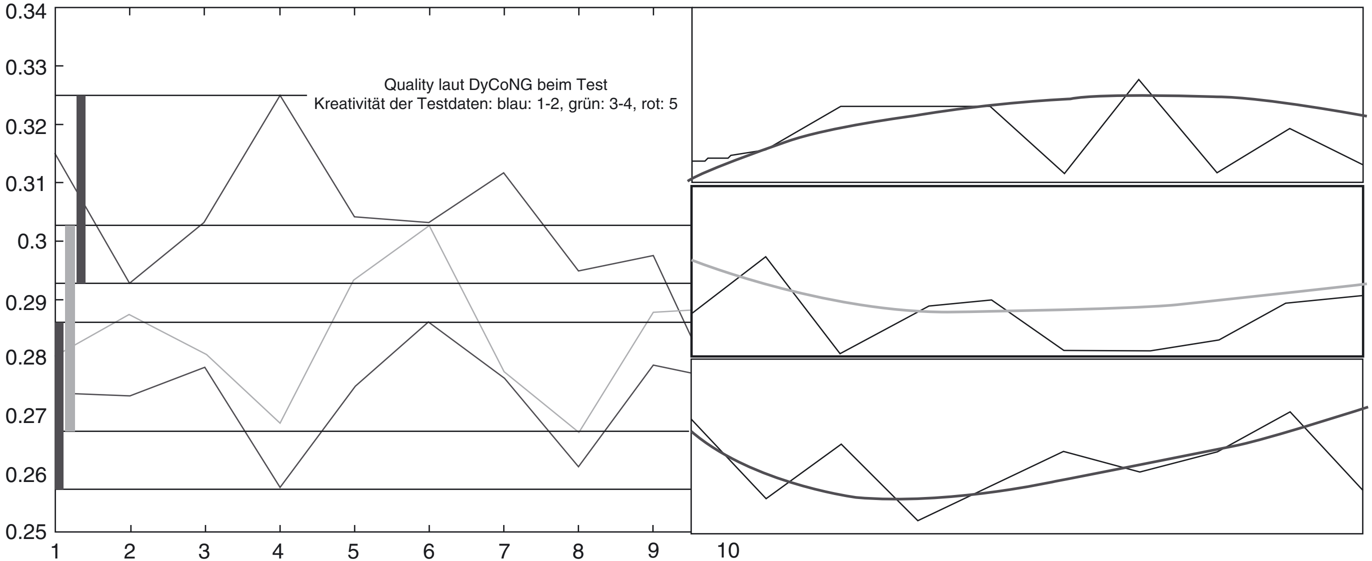

Figure 34: Profiles of mean quality values corresponding to the originality classes high, middle and low (left from top to bottom) compared to corresponding types of original learning profiles (right).

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Approaching a formal soccer theory from behaviour specifications in robotic soccer*

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Abstract

This chapter discusses a top-down approach to modelling soccer knowledge, as it can be found in soccer theory books. The goal is to model soccer strategies and tactics in a way that they are usable for multiple robotic soccer leagues in the RoboCup. We investigate if and how soccer theory can be formalized such that specification and execution are possible. The advantage is clear: theory abstracts from hardware and from specific situations in different leagues. We introduce basic primitives compliant with the terminology known in soccer theory, discuss an example on an abstract level and formalize it. The formalization of soccer presented here is appealing. It goes beyond the behaviour specification of soccer playing robots. For sports science a unified formal soccer theory might help to better understand and to formulate basic concepts in soccer. The possibility of the formalization to develop computer programs, which allow to simulate and to reason about soccer moves, might also take sports science a step further.

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1 Robotics and soccer

In 1997, the first *RoboCup*, the international world championship in robotic soccer was held. The event was part of the International Joint Conference on Artificial Intelligence (IJCAI), and set a new benchmark: the goal of RoboCup is to foster artificial intelligence (AI) and robotics research so that by 2050 a team of autonomous humanoid robots can be built that will be able to win against the human soccer world champion [2]. Similar to the goal of beating the human world champion in chess with a computer, in RoboCup the journey is the reward.

The initiators of RoboCup have chosen soccer as a test bed and common research platform because it covers a wide range of problems from robotics to AI: from energy supply, creating robust robots, over vision and sensor fusion to coordination, cooperative multiagent systems, behaviour programming, machine learning, strategy acquisition and many more issues have to be solved until it will be possible to reach this goal. Soccer is an interesting research problem because it is a multiagent domain where agents have to cooperate with their team-mates and deal with adversarial agents in real-time simultaneously.

Moreover, during the first years of research in robotic soccer it has already turned out that soccer playing robots can also be interesting by themselves, because matches between robots or computer programs can be quite entertaining and exciting – not just for the developers of the respective teams.

1.1 RoboCup leagues

To place the emphasis on different aspects, a number of leagues have been introduced in the RoboCup. In this section, we will briefly discuss these different leagues and their particular properties.

Simulation league. The 2D simulation league, one of the first leagues in RoboCup, concentrates on research in multiagent systems (architectures and coordination mechanisms). Two teams of eleven agents compete in a virtual soccer match in a real-time, but highly abstracted discrete time simulation. A simulation server, called Soccer Server [3], receives the action commands from the agents. Based on these commands it updates the state of the world and dispatches current sensory information to each agent in the next simulation cycle. The simulator also controls the game play. An automated referee judges offsides, throw-ins and counts the goals. The frame of reference for sensory inputs and agent commands is egocentric, i.e. the positions of all visible objects are given as distance and direction to the respective agent. Besides the visual information, the Soccer Server also sends aural messages to the player, i.e. a player can send 10 bytes per simulation cycle, and within a close range around the agent the message may be heard by other players. By this an unreliable low-bandwidth communication among players can be realized, which most teams use for exchanging parts of the agents' local world models. Agents can settle actions by sending one of five basic actions back to the server. These actions are *dash*, *kick*, *turn*, *catch* (for the goal keeper) and *tackle*. Communication is handled with the help of an extra *say* action. In recent years a more realistic but still abstract 3D simulation has been added which will soon replace the 2D simulation. This slowly evolves into a simulation of humanoid robots.

Small-size league. The Small-size league is a robotic league. Five small wheeled robots play on a field of the size of a table tennis board with a golf ball. As the robots are too small to carry sensors on-board, a ceiling camera is installed above the field. The camera images are sent to each team. Vision processing extracts the relevant information from the images. To alleviate the recognition, each player has a special colour coding on top. With these information the actions that the robots should perform are calculated by a computer off the field. The actions are sent back to the robots via radio. Thus, the league is partly autonomous. The research focus here is mainly on image processing and decision making. In contrast to the other leagues mentioned, player behaviour can be derived from a global, allocentric world model.

Middle-size league. Here, two teams of up to five fully autonomous wheeled robots compete on a field of the size 8×12 m. The robots may have a maximal size of 50×50 cm and the height may not exceed 80 cm. The research focus of the Middle-size league is on robotics, decision making, sensor and actuator systems and the integration of software and hardware. Especially in this league it turns out that the whole system, hardware as well as software, must form one unit. Only completely well integrated systems are competitive.

Four-legged league. While in the Small-size and the Middle-size league the hardware is developed by the participating teams and this development is part of the research, the Four-legged league aims at developing robot control software on a common platform. The robots here are Aibo dog robots from Sony. The different developments can well be compared as they all work on the same platform. The capabilities of the robots are limited. It has only a very small camera resolution, the sensor values of the joints in the legs of the dog are bad. Another problem in this league regarding the hardware platform is that Sony does not provide too many information about the hardware such that several controllers had to be reverse-engineered in order to learn how they work. Finally the quadruped walk and therefore, changing horizon, pose difficulties in this league. Another remarkable thing in this league is that code development is highly distributed. Within the *German Team* [4] several German universities work on a common code base. While their respective teams compete against one another in national events, the most promising approaches are integrated in a national team that participates quite successfully in the RoboCup world cups. Clearly, this is supported by the shared hardware. Unfortunately, this league will come to an end, as Sony stopped the production of Aibo robots in 2006.

Humanoid league. The ultimate goal of the RoboCup initiative is to play (robotic) soccer with humanoid robots. Of course, research on human-like robots must be conducted in order to achieve this goal. The humanoid league exists for three years now and has already made remarkable progress since then. In the beginning, the competitions were only so-called technical challenges, where the teams showed the capabilities of their robots. Today, there are already soccer matches two-on-two. There exist two different sub-leagues based on the sizes of robots, the so-called Kid-size league and the Teen-size league. In the Kid-size league robots with a height from 30 to 60 centimetre compete while a typical Teen-size robot measures between 65 and 130 centimetre, although in special cases robots up to 180 cm may participate in this league.

Non-soccer leagues. In order to address robotic and AI related problems not covered by the soccer-playing robots scenario, additional RoboCup competitions have been created: the RoboCup@Home and the RoboCup Rescue leagues. In the former, robots should fulfil helper tasks in human home environments. In the latter, autonomous agents and robots have to solve large and small scale rescue tasks, namely coordinating rescue teams in a (simulated) earthquake scenario and rescuing entombed people from an urban disaster area.

1.2 Challenges in robotic soccer

Participating in RoboCup, one faces a variety of problems in order to enable the robots to play soccer. Some of the problems are purely related to robotics: one has to deal with sensors and actuators, making the robot run. Other aspects are related to software design accounting for the real-time aspects of the soccer domain. The software system must be designed in such a way that sensor information coming in with high frequency can be processed promptly. Upon these data the robot must decide on appropriate actions like *kicking* or *dribbling* and compute the corresponding actuator commands. Further problems like navigation, collision avoidance and localization have to be solved. Beyond these problems it comes to the question how the processing from sensor inputs to actuator output is designed. State of the art for soccer robots are so-called reactive systems. Usually the robots make up a model of the accessible world from their sensor data. Such a world model contains data like the own position on the field, the position of the ball and the positions of opponents perceived. In a reactive system, a particular configuration of the world state, i.e. a configuration of world model variables, are mapped to an action the robot can take. In reactive systems, the occurrence of certain variable values is mapped directly onto a specific action without considering what happened in the past. These actions are rather complex actuator signal sequences. For an intercept action, for example, the system has to take into account the position of the ball, its velocity and the relative direction to it to set appropriate motor commands such that the ball is finally in the gripper of the robot.

At this stage of development the designer of such a robot system has to think about how the behaviour of the robot should be set up. As laid out before, one possibility is to directly couple sensors and actuators (possibly via a world model representation). The system designer now has to think about the abilities the robots have and she/he has to think about how soccer is played. With a soccer robot and its restricted abilities, currently, the behaviours are quite simple: usually, one robot captures the ball, dribbles towards the opponent goal and tries to score.

1.3 Learning from human soccer

Keeping in mind the RoboCup vision, only utilizing such simple behaviour patterns is not sufficient. One has to think about how humans play soccer. What are the different moves, strategies and tactics? Clearly, a humanoid robotic system must be able to perform moves that are as sophisticated as the ones used by human soccer teams in order to be competitive.

That is why we started investigating human soccer theory to learn more about the core of soccer in [1]. The aim of this joint research with background in different RoboCup leagues was to come up with a general theory of soccer for robots. We approached building this theory by investigating existing soccer literature to work out formal aspects of soccer. Particularly, we looked at a textbook by Lucchesi [5]. In this book soccer moves are described by diagrams containing important player positions. Several actions like *dribble* or *move* are depicted with arrows pointing to other positions on the pitch. In most of the diagrams the positions of opponent players are left out. This is due to the abstract character of the representation. To be able to understand the idea of the moves a common soccer ontology is assumed. In general, humans are very good in understanding such abstract qualitative representations. In brief, qualitative knowledge is obtained by comparing features within the object domain rather than by measuring them in terms of some artificial external scale. Thus, qualitative knowledge is relative knowledge where the reference entity is a single value rather than a whole set of categories [6]. Though, for a robot these representations do not help at first. The diagrams have to be translated into a formal, mathematical description of the scene before a robot could perhaps make use thereof. It starts with fixing an ontology for soccer defining, for example, what it means for a player to be a defender or an attacker. Furthermore, the spatial relations used within the descriptions have to be defined. The questions to be answered here are, for example, in which situation is a soccer move applicable, or when can a pass be played to a team-mate and finally, how can the sequence of actions of the soccer move be formally described.

1.4 Overview of the rest

This chapter is about the ongoing work to formalize soccer theory for the behaviour specification of soccer robots. The future direction we pose here is to come to a formal description of soccer. Beyond robotic soccer it could help to better understand soccer, to be able to better analyse soccer, and to simulate soccer moves with a computer program.

The chapter is organized as follows. In Section 2 we sketch the specification language Readylog and motivate spatial relations we use for formalizing soccer theory. In Section 3 we introduce soccer moves as given by Lucchesi in [5], deriving the soccer ontology and the building blocks for soccer in terms of actions and their preconditions. We also present a robotic soccer example and show how elements of soccer theory can be adapted to soccer robots. Here, we also sketch the qualitative world model we defined in order to describe important regions on the soccer pitch. We conclude with a discussion of the related work and a perspective outlook on this work (Section 4).

2 Theoretical background

In this section we briefly introduce the language *Readylog* which we use for the behaviour specification and programming of our soccer robots. This language is a formalism for combining robot programming with planning. It is also very well suited to formalize the soccer domain. We start with an introduction to the situation calculus, that is the formalism which Readylog is based on. Then we give an overview of Readylog and the different programming constructs which are available. We leave out the formal definition of the language constructs. It is important to note that a formal semantics for the language exists, i.e. the execution of programs of Readylog is not dependent on a particular implementation, which makes it very well suited to formalize soccer theory. In the rest of this section, we explain spatial relations that are needed for a formalization of soccer theory.

2.1 Situation calculus

The situation calculus [7, 8] is a logical second-order language proposed by John McCarthy in 1963. It allows us to reason about actions and change. The world evolves from an initial situation due to primitive actions. Possible world histories are represented by sequences of actions. The situation calculus distinguishes three different entities: *actions*, *situations* and domain dependent *objects*. There exists a special binary function $do(a,s)$ which denotes the situation that arises after performing action a in situation s. The constant s_0 denotes the initial situation, i.e. the situation where no actions have occurred yet.

The state of the world is characterized by relations and functions with a situation term as their last argument. They are called *relational* and *functional* fluents. As an example consider a robot lifting an object. The fluent $holding(s)$ describes whether the robot has lifted the object and holds it in its gripper. In the initial situation s_0 the robot has not picked up the object, thus $holding(s_0)$ is false. Now the robot performs the action $pickup(object)$. The situation describing the new state of the world is $s_1 = (do(pickup(object),s_0))$. The effect of the action can be described in terms of the fluent *holding*. It should hold that after performing the pickup action the fluent

$$holding(do(pickup(object),\ s_0)) \equiv true,$$

i.e. the robot has lifted the object and holds the object in its gripper. What is needed to make this true is a so-called effect axiom which describes the effects of the action *pickup*. A possible effect of this action is

$$holding(object,\ do(\ pickup(object,\ s))).$$

This means that if the robot performs the action pickup, it follows that in the successor situation $do(pickup(object, s))$ the fluent $holding(object)$ becomes true. What is further needed is a set of axioms which describe when an action is possible. For our pickup action a precondition could be that the box must not be too heavy, or expressed formally

$$Poss(pickup(object), s) \equiv \sim heavy(object, s).$$

Poss is a predicate which denotes the possibility to execute an action in a particular situation. Summarizing the basic ingredients of the situation calculus, one specifies a formal theory defining fluents, actions, their preconditions and their effects. Now, one can reason, for example, if at some state of the world after performing a sequence of actions, particular properties of the world are true or false. With this formalism one can easily simulate sequences of actions and find out how the world looks like afterwards. We only briefly sketched the situation calculus. For a thorough discussion about the situation calculus we refer to the textbook written by Reiter [8].

2.2 Readylog

Readylog [9, 10] is a variant of Golog [11] which is based on Reiter's variant of the situation calculus [7, 8] as described above. We will very briefly sketch the constructs of Readylog in the following. The original *Golog* evolved to an expressive language over the recent years. It not only has imperative control constructs such as loops, conditionals and recursive procedures, but also less standard constructs like the nondeterministic choice of actions. Extensions exist for dealing with continuous change [12] and concurrency [13], allowing for exogenous and sensing actions [14] and probabilistic projections into the future [15] or decision-theoretic planning [16] which employs Markov Decision Processes (MDPs).

Readylog integrates these extensions in one agent programming framework [9, 10]. For specifying the behaviour of an agent or robot the following constructs exist:

1. sequence: $(a; b)$
2. nondeterministic choice between actions: $(a|b)$
3. nondeterministic choice between action arguments: *pickBest*
4. MDP solving: $solve(p, h)$,
   p is a Golog program, h is the MDP's solution horizon
5. test actions: $?(c)$
6. event-interrupt: $waitFor(c)$
7. conditionals: $if(c, a_1, a_2)$
8. loops: $while(c, a_1)$
9. condition-bounded execution: $withCtrl(c, a_1)$
10. concurrent execution of programs: $(p_1 \parallel p_2)$

11. probabilistic actions: *prob*(val_{prob}, a_1, a_2)
12. probabilistic (offline) projection: *pproj*(c, a_1)
13. procedures: *proc*(*name*(*parameters*), *body*)

To encode the behaviour one has to give a domain axiomatization including the actions the robot can perform together with their effects, and the fluents which describe the properties of the world, e.g. the ball position. Examples of domain descriptions for the soccer domain can be found in [17, 18].

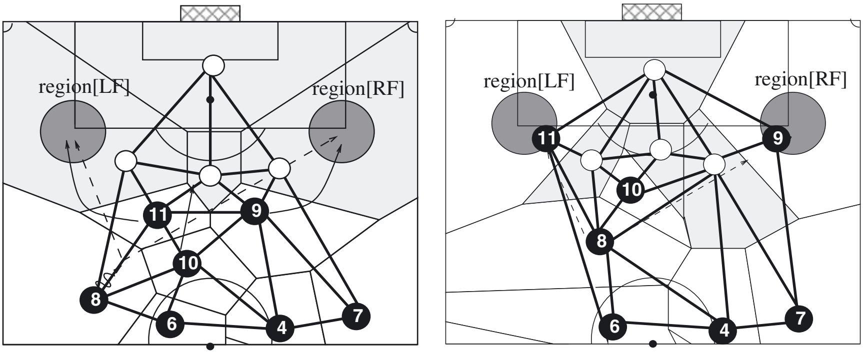
2.3 Spatial relations

In contrast to formal descriptions of (soccer) knowledge by means of mathematical equations or the situation calculus and their derivatives, human representations of soccer are as such qualitative. Distances between players on the pitch are, of course, never quantitatively represented or perceived by human players. A player would never express: I have to play the pass when my team-mate has a distance of exactly 2.35 metre and she is at an angle of 48° to me. This is one of the problems when trying to transfer the human soccer theory to soccer robots. Adequate human-readable models have to be found in order to be able to transfer human expert knowledge to a robot. In the following, we list some basic spatial categories.

Distance and orientation. The basic notion needed for describing soccer moves is a notion of space and distance. The approach described in [19] is based on [20, 21]. We started with an egocentric relation of distance. One defines a metric for IR^1, builds equivalence classes for ranges of IR^1 and assigns constants like *near* or *far* to each class. To build the orientation relation we build equivalence classes over ranges of angles. Each sector is assigned an orientation like with a compass rose. We use eight different orientations like *front*, *front-right*, *right* and so on. With these models for distance and orientation the robot is able to describe objects in a qualitative egocentric fashion like: the ball is located in the front-left direction at a medium distance.

Tactical regions. What is further needed to describe the soccer scenario, is a qualitative notion of strategic positions in a global frame of reference. In soccer, there are several strategic roles a player can have like *defence*, *midfield* and *offence*. Further, one can distinguish between three sides of the pitch as in [5]. The play can be on the left or right side or in the centre of the field. For our qualitative world model we defined five zones ranging from *farFront*, which is a zone directly in front of the opponent goal, to *farBack* which includes the own goal, and the sides *left*, *middle*, *right*. Again, we refer to [19] for details.

Reachability of regions or objects. To express reachability mathematically, one needs a model which takes into account the amount of free space available between the positions of team-mates or opponents. One possible model is to use Voronoi diagrams and their dual, the Delaunay triangulation as they separate the field into non-intersecting regions and we get a connection graph between the players. (A Voronoi diagram $V(S)$ of a set S of n point sites is the partitioning



(a) Initial situation (b) Intended resulting situation

Figure 1: Delaunay triangulation (bold lines) and Voronoi regions (white/grey) for the counter-attack example.

of a plane with n points into n convex polygons such that each polygon contains exactly one point $p \in S$ and every point in the given polygon is closer to p than any other point $p' \in S$. For a more detailed account on Voronoi diagrams and their dual, the Delaunay triangulation DT(S), see e.g. [22].) Figure 1 depicts the Delaunay triangulation and the Voronoi regions for the positions of the players in a counter-attack situation. The intention of this move is that after player 8 captured the ball, it dribbles towards the centre of the goal area until player 9 or 11 become reachable for a pass at the (in Figure 1) marked regions LF and RF, respectively. The bold lines represent the triangulation, the white and grey regions correspond to the Voronoi regions of the attacking team and the defending team, respectively. Figure 1(b) shows the diagram for the intended situation after player 9 and player 11 have taken their positions in their regions near the goal area. Note that we ignore offside for simplicity here.

The Voronoi diagram gives us information about which position on the field is closest to which player. In Figure 1(a) we draw the conclusion that the opponent defence controls the goal area, whereas after the successful counter-attack this line of defence is penetrated. The triangulation yields a conservative estimate about which player can receive a secure pass. In this particular example there is no connection between player 8 and player 9 and this resembles our intuition that the pass is not secure. In Figure 1(a) player 9 and player 11, respectively, can test if their target regions are occupied by opponents and they can also test the distance of the defenders to their particular region. Player 8 can dribble the ball as long as no opponent is in a distance where it can tackle player 8.

3 Formalizing soccer strategies

In this section we describe our approach to formalize soccer strategies for soccer robots [1]. The idea was to derive the basic behaviour patterns of soccer as described in [5] and adapt them to the different soccer leagues in RoboCup. The formalization of the soccer moves was done in Readylog which is also very suited for this task because of its formal semantics. In [1] we also started a case study how to apply the soccer moves to the different leagues. We leave out this part here, concentrating on the qualitative aspects of the formalization and refer to [1] for further details.

In the following, we first describe the basic ontology for soccer strategies and (related with this) the basic actions of a soccer player, before we derive the basic qualitative predicates needed to formalize soccer moves. Further, we give an example specification of a soccer move which can almost directly be encoded as Readylog program that is executable on a soccer robot.

3.1 The organization of soccer knowledge

Among modern soccer publications, Lucchesi's book [5] is one of the most interesting ones because it concentrates on strategic aspects of soccer rather than on training lessons. Soccer strategies in literature (e.g. [5, 23]) are not as highly structured as, say, strategies for American football. Though, they are structured enough to build a top-level ontology for it. According to [5] there are two phases in a soccer game: (1) the defensive phase and (2) the offensive phase. In the defensive phase the ultimate goal of the team is to *prevent the opponent from scoring a goal* and to *gain ball possession* again. When the second sub-goal of this phase is fulfilled the game enters the offensive phase. Here, a controlled *build-up of the play* has to be performed. In general, there are two ways to build up the play: either we introduce this phase in a counter-attack manner, i.e. fast and direct with a long pass, or deliberately by a diagonal pass or by a deep pass followed by a back pass. The taxonomy for soccer strategy is depicted in Figure 2, where 3-4-1-2 stands for the basic tactical setup of the team. The pattern 3-4-1-2 means that the team is playing with three defenders, four midfielders, one offensive midfielder and two forwards.

In the following, we will concentrate on the building-up phase for an illustration of how to derive basic behaviour patterns for soccer play. Figure 3 shows two example diagrams from [5]. The goal of the attacking team after building up the play is to *create a scoring opportunity*. The final move then is to try to *score a goal*. In soccer, there exist several strategic groups, each having a particular task in fulfilling the strategy just mentioned. The defence has to prevent the opponent team from scoring and must build up the play. The midfielders work to create a scoring opportunity and the offence has to score the goal.

Accordingly, a soccer strategy can be defined as a tuple $str = \langle RD, CBP \rangle$. Here, *RD* is a set of *role descriptions* that describe the overall abilities required of each player position in relation to *CBP*, the set of *complex behaviour patterns* is associated with the strategy. Given the strategy *str*, the associated role description $rd \in RD$ can be described by the defence tactics task, the offence tactics task, the tactical abilities and the physical skills.

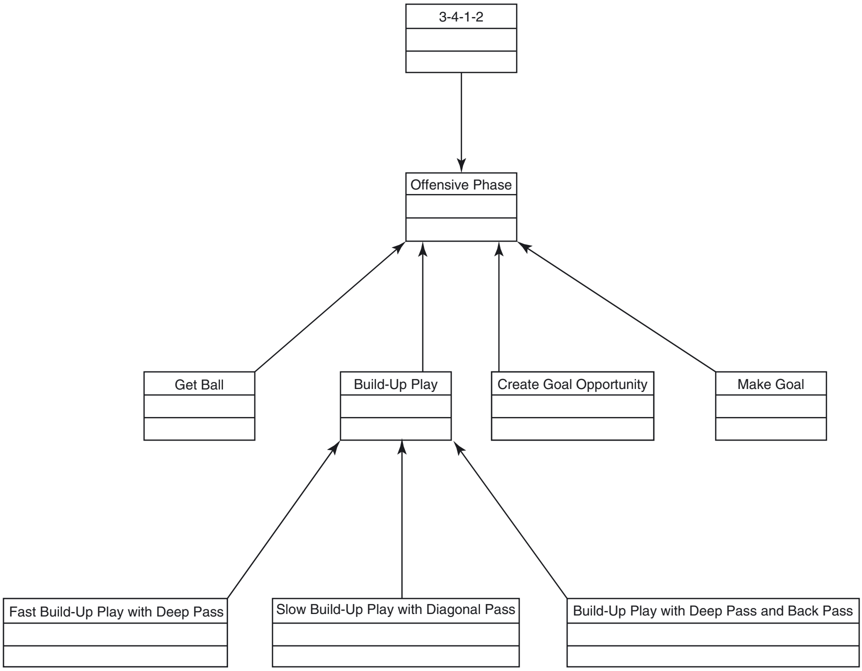
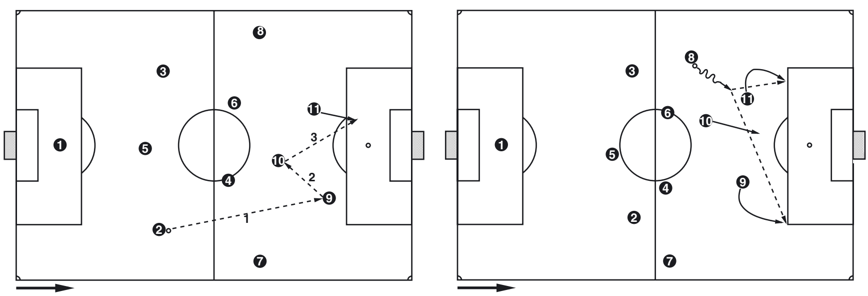


Figure 2: Top-level ontology according to [5].



(a) Diagram 4 from [5]

(b) Diagram 21 from [5]

Figure 3: Two tactical diagrams from [5]. The bold arrow next to the field indicates direction of play. Player movements are represented by arrows (→ or ↷), passes are indicated by dashed arrows (⇢), and squiggly arrows (⇝) stand for dribbling. Opponents are not shown.

3.2 An example: build-up play

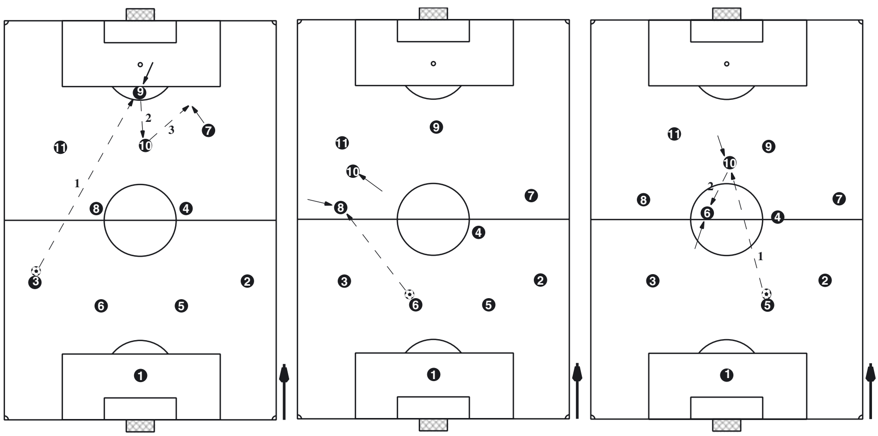
In this phase of the game, the team's objective is to take the ball towards the opponent goal in order to establish a setting which allows for creating a scoring opportunity. The ball has to be taken from the defensive players to the offensive players. There are a number of ways to build up the play:

Build-up play immediately with long pass. The long pass enables the team to take the ball up-field towards the opposing goal very quickly. There is an immediate reversal of play and the risk of losing the ball near one's own penalty area is very low. However, the long pass is difficult to receive, so the opponent may be able to steal the ball more easily. Moreover, as there is not much time, the team cannot move forward in a coordinated way.

Build-up play deliberately with diagonal pass. The diagonal pass allows for a coordinated way to move forward with the ball and it is easy to receive. The time to get close to the opponent goal is longer than with the long pass. Thus, chances of losing the ball in a dangerous area are higher.

Build-up play deliberately with deep pass and subsequent back pass. This way of building up play requires very good timing as it involves three players who have to move in a coordinated way. If such a move is carried out successfully it allows the team to move forward up-field without great risks if they lose the ball. We depict one exemplary tactical move for each of the three patterns to build up play mentioned in Figure 4.

The decision which pattern to choose certainly depends on the opposing team as well as on the particular situation. That is to say, when playing against an



(a) A long pass (b) A diagonal pass (c) A deep pass and a subsequent back pass

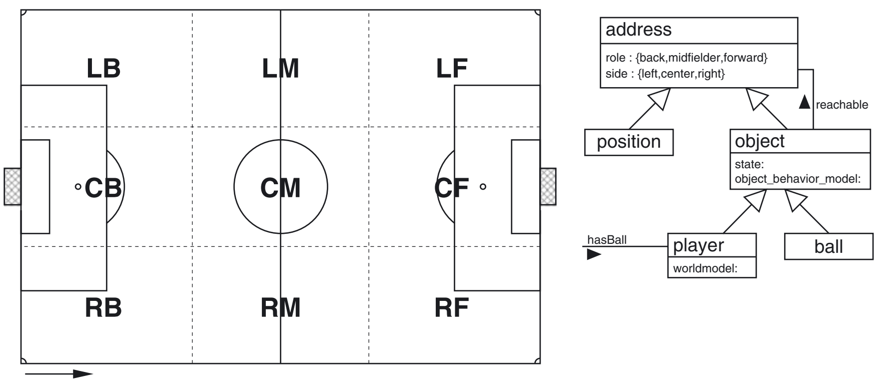
Figure 4: Three different ways to build up a play. Dashed lines represent pass ways and solid lines denote a player movement. The bold arrow next to the field indicates the direction of play.

opposing team which has many players in the midfield one would perhaps favour to build up a play with a long pass whereas with a team leaving lots of space uncovered in the midfield one would prefer the deep pass.

Basically, all the possibilities mentioned above are meant to take the ball up-field and establish a more offensive setting for the team while remaining in possession of the ball. The ball is either taken forward from the defence to the midfield section or in the case of the long pass directly to the offence section. Both can be done through the centre of the playing field or by using the wings of the pitch. Depending on how the play was built up there are several ways to create a scoring opportunity.

3.3 Basic primitives

From the example of the previous section one gets quite a good idea which behaviour patterns are needed for a soccer formalization. Following the lines of [5], we distinguish between *role* (back, midfield, forward) and *side* (left, centre, right) in soccer. This distinction is more or less independent from the pattern of play (e.g. 3-4-1-2 or 4-2-3-1). The combination of role and side (e.g. centre forward) can be interpreted as *type* of a (human or robotic) soccer player or as *position* (region or point) on the soccer field. In the latter case, there is a certain *zone* corresponding to the three roles back, midfield and forward. Altogether, this leaves us with basically nine different positions, as illustrated in Figure 5(a).



(a) Tactical regions on the field

(b) Class hierarchy for soccer dervied from [5]

Figure 5: Tactical regions and abstract position hierarchy derived from [5]. The field is divided into three rows (corresponding to player roles): back (B), midfield (M), and forward (F), and three lanes (sides): left (L), centre (C), right (R). An address may be one of the nine regions or player types.

The notions, player type and position, can be seen as instances or specializations of the notion of an *abstract position* or *address* for short usually associated with its (actual) coordinates or a region on the soccer field. Also the position of the ball is abstract, i.e. the parameter or goal of a test or operation of a soccer player (agent). A movable *object* in the context of soccer may be a player or the ball. An object is in a current *state*, which besides other data includes information such as the current speed or the view direction. Although not explicitly mentioned, a *model of behaviour* is assigned to every object, e.g. average or maximum speed or, as a special case, a deceleration rate for the ball. Additionally, every player needs to hold data about other agents' states. We abstract this by the term *world model*. All this is summarized in the class diagram in Figure 5(b).

In [5, p. ii] only few symbols are introduced that are used throughout the many diagrams in that book: players (in many cases only the team-mates, not the opponents are shown), the ball, passing, movement of the player receiving the ball and dribbling. Conceptually, all symbols correspond to *actions*, which we abbreviate as *pass* , *goto* and *dribble* . Since all actions are drawn as arrows starting at some player, naturally two arguments can be assumed: *player* and *abstract position*. $goto(player[LF\,], region[CF\,])$ means for instance that the left forward player moves in front of the opponent goal.

Although in most cases this is not explicitly mentioned in [5], actions require that certain prerequisites are satisfied, in order to be applicable. Since our approach aims at a very abstract and universal formalization of soccer, we restrict ourselves, for instance in case of a pass, to only two tests: possession of ball and reachability. Each of them can be seen as a *predicate* with several arguments: *hasBall* has the argument *player* (the ball owner); *reachable* has two arguments, namely an object and an address.

A pass e.g. presupposes reachability, i.e. it should be guaranteed that the ball reaches the team-mate. Clearly, the implementation of the reachability test is heavily dependent of the respective soccer league and its (physical) laws. Therefore, at this point, we only give a very general and abstract definition: Object o can reach an address a iff o can move to a and after that the ball is not in possession of the opponent team. This also covers the case of going to a position where the ball will be intercepted.

The primitive actions we consider here are $goto(player, region)$, $pass(player, region)$ and $dribble(player, region)$. Further we need the action *intercept* which is a complex action built from the primitive ones. The arguments of the actions are *player* and *region* denoting that the particular player should go to, pass or dribble the ball to the given position. For describing the properties of the world on the soccer field we need the fluents *reachable* and $hasBall(player)$ among others. The precondition axioms for the actions are:

$$Poss(pass(player, region), s) \equiv hasBall(player)$$
$$Poss(dribble(player, region), s) \equiv hasBall(player)$$
$$Poss(goto(player, region), s) \equiv true$$

For our formalization of soccer, reachability is central. Reachability strongly depends on the physical abilities of the robot. Besides the physical abilities the reachability relation has some independent properties. In general, we can distinguish three different reachability relations:

go-reachability: a player p not being in ball possession will reach an address a on the field before any other player: $reachable_{go}(p, a)$ with prerequisite $hasBall(p)$

dribble-reachability: a player p being in ball possession is able to dribble towards address a with high probability of still being in ball possession afterwards: $reachable_{dribble}(p, a)$ with prerequisite $hasBall(p)$

pass-reachability: a player p being in ball possession is able to pass the ball b towards address a with high probability of a team-mate being in ball possession afterwards: $reachable_{pass}(b, a)$ with prerequisite $hasBall(p)$

With the Voronoi model presented in Section 2.3, we can define our *reachable* relation as a connection between vertices in the Delaunay triangulation. Note that this approach is only one possibility for implementing reachability. The practical experiences made in robotic soccer show that this model is useful as a mathematical description of all three kinds of reachability.

3.4 Deriving the specification of soccer tactics

For our soccer domain axiomatization, we give successor state axioms for the *ballPos* function (ball position) and *hasBall* fluent as examples. We assume, that the ball position changes only if we pass the ball to a team-mate or dribble with the ball.

$$\begin{aligned} &ballPos(do(a, s)) = b \equiv \exists player \exists region \\ &\quad ((a = goto(player, region) \wedge ballPos(s) = b) \\ &\quad \vee((a = pass(player, region) \vee a = dribble(player, region)) \wedge b = region)) \end{aligned}$$

A player is in possession of the ball if its position is the same as the position of the ball. Of course, the player should be located in a certain area around the ball, but for ease of presentation we leave this out. If the player passes the ball to another position, the fluent value becomes false.

$$\begin{aligned} &hasBall(player, do(a, s)) \equiv \exists region \\ &\quad ((a = goto(player, region) \wedge ballPos(s) = region) \\ &\quad \vee(hasBall(player, s) \wedge \neg\exists region\ a = pass(player, region))) \end{aligned}$$

Please note the difference between effect axioms and successor state axioms. In Section. 2.1 we introduced effect axioms to describe the effects of actions. A successor state axiom is defined for each fluent and defines all possibilities how the value of this fluent is changed by any action (cf. [24]).

With these basic actions and their effects we can easily formalize examples of building up play from Figure 3, starting with Figure 3(a) showing a long pass as first action. There, back player 2 makes a long pass to forward 9, who then passes back to the centre midfielder 10, who can make a pass to forward 11, who cuts in deep down-field, as written in [5, p. 29]. Four agents that are team-mates are actively involved in this manœuvre: back player $p_2 = player[B]$ (whose side needs not to be specified), the centre midfielder $p_{10} = player[CM]$, and two forwards $p_9 = player[xF]$ and $p_{11} = player[yF]$ on different sides, i.e. $x \neq y$.

Before we are able to formalize the whole manœuvre, we have to think about what passing means exactly. A pass from player p to p' requires that p is in ball possession and that the ball can be passed to p', i.e. the logical conjunction $hasBall(p) \wedge reachable(ball, p')$. Afterwards p' is in ball possession, i.e. $hasBall(p')$. In [5, p. 27], three different types of passes are mentioned. They can be formalized by additional constraints:

1. long pass with $p.role = B \wedge p'.role = F$,
2. diagonal pass with $p.side \neq p'.side$, and
3. deep pass with $p.role < p'.role$ where we assume that the roles (which can also be understood as rows in Figure 5(a)) are ordered.

With these definitions and constraints for passing, the tactics in Figure 3(a) can be described by the following program in a straightforward manner:

proc build-up-play
(pass(p_2, p_9); pass(p_9, p_{10})||goto(p_{11}, r));pass(p_{10}, r)
endproc

Algorithm 1: Build-up-play algorithm.

Recall that subsequent actions (sequences) are marked with semicolon; concurrent, i.e. parallel actions are separated by the symbol ||. In addition, $r = region[CF]$ denotes the region in front of the opponent goal. Since we take the allocentric view from the diagrams in [5], we may have parallel actions of different agents (e.g. player 11 running in front of the opponent goal, while player 9 or 10 initiates the pass). Clearly, this has to be turned into an implementation for each agent.

As another example, consider the move depicted in Figure 6 which is a possible move for a counter-attack. There, player 8 just captured the ball from the opponent team and dribbles toward the goal while the forwards (player 9 and player 11) revolve the opponent defence in order to get a scoring opportunity from both corners of the penalty area while player 10 starts a red herring by running to the centre. The white circles represent opponent players. In the original Figure [5, diagram 21] (see Figure 3(b)), there are neither opponent players nor dedicated regions; we inserted them here for illustration purposes.

proc counterattack_21
intercept;
startDribble (*region*[CF]);
waitFor($reachable(p_{11}, region[LF])$) $\vee$

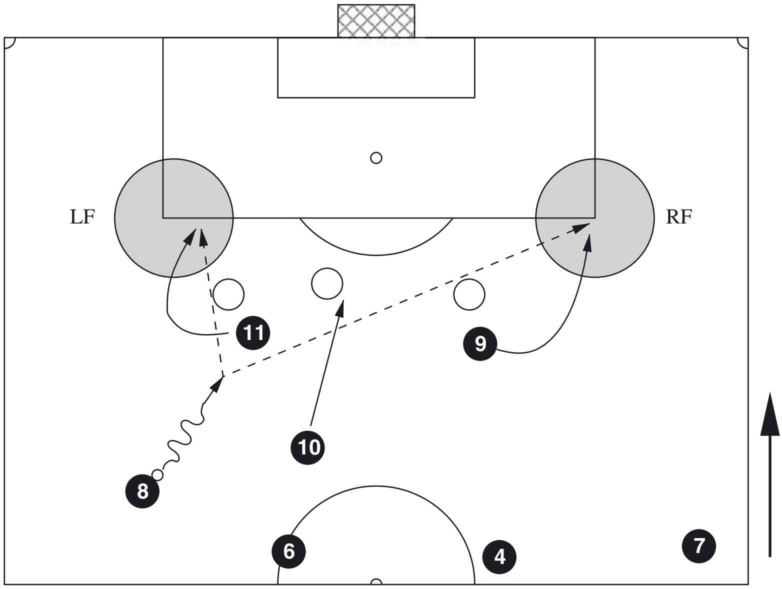


Figure 6: Extended diagram 21 from [5].

reachable $(p_9, region[RF]) \vee$
$\exists x.opponent(x) \wedge Tackles(x))$;
endDribble;
if $reachable(p_{11}, region[LF])$ **then**
pass(*region*[LF]);
else if $reachable(p_9, region[RF])$ **then**
pass(*region*[RF]);
endif
endproc

Algorithm 2: Counter-attack program.

Algorithm 2 is from the point of view of player 8, that is, all actions and tests are performed by this player. Player 8 gains the ball with an intercept action. He dribbles towards the centre (denoted by *region*[CF])) until either player 11 or player 9 is able to receive the pass or an opponent forces player 8 to do another action (which is not specified in this example). In the specification above, we use the action pair *startDribble* and *endDribble* instead of a single *dribble* action accounting for temporal aspects of that action. Splitting the dribble action into initiation and termination is a form of implicit concurrency since other actions can be performed while dribbling.

The next step in the presented sequence is a *waitFor* construct. It is used to specify that no further actions are initiated until one of the conditions becomes true, i.e. players 11 or 9 are able to receive a pass in their respective regions or an opponent tackles player 8, i.e. an opponent could probably intercept the ball.

Note that during the blocking of the *waitFor*, the dribbling of player 8 continues and sensor inputs are processed to update the relation *reachable*.

Finally, in the conditional we have to test which condition became true to choose the appropriate pass. Note that we do not choose an action in the case of both player 9 and player 11 cannot receive the pass as this would be the matter of another soccer move procedure. The counter-attack programs for other players participating in this move can be specified similarly.

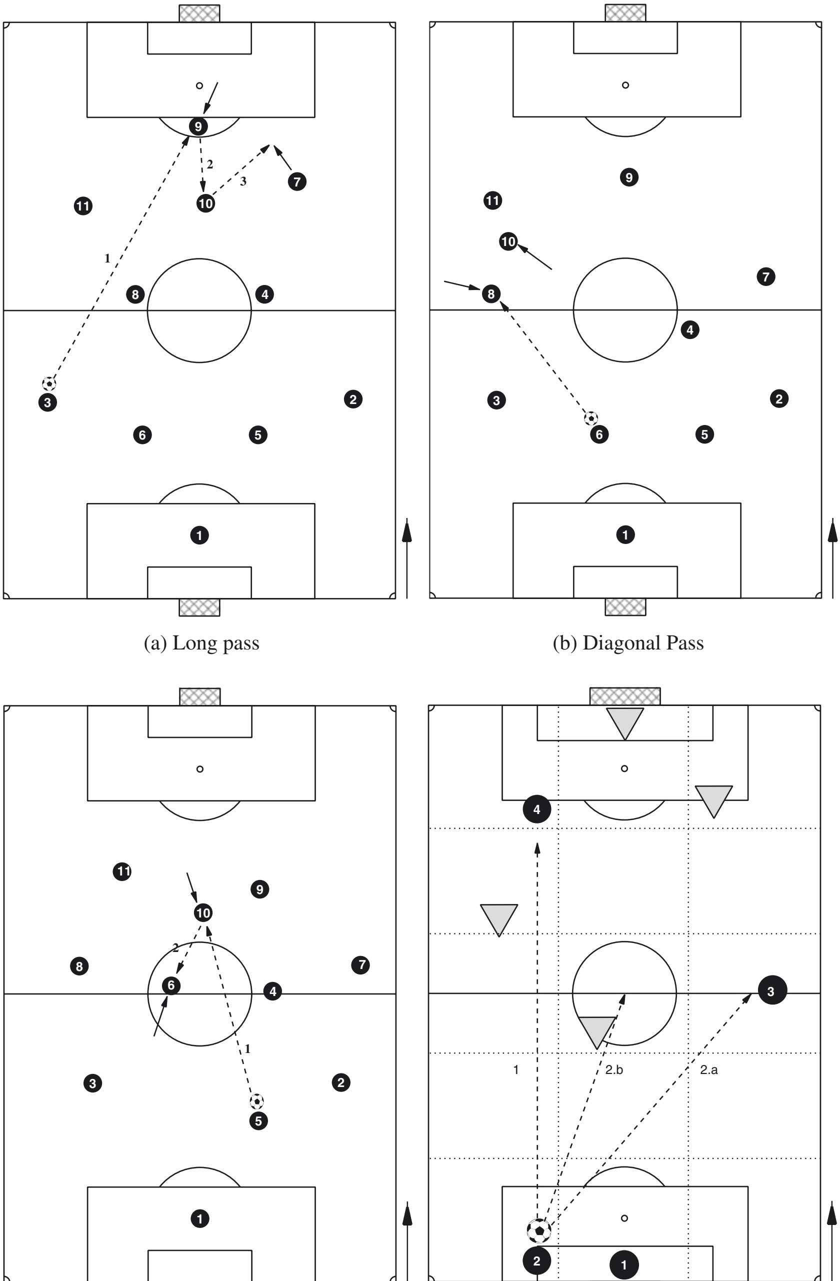
3.5 An example move on a robot

We now specify the soccer move build up play in Readylog and we show that our qualitative world model supports the specification. We adapted three possible ways to build up a play as discussed in [5] (see also Section 2.3).

The first way to build up play is with a long pass (Figure 7(a)). We immediately notice that the term long is one of the coarse, qualitative notions we need to establish in order to adapt human soccer theory for our autonomous soccer agents. We could also formulate this as passing the ball from a back position to a front position on the playing field. The second way to build up play is with a diagonal pass as depicted in Figure 7(b). This time, the term diagonal is of qualitative nature. Diagonal means passing to the side being opposite to the current one. Figure 7(c) shows the last possibility to build up play which is with a deep pass (dashed line labelled with 1) followed by a subsequent back pass (dashed line labelled with 2). The term deep is used to denote the space behind or in between a group of opponent players. The endpoint of such a pass has to be the most free position available in-between or behind the group of opponents.

We now try to adapt as much of these descriptions as possible by integrating their most essential parts into one pattern. All three possibilities have in common that the ball is located in the back part on the pitch. According to a role ontology it is a player currently having a defensive role which is about to initiate the pattern to build up play. We already characterized the possibility of a long pass as bringing the ball to the front part of the pitch. Therefore, in this case the agent chooses to pass to a team-mate located in the attacking zone. For the two other possibilities the destination of the pass is the midfield. The agent can either make a diagonal pass, that is the case if the target position is on the opposite side of the field, or it can simply pass to a free area on the same side or in the centre of the pitch. To illustrate our adaptation of the build up play patterns for the Middle-size league we depicted a diagram similar to the ones in [5] in Figure 7(d).

proc build_up_play_defender,
    if *haveBall*(*ownNumber*) **then**
        getFreeSide(*offense*,*FreeSide*);
        getPassPartner(*offense*,*FreeSide*,*PassPartner*);
        solve (
          if ¬*isKickable*(*ownNumber*) **then**
              interceptBall



(a) Long pass

(b) Diagonal Pass

(c) Back pass

(d) Adaptation for the MSL

Figure 7: Example for the *build-up play* move.

```
            else
                if isPassReachable(ownNumber, PassPartner) then
                    passTo(ownNumber, PassPartner)
                endif
            endif
            | pickBest (bestSide,{leftSide, middleSide, rightSide}
                dribbleTo(ownNumber, middleZone, bestSide)
                | kickTo(ownNumber, middleZone, bestSide))
                /* end of pickBest */
            | interceptBall; kickTo(ownNumber, middleZone, middleSide),
        3, func_Reward) /* end solve with horizon 3 */
    else
        interceptBall
    endif
endproc
```

Algorithm 3: The build-up play program for the defender.

Algorithm 3 shows a program in our action language Readylog capturing the above example. Note that this specification contains several qualitative elements such as middleZone, leftSide and offence as well as qualitative predicates such as isPassReachable. With our qualitative world model we are able to simply transfer the qualitative notions from the specification in [5]. Moreover, the use of qualitative terms and predicates makes the program applicable in many game situations.

In the first part of the procedure the agent assigns the most free side in the offensive zone to the variable *FreeSide*. It further picks a team-mate in the offense that may receive a pass. Then the agent starts deliberating with the solve statement. Using decision-theoretic planning it decides which of the options separated by the | to take. The first possibility is to check whether the ball is kickable. If it is not kickable the agent needs to intercept the ball. If the pass partner which was determined initially is reachable with a pass the agent is supposed to carry out the *pass* action. The second possibiblity is to use the *pickBest* statement to choose the best argument for the subsequent action. That is to say, the agent decides to call the action *pass_to* with the best value taken from the list of arguments specified with the *pickBest* statement. This list of positions corresponds to the set of possibilities to build up a play we depicted in Figure 7(d). It can choose here whether to dribble or to kick to the position chosen by *pickBest*. The last possibility available is to intercept the ball and directly kick it towards the centre of the field. Further details and case studies on formalizations can be found in [1, 19].

4 Discussion

In this chapter, we presented an approach towards a formal specification of soccer. For the behaviour specification of our soccer robots we started thinking if it could be helpful to review the soccer literature in order to learn more about how soccer is specified. What showed up was that, on the one hand, there exists work on soccer strategies and tactics and, on the other hand, that these strategies are not formalized in a way which is appropriate for soccer robots.

As soccer is a structured game, a top-level ontology can be extracted quite easily. Also does the soccer literature mention only few basic primitives like *pass* or *run*. With the appropriate preconditions for these actions one can define a basic action theory for the soccer domain. For our soccer robot application it is possible to define spatial relations like distance or reachability in a qualitative fashion. One has to remark that our approach works for soccer playing robots. Trying to adapt the results to human soccer play in order to gain more insights about human soccer strategies and tactics it becomes obvious that especially the spatial relations have to be adapted, too. One has to find appropriate models which reflect the mobility of human soccer players and which model the possibility to play headers and high cross passes.

4.1 Related works

The benefit of mathematics for detailed analysis and improvement of sports was described formally before, e.g. in [25]. These approaches concentrate in many cases on the optimization of single tactics, as e.g. on downwind sailing in [26]. Other approaches on formalizing sports exist. For example, in [27] tactical patterns for water polo are defined. Similar to our approach basic action primitives are identified and tactical formations are described formally. There is also work in the field of automatic commentating and analysing sports.

Automated commentator systems. Specifically related to the RoboCup domain there are three groups which developed systems for automatic real-time commentary. Their systems together won the scientific award at RoboCup 98 [28]. An overview on the three systems can be found in [29]. Of particular interest are the two systems Rocco and Mike since both try to model and identify certain aspects of soccer.

Rocco evolved from the Soccer system [30] which generates natural language descriptions of a soccer game. It works on information provided by the RoboCup soccer simulation server. Based on elementary events (like *kick* or *catch*) and geometric data provided by the Soccer Server , Rocco performs a high-level scene analysis by an incremental event-recognition. Declarative concepts of events represent a priori knowledge about typical occurrences in a scene. These concepts are organized in an abstract hierarchy, grounded on specialisation and temporal decomposition. There exists a simple recognition automaton for each concept.

Mike also uses the information provided by the Soccer Server as its input. Mike consists of six analysis modules running concurrently that post propositions of information gathered to a pool. One of the six analysis modules also makes use of Voronoi diagrams. Their application enables Mike to determine the defensive areas covered by a player as well as to assess the overall positioning. Players are considered to be free if they are positioned as close as possible to a Voronoi vertex of the diagram of the opposing team. Furthermore, triangular shapes in a Voronoi diagram indicate a tight formation since the average shape of a Voronoi area is hexagonal. These two observations seem to provide further qualitative insight from a tactical point of view.

Real-time analysis tools. In a recent work [31], Beetz *et al* overview the FIPM system, a real-time analysis tool for soccer games. Based on position data of the players and the ball they interpret common soccer concepts. In [31] they report on first results drawn from data from the RoboCup simulation league. They use first-order interval temporal logic to represent events or situations. Their model consists of five layers comprising a motion, situation, action and tactical layer. On the situation layer they identify concepts like *ScoringOpportunity*. With data mining techniques they assess the conditions for such situations. On the action layer they distinguish between several kind of models. The observation model for example classifies shots to belong to a dribbling or a pass, the predictive model use decision-tree learning to form rules for predicting the success rates of goal shots. They also provide, for example, information about the physical abilities of players based on the distances the player covers during a match and also tactical patterns of a team can be derived. These information are especially useful for soccer coaches.

Miene *et al* [32] report on successful experiments on detecting and predicting offside positions based on data also from the simulation league. They developed an algorithm for rule-based motion interpretation. The rules are given as background knowledge in first-order logic. The input data are first temporally segmented based on thresholds and monotonicity criteria. Then the segmented motion data are mapped into qualitative classes like *no motion*, or *slow*. They use logical representations to model game situations like a player being in an offside position. They are able to detect offside positions successfully and can also predict if a player risks to run into an offside trap. Important to note is that they do not regard static situations but analyse the motion data. This covers especially the dynamic aspects of soccer.

Formalizing teamwork and strategies. One approach for specifying teamwork among others is the *communicative multiagent team decision problem* (COM-MTDP) model [33]. Communication is explicit in this framework and uncertainty can be expressed by probabilities. A reward function allows analysing the optimality of behaviour, which could be done with model checking or theorem proving techniques for Golog or similar specifications in our context. However, the main focus of this paper is on the question *what* should be evaluated, and the answer is dependent on the chosen domain. Therefore, if we want to evaluate the behaviour of multiagent systems for the RoboCup scenario, we need primitives for describing the behaviour of robots in this domain as done here.

In a recent paper [34], the four-legged league champion team NUbots 2006 was tested against more aggressive and more defensive strategies. The results indicate that global team tactics should be considered in conjunction with a team's style of play. A set of metrics was developed which may enable a future robot soccer team to observe, reason and modify its global strategy to suit that of an opposing team.

McMillen and Veloso [35] present a framework for distributed, play-based role assignments. The proposed framework allows to specify several team play strategies on a very high level. In addition, some applicability conditions for each strategy must be given, e.g. second half of the game and the team is winning. Finally, roles (goalkeeper, defender etc.) must be listed. In [35] a successful case study with Aibo robots in the four-legged league is also reported. However, no clear formal semantics of the calculus is stated which we get for free in related approaches e.g. with state machines [36] or the situation calculus as presented in this paper.

4.2 Final remarks

Finally, it will be interesting to see if, in the future, a formal approach to tactics cannot only be useful for computer scientists trying to specify a system but also, this work as a starting point, for sport scientists to build formal models of their respective sports discipline. Future work in this direction for soccer has to concentrate on appropriate models for the mobility of human players to find a unified theoretical model for soccer. We believe that such formal approaches in general will help sport scientists to better understand and to analyse their sport disciplines.

The biggest lesson we learnt is that we *are* able to formalize soccer theory on an abstract level. This might not be surprising, however, some of the concepts real soccer experts use are quite fuzzy and therefore difficult to define and implement. One of the challenges of Computer Science in Sport is to get researchers from sport and computer science together to find a common language. This will help both sides to bring research further.

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3. Biomechanics

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Biomechanical modelling in sports – selected applications

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Abstract

In the past decade computer models have become very popular in the field of sports biomechanics due to the exponential advancements in computer technology. Biomechanical computer models can roughly be grouped into multi-body models and numerical models. The theoretical aspects of both modelling strategies will be shortly introduced. This chapter focuses on the presentation of instructive application examples each representing a specialized branch within the field of modelling in sports. Special attention is paid to the set-up of individual models of human body parts. In order to reach this goal a chain of tools including medical imaging, image acquisition and processing, mesh generation, material modelling and finite element simulation becomes necessary. The basic concepts of these tools are thoroughly described and first results presented. The chapter ends with a short outlook into the future of sports biomechanics.

Keywords: biomechanical models, mesh generation, finite elements, sports

1 Introduction

1.1 Why models?

The field of sports biomechanics suffers from one very severe restriction; in general it is not possible for ethical reasons to measure forces and pressure inside the human body. Thus, typical measurement technology in biomechanics works on the interface between the body and the environment. Force platforms for instance dynamically quantify reaction forces when a person is walking or running across the sensor, electromyography (EMG) monitors action potentials of contracting muscles with electrodes detached to the human skin. The information provided by the measurement technology is very important to investigate movements in sports, but is not sufficient to answer questions such as

1. How can we maximize the output (e.g. height of a jump) while minimizing the loads on the joints (e.g. during the landing phase)? Or: How can we better understand mechanisms of sports injury? These questions are related to the human body.
2. How do we have to design the sports equipment to optimally suit to the athlete's requirements in terms of mechanical behaviour? These questions are related to the technical equipment. This optimization process has three aspects:
   - Ineffective and destructive loading on the athlete's body has to be minimized (e.g. by increased damping through improved cushions in the sole of the sports shoe).
   - The athlete's protection has to be maximized (e.g. by the design of a helmet for cyclists to avoid head injury caused by a crash, see section 3.2.1).
   - The output has to be maximized (e.g. by a concept for an optimized cricket bat, see section 3.2.2).

The only possible way to answer the questions related to the human body is to set up mechanical models of the human body or at least of human body parts. The set-up of a sports-biomechanical model is the only possibility to gain insight into the mechanical behaviour of the inner human body. Thus, modelling has become extremely popular because it, to some extent, heals the fundamental dilemma of biomechanics that has been described at the beginning of the chapter. Therefore, a software tool chain for the automatic generation of anatomical structures is presented in Section 3.3.

As we will see in Section 3.2 the set-up of models representing sports equipment is also an important task in sports biomechanics. Here, computer analyses are applied to better understand the mechanics of sports equipment during exercise.

However, in the field of sports biomechanics, measurement technology still plays an important role (see Figure 1): the information provided by the measurements is either input for a model (e.g. reaction forces acting on the foot) or used to validate the model (e.g. comparing the simulation results with EMG data). Thus, it is almost trivial to mention that models are of no scientific use without validation.

1.2 A classification of models

When looking at the progress being made in the field of biomechanical modelling related to problems stemming from sports one can see two major directions of development:

1. Multi-body systems (MBS) have been set up yielding important results in gait analysis, jumping, throwing and gymnastics [1, 2, 3].

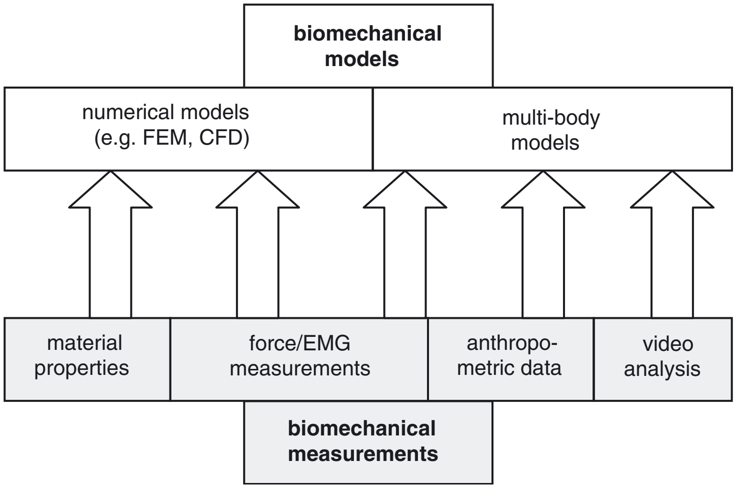

Figure 1: The relation between models and data.

2. Numerical models using finite elements (FEM) or computational fluid dynamics (CFD) have been successfully applied to a variety of sports-biomechanical problems such as improving injury prevention [4], ameliorating the design of pieces of sports equipment [5] and better understanding and optimizing sports techniques [6].

Both types of models have their advantages and disadvantages: numerical models enable the computation of the whole body's deformation, whereas multi-body models only provide forces at a limited number of body points. But, the price to pay for taking into account the body's deformation is a much higher demand in terms of computer power for the finite element method. This fact partially explains why frequently parallel computers enter the stage in order to arrive at accurate FE results. Meanwhile, software packages are available that enable the user to use both methods MBS and FEM simultaneously.

The remainder of this text is organized as follows: the next chapter deals with the basic concept of multi-body models to then discuss one MBS model in detail. Chapter 3 gives a short introduction to the finite element method, shows some example applications and finally describes a software tool chain to set up FE models of human body parts starting from medical image data. Finally a short outlook into the future of sports-related modelling is given.

2 MBS in sports biomechanics

Within the last two decades multi-body models have frequently been applied to solve biomechanical problems in sports. Some selected MB applications are for instance simulations for impact analysis [1], investigations of the trampoline jumping [2], studies about walking and running [3] or the discussion of forces encountered in bicycle sports [7]. MBS can be used in two different ways: as forward or as inverse models.

2.1 Forward multi-body models

Many example applications found in literature make use of the so-called forward models. Here, the physical forces and moments (e.g. gravitation and external forces, see Figure 3) are the given quantities. Together with geometric data (e.g. length of body segment) and mechanical parameters (e.g. moments of inertia J, centre of mass) the resulting body movement can be computed. The movement is fully described by the laws of Newtonian dynamics that is mathematically described by the following equations.

$$\mathbf{F} = m\mathbf{a} \tag{1}$$

$$\mathbf{M} = J\boldsymbol{\alpha} \tag{2}$$

In general, F, a, M and α are three-dimensional vectors denoting force, linear acceleration, moments and angular acceleration, respectively. The mass m is a scalar and the moment of inertia J is in general a tensor represented by a 3×3 matrix. To be able to solve the underlying differential equations a kinematical chain of simple geometric entities (e.g. an ellipsoid representing the thigh) has to be set up (see Figure 2). In order to arrive at the quantities of interest (e.g. the load in the hip joint while landing) segment after segment has to be processed. The segments are linked by hinges whose degrees of freedom are defined according to those of the anatomical articulations. The rigid body motion (i.e. translation and rotation) of the current segment (e.g. the foot) can be calculated when the external forces (e.g. measured by a force platform) and the body weight of the

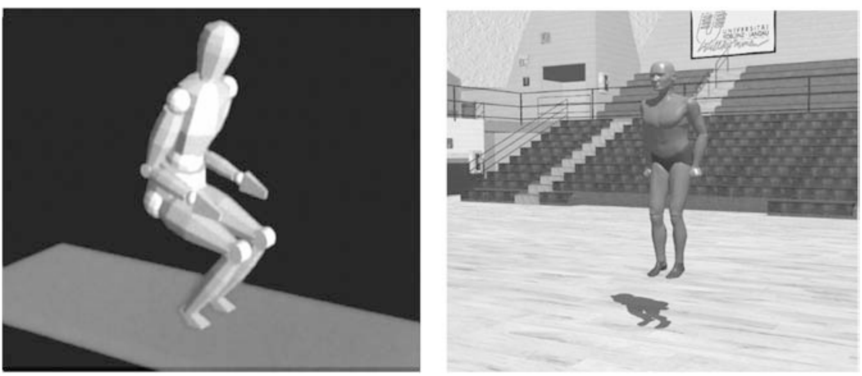

Figure 2: Multi-body models in different visualizations.

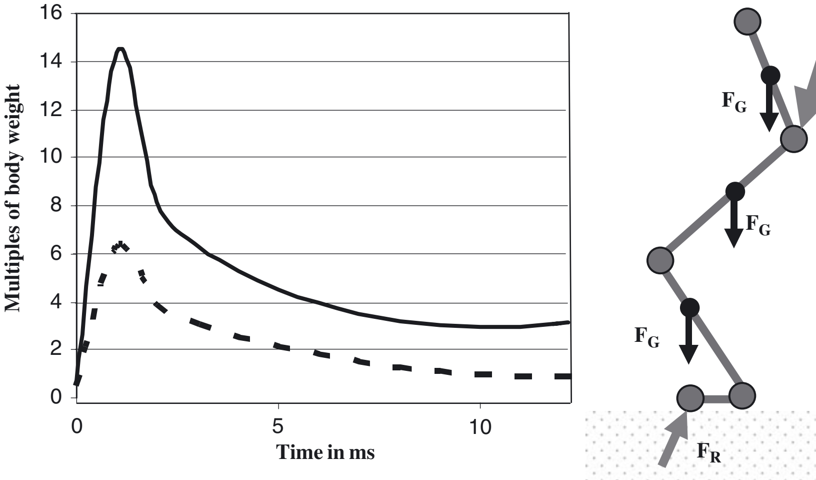

Figure 3: Link segment model of the human leg and calculated forces in the hip joint for different kinds of landing (dotted line = soft landing; straight line = hard landing).

segment are given. The mechanical influence of the next segment in the chain (e.g. the shank) on the current segment is represented by a reaction force. These reaction forces are most interesting as they give a measure of the load present in the joint during sports exercise. The reaction force determined for one segment is then input (only switching the sign) for the calculation of the rigid body motion of the next segment. After having processed all body segments the complete dynamics for the motion of interest is computable if a time integration scheme is applied. Figure 3 shows the results of such a computation for different kinds of landing after a jump. The reaction forces in the hip joint are depicted for a soft landing (with the use of the body damping system) and a very hard landing (with the body kept stiff). The analysis shows that the peak force in the hip joint is more than doubled for the hard landing. The forward model has to be validated against experimental data. Here, the measurement of the landing phase for the different types of landing are monitored and subsequently compared with the body reaction forces calculated with the multi-body model. The simulation results are in good accordance with the experimental data. Another example application of MB models in the field of sports is briefly presented in Figure 4. A back flip jump is shown that has been investigated with three different analysis tools. The last row shows the results of a forward solution using a multi-body model of the human body. The computed motion almost perfectly matches the real body movement that is captured by a high-speed camera depicted in the second row. The first row shows the typical result of a motion analysis that will be further described in section 2.2.

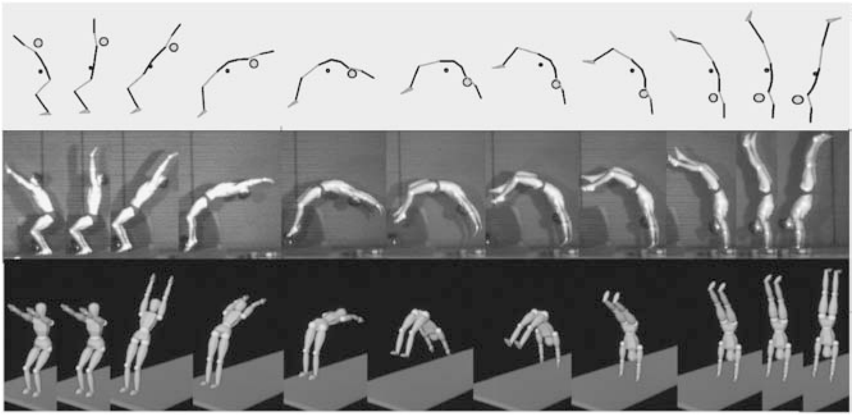

Figure 4: The backflip by motion analysis (first row), high-speed video (second row) and multi-body models (last row).

2.2 Inverse multi-body models

For the set-up of an *inverse* multi-body model the law of cause and effect is reversed. Here, the effect (i.e. the body movement monitored by coordinates, velocities, accelerations of selected anatomical landmarks) is the basis for the calculation of the cause (i.e. the forces and moments that enable the movement). Thus, the basis of this type of model is the kinematics of the body given by the three vectors

$$\mathbf{r}(t),\ \mathbf{v}(t),\ \mathbf{a}(t), \tag{3}$$

where $\mathbf{r}$ is the vector of coordinates, $\mathbf{v}$ denotes its velocities and $\mathbf{a}$ the accelerations. In this section the investigation of the joint forces and moments during bicycle performance is presented as an example application of an inverse model. Until recently, there has been little research in bicycling dealing with joint reaction forces and moments, although these parameters are of great interest for professional and non-professional athletes, coaches, therapists and medics.

One reason for this lack of research is the difficulty of having a rotating system during cycling performance. While a fixed force plate is used in gait analysis a force measuring device which is rotating within the pedal in cycling analysis is needed for the set-up of an inverse model in order to calculate joint reaction forces and moments. Thus, the complete analysis consists of a pedal force measurement together with a synchronic (high speed) video shoot. Figure 5 (left) shows *one* image of a high-speed video sequence during the bicycle exercise. After the anatomical landmarks have been defined by reflective markers the whole image sequence is processed to yield the marker positions in time. Figure 5 (right) depicts the trajectories of the five markers together with the simplified representation of

Figure 5: A single frame of a high-speed video and marker trajectories.

the human leg at two different points in time. This result enables the calculation of the marker velocities and accelerations if the camera frequency is known. However, one should be aware of the fact that the twofold derivation of the marker coordinate functions leads to a significant amplification of the noise inherent in the data. Therefore, the marker coordinate functions have to be filtered beforehand. The marker accelerations are used as input for an inverse multi-body model [7]. As already mentioned in the preceding chapter anthropometric data are required. The link segment model is the simplification of the complex anatomy of the human body in which the joints are replaced by hinge joints and body segments.

The inverse dynamics is calculated for male and female subjects using different pedalling conditions such as pedalling rate, power and seating position. In order to measure the external pedal force a measurement device called the Powertec-System® was used [8]. The instrument is based on two sensor systems that determine the magnetic field variations as a result of the displacement of a small sensor with respect to a magnet. The aim was to see how the joint reaction forces and moments vary during different tests. Joint reaction forces and moments for the ankle for several cycles are shown in Figure 6.

3 Finite element models in sports biomechanics

The finite element method (FEM) is a very popular tool in the field of (fluid)-mechanical and electrical engineering to solve partial differential equations (PDEs) on a computer. The success of FEM is mainly explained by the rapidly increasing availability of computer resources. Currently, very accurate calculations can be

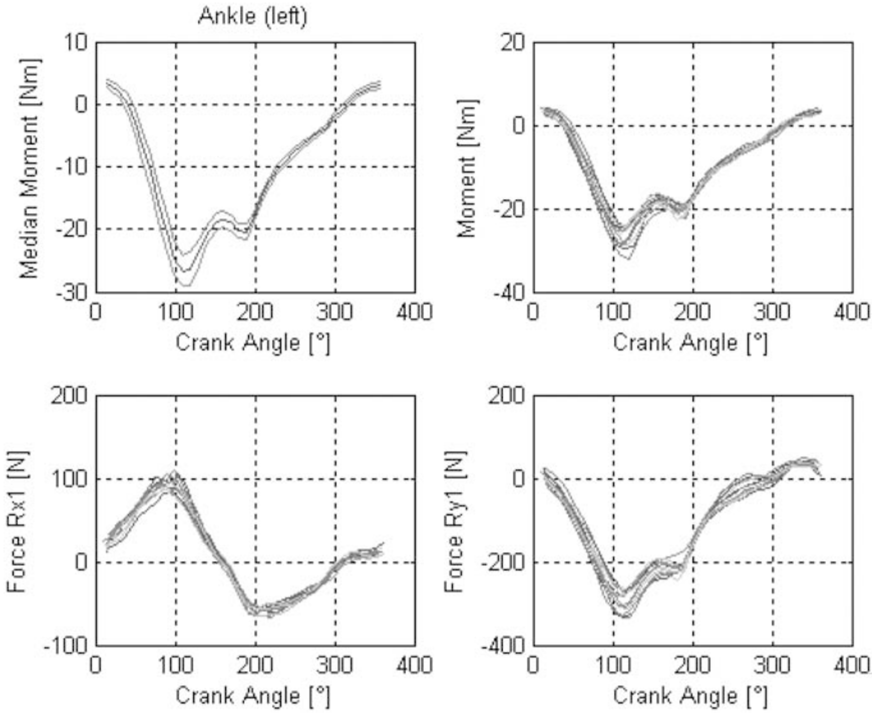

Figure 6: Reactive joint forces and joint moments for the ankle during bicycle performance.

carried out on personal computers within minutes. However, very complex simulations are still candidates for the use of high-performance computing. In particular, applications stemming from the field of biomechanics profit from the use of parallel computers [9]. The complex geometry of anatomical structures requires a high spatial resolution of the model leading to possibly huge demand of computer power. In Section 3.3 an automatic tool chain to generate individual models of human body parts is presented that takes advantage from the application of parallel computers. Before describing the tool chain in detail we will have a look at the basic ideas of FEM (see Section 3.1) and then look at the two applications related to the field of biomechanics in sports (see Section 3.2). The first application deals with the optimization of helmet design to improve injury prevention. The second application gives an impressive example how FEM can be employed to optimize a piece of sports equipment and to better understand the mechanics of a certain kind of sport.

3.1 The basic concept of the finite element method

The basic idea of FEM is quite simple: Let us assume that a physical problem that can be described by a PDE is defined on a complex geometry. Due to the complex geometry an analytical (i.e. a mathematically correct) solution is impossible. Correct mathematical solution can only be determined if the system under consideration has a simple geometry (e.g. a sphere or an ellipsoid). At this point FEM enters the stage: The idea is to approximate the complex geometry by a multitude of simple geometric entities (e.g. tetrahedral or hexahedral elements). Each element is then individually processed. Within an element adequate functions (so-called basis functions) are chosen that are used to interpolate the desired function. The general procedure of FEM is summarized in six steps:

a. **Generation of a discrete representation of the object of interest**
   The mesh generation step (see Figure 7 showing a bicycle helmet mesh) is crucial for the rest of the analysis as the spatial resolution and the element quality to a large extent affect the robustness and the accuracy of the simulation result. In order to achieve high accuracy in a physically interesting region (e.g. the area of large deformation in an impact scenario) a mesh refinement in such regions of special interest is indicated. Mesh refinement means to increase the number of elements and likewise the number of mesh nodes (in the simplest case nodes can be regarded as the corner points of an element). Thus, FE meshes can have millions of mesh nodes. For instance, the result of 3D mechanical FE study is the displacement function of the nodes (i.e. the body's deformation) in three directions of space.
b. **Defining the physical behaviour**
   In order to set up a realistic model the physical behaviour of the object has to be integrated. At this stage two important decisions have to be made. An appropriate material model has to be chosen and the boundary conditions have to be selected. The simulation results are very sensitive to these settings. Human soft tissue can be modelled in the simplest case by assuming linear elastic behaviour. Here, two mechanical parameters (Young's modulus and Poisson's ratio) suffice. However, the reliability of this choice is doubted as we will see in section 3.3.4.
c. **Set-up of the stiffness matrix**
   For each finite element a stiffness matrix has to be set up. A prerequisite for this step is the choice of adequate interpolation or basis functions within an element. Depending on the number of nodes of the element (e.g. a tetrahedral element can be defined to have four nodes on each of its corners or ten if nodes on the connecting lines are added) the interpolation functions are chosen to be linear or quadratic. Increasing the polynomial order improves the accuracy of the simulation results. But the price to pay is higher demand in terms of computer resources. The element stiffness matrices are then summed up (taking into account the element connectivity) to form the global stiffness matrix **K** that represents the complete system. If a transient or dynamic FE analysis is desired a mass matrix **M** and a damping matrix **D** have to be assembled to describe the inertial and the damping behaviour of the system, respectively.
d. **Numerical solution of the problem**
   After the system matrices **M**, **D** and **K** have been assembled, a numerical equation solver is started to calculate the vector of nodal displacements **U** of the body when an external force defined by a force **F** is applied. The simplest FE

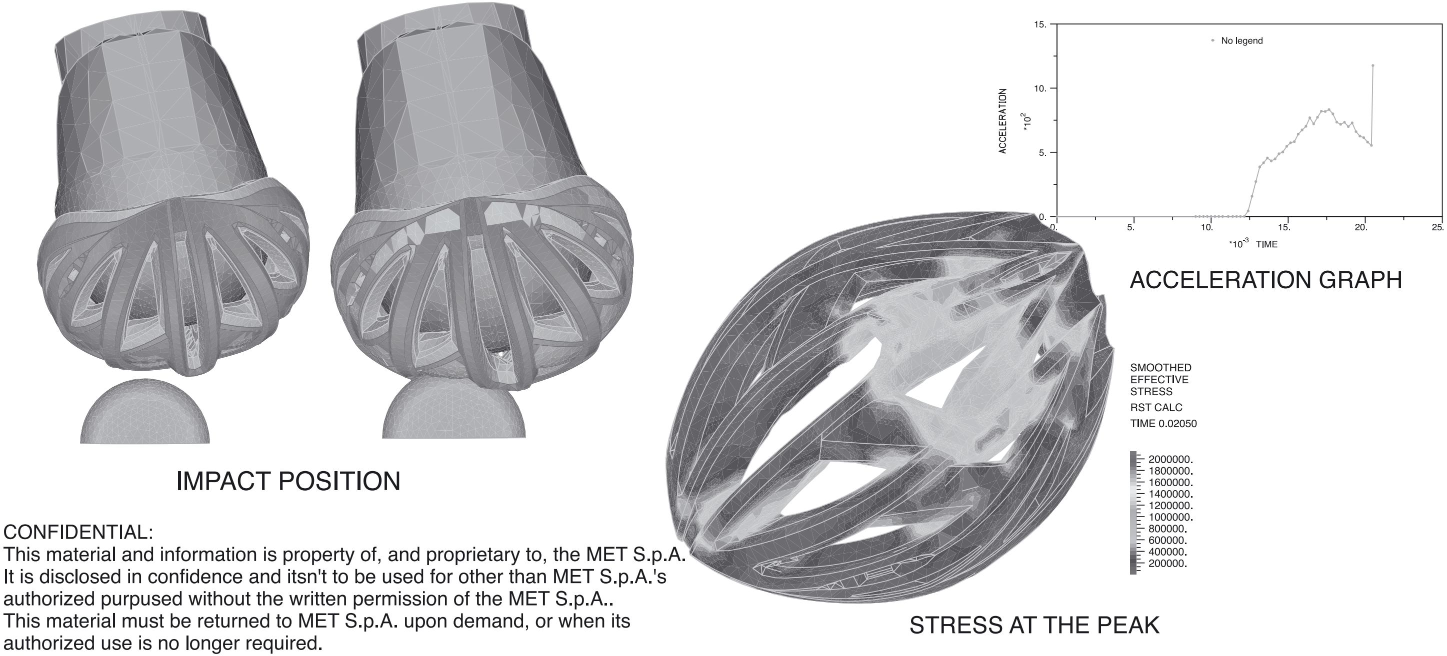

Figure 7: Helmet Impact Analysis Geometry model created with Unigraphics. (Courtesy of MET)

analysis is the computation of the new static equilibrium for a body under load. The equation system to solve is then given by

$$\mathbf{KU} = \mathbf{F}. \tag{4}$$

Sometimes it is of great interest for the developer what the eigenfrequencies ω of a piece of sports equipment are and how the corresponding eigenmodes **U** look like (see Section 3.2.2). Then the eigenvalue equation system looks like

$$\mathbf{KU} = \omega^2 \mathbf{MU}. \tag{5}$$

In general, only a few of the eigenmodes **U** are of interest. To solve the above equation system sophisticated software is needed.

For a dynamical analysis the velocities and accelerations of the mesh nodes are calculated as well. The integration scheme is then solving the following system of linear equations:

$$\mathbf{M\ddot{U}}(t) + \mathbf{D\dot{U}}(t) + \mathbf{KU}(t) = 0 \tag{6}$$

3.2 FEM applications to improve sports equipment

In this section selected applications of the FEM in the field of sports biomechanics are presented. The first example (Section 3.2.1) is chosen to show how injury prevention profits from biomechanical modelling. The second application (Section 3.2.2) is a perfect example for the optimization of sports equipment.

3.2.1 The bicycle helmet

Engineers at MET s.p.a. Italy have used the ADINA® FEM software successfully to analyse their new helmet design (Figure 7). Their simulation model as shown in Figure 7 consists of the head with the helmet impacting on the anvil at a velocity of 4.57 m/s. The objective is to ensure that the helmet provides adequate protection for the head; in particular, the deceleration on the head must not exceed 250 g. In the past, engineers at MET had to rely on results obtained from actual impact tests performed on prototype models in the laboratory to evaluate the performance of a new helmet design. Now, with the use of ADINA, the engineers are able to gain better insight into how the helmet performs, e.g. clearance distance between the head and the anvil can be obtained easily from the simulation results. Comparison of the simulation and laboratory test results shows a very good agreement.

3.2.2 The cricket bat

3.2.2.1 Introduction Over almost the entire history of the cricket game, the design and manufacture of cricket bats has changed very little. With one or two exceptions, the cricket bats used by today's professionals appear very similar to those used by the players of yesteryear. However, in an increasingly competitive marketplace, scientists and manufacturers are now looking towards more radical designs and even alternative materials. If these new ideas are to translate into more successful bat designs, then they must be based around a sound understanding of the mechanics of the bat–ball impact. The following FE analysis has been carried out by J. Penrose using the commercial FE software package ANSYS® [10, 11].

It is envisaged that computational techniques can be used to provide a greater understanding of this impact. In addition, provided that they can be proved realistic and accurate, computational simulations could be used to evaluate new designs and make the prototyping process more efficient.

$$T_c = 2.87\left(\frac{m^2}{RE^{*2}V_z}\right)^{1/5} \tag{7}$$

$$\delta_z = \left(\frac{15mV_z^2}{16R^{1/2}E^*}\right)^{2/5} \tag{8}$$

Classical theory of impact stems from initial analytical work by Hertz. Equations (7) and (8) relate the duration of the contact T_c and the maximum compression of the two bodies δ_z* to R (effectively the radius of the ball), m (effectively the mass of the ball) and E^* (effectively the stiffness of the ball). These equations estimate $T_c = 0.8$ ms, and $\delta_z = 7$ mm (diameter of contact area ≈ 3 cm) for a 55 mph impact. Whilst these equations can offer a reasonable starting point for investigation, they make many assumptions that are unrealistic (such as a quasi-static impact) and they do not predict the influence of the flexibility of the bat. It is proposed that the impact of a ball on a bat can be described by the superposition of local Hertzian contact and the general vibrational properties of the bat.

3.2.2.2 Modal analysis A detailed 3D finite element modal analysis of a cricket bat was initially conducted in order to elicit the vibrational characteristics, and their fundamental frequencies. In other words, eqn (5) was solved using ANSYS. These vibrational characteristics are largely affected by the geometry of the bat, and also by the quality of the wood.

The shapes of the first three flexure modes of vibration were calculated (shown exaggerated in Figure 8), together with their respective fundamental frequencies. These were found to be approximately 80, 360 and 670 Hz, respectively. It is postulated that during an ideal impact, it would be a combination of these modes (and perhaps some higher order ones) that would be excited, to greater or lesser degrees.

3.2.2.3 Dynamical analysis A finite element analysis of the bat–ball impact was conducted using ANSYS/Ls-Dyna to solve eqn (6) in order to examine the variation of post-impact velocity with impact position on the bat face. Realistic material properties, including an orthotropic wood model, were used in these analyses, together with a ball speed of approximately 60 mph.

Figure 8: Computer model of the bat and its three lowest eigenmodes.

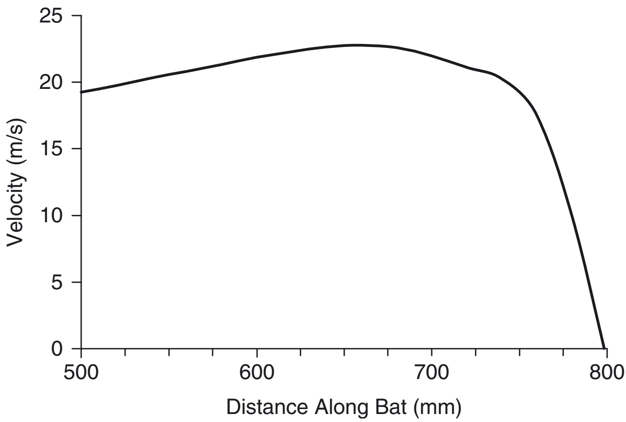

Figure 9: Relation between location of impact and velocity of the ball.

3.2.2.4 Variation of post-impact velocity The analyses showed that the post-impact velocity was indeed greatest in the region traditionally called the 'middle' (Figure 9). The actual impact can be visualized, and the stress contours on a midline slice through the bat can be calculated (Figure 10). It was interesting to note that the position of the distal node of the first flexure mode (about 610 mm along the bat) was similar to the point of impact with greatest post-impact velocity. The duration of impact was found to be about 0.8 ms.

3.2.2.5 Validation In order to validate the computational analyses, a practical experiment was undertaken whereby balls were fired from a bowling machine

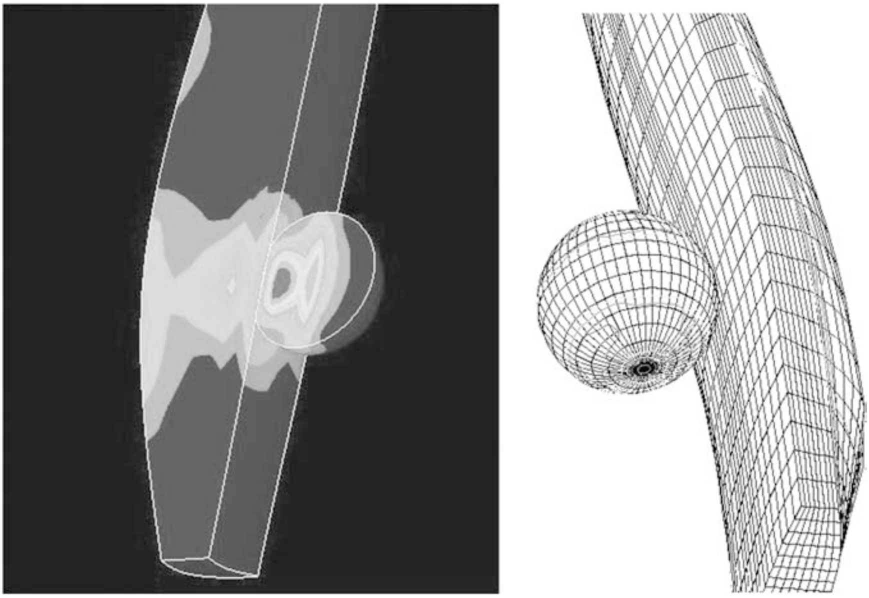

Figure 10: Stress plot and mesh plot of the ball impacting the bat.

(with a speed of up to 55 mph) at a cricket bat held by one of the investigators. The bat was fitted with a piezo-electric sheet on the face which, when struck by the ball, produced a voltage signal which was directed to a digital recording oscilloscope.

The output signals were then analysed. Comparison of the frequency spectra for the three impacts shows that specific modes of vibration can be recognized, and their frequencies agree well with the simulations.

3.2.2.6 Conclusion These studies are working towards providing a better understanding of the underlying mechanics of the bat–ball impact. It has been shown that the flexural properties of the bat can greatly influence its performance, in terms of the post-impact ball velocity, and that these flexural properties can be examined by using both numerical and practical methods. We suggest that any future innovations in materials and design should be motivated by the desire to control and optimize the flexural properties of the bat.

3.3 The set-up of individual models of human body parts

3.3.1 Motivation

It is a trivial observation that human beings anatomically differ from each other. However, it is less obvious that this anatomical diversity has real consequences on the mechanical response of a human being due to loading. Certainly, a thin skull is more likely to crack due to a defined impact than a thick skull. Or, reformulated as a number of questions: Why does a loading event cause a severe injury in one case but just a small haematoma in the other case? What are the undesired biomechanical side effects of anatomical pathologies (e.g. a missing toe)? Why is the crucial ligament of that football star so unstable? How can such special aspects be taken into account for a simulation? The answer is simple but the solution is complex; individualized models are urgently needed! In the following sections the basics of computed tomography are recapitulated and a software tool chain is presented that enables the set-up of individual FE models of human body parts for sports applications. The chain consists of three links:

1. An image-processing tool for soft tissue segmentation
2. A mesh-generation tool to produce FE representations of the object
3. A possibly parallel FE code with suitable material models available.

3.3.2 Basics of computed tomography and visualization

This brief overview on CT data acquisition and data visualization summarizes the data-processing steps and the operation principle of the equipment. The imaging and visualization principles will be illustrated with the example of a vertebra element. A comprehensive introduction to the physics and mathematics of computed tomography can be found in [12]. The fundamental problem of computed tomography is easily described: Reconstruct an object from the shadows – or, more precise, projections – of this object. X-ray photons penetrate the object to be examined, e.g. the abdominal region, with a fan beam. In the so-called third-generation scanner principle, the fan-shaped X-ray beam fully covers a slice section of the object. Depending on the path of rays, the X-rays are attenuated at different extents when running through the object, and local absorption is measured with a detector array. Of course, the shadow cast in only one direction is not an adequate basis for the computation of the spatial structure of the three-dimensional object. In order to determine this structure, it is necessary to transmit rays through the object from more than one direction. Figure 11 illustrates this principle. The projection integral, i.e. the sum of absorption coefficients along the X-ray path through the object, is measured by a solid-state X-ray detector for each angle. Therefore, the absorption data – plotted against all angles (right) – take a sinusoidal course. This plot that collects the raw data of the measurement is called sinogram. Based on the complete set of acquired data, the spatial distribution of X-ray attenuation coefficients in the sectional plane of the object is estimated and displayed. The difference between computed tomography and conventional radiography is the production of non-overlapping images with high contrast.

From a mathematical point of view image reconstruction by computed tomography is the task of computing the spatial structure of an object that casts shadows by using these shadows. The solution of the problem is complex and involves physics, mathematics and computer science. Image reconstruction is a so-called inverse problem. Figure 12 shows the results of the projection X-ray technique and computer tomography for a vertebra element.

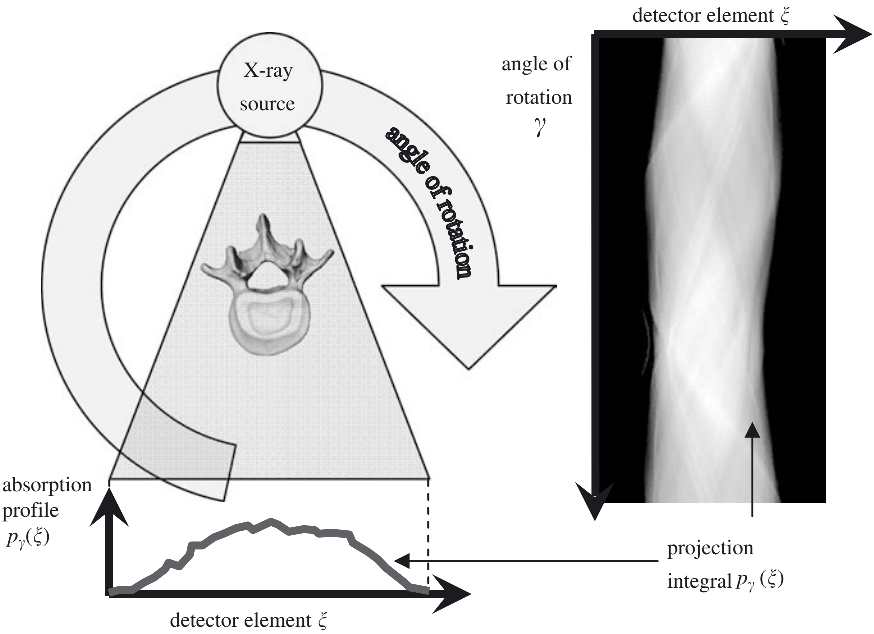

Figure 11: The X-ray source rotates around the object. The different attenuation or absorption profiles are plotted vs. all angles.

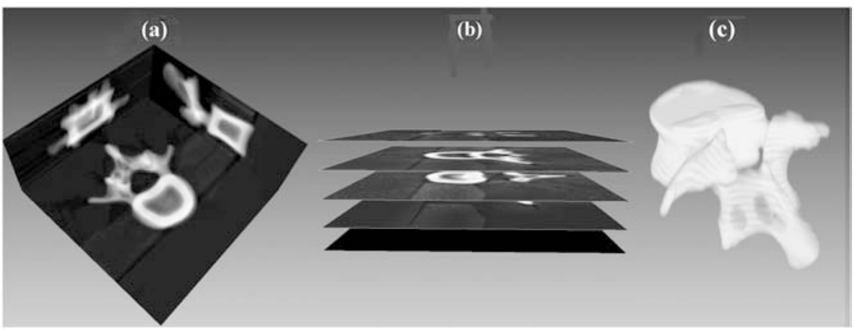

Figure 12: Different visual representations of a CT scan of a vertebra.

Figure 12a shows the simple projections from the three main directions; for better orientation they have been projected onto the inner sides of a cube. Figure 12b shows a sequence of five layers through the vertebra.

In practice we reconstruct not only 5, but 50–100 layers which – stacked at intervals of sub-millimetres above each other – result in a data stack. Figure 12c shows a volume rendering of a vertebra based on a stack of CT slices. This method assigns a physical light reflection and scattering value to each 3D pixel, the so-called voxel. The computer is then used to illuminate this ‘data fog’ with a virtual light source and to compute the optical impression.

An alternative to volume rendering is surface rendering as illustrated in Figures 13 and 14. The individual shades of grey of the layers in the data stack represent the degree of physical attenuation of the X-ray beam. In a clinical

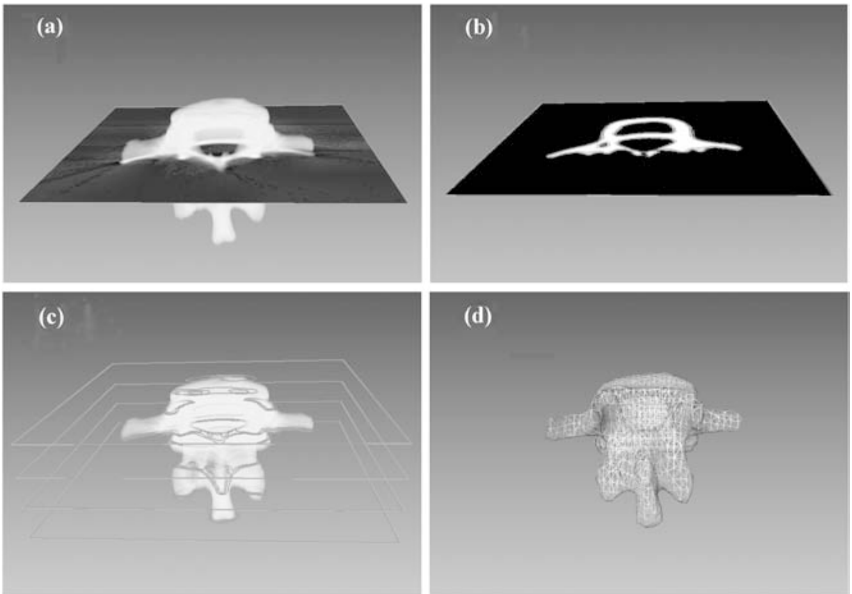

Figure 13: Surface rendering of CT scan data.

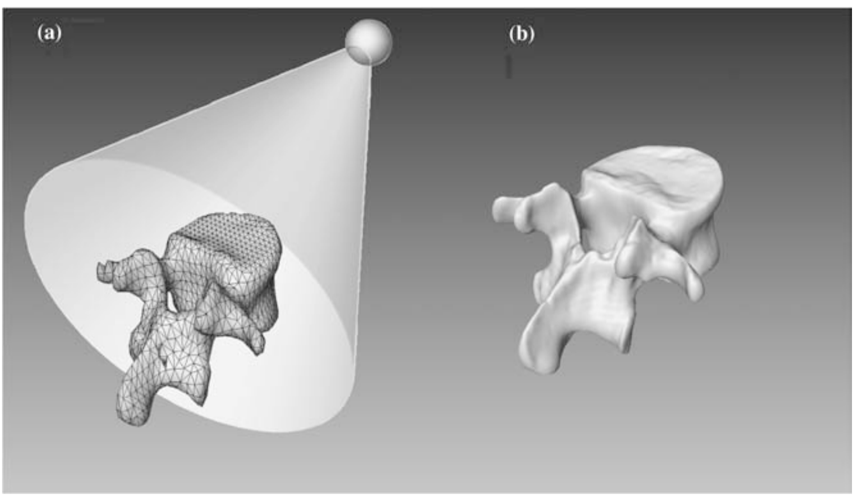

Figure 14: Surface rendering of the vertebra element.

context deviations from the normal distribution of these values may give clues to pathological changes in the patient. Figure 13a shows a layer from the stack. For better orientation a representation of the vertebra created by using the volume rendering technique is also shown.

During visualization we can decide to visualize certain ranges of grey values, and to selectively suppress others. In each of the two-dimensional sections of the CT image sequence the grey values must be analysed. If the viewer chooses a constant grey value, i.e. a threshold, all spatial points with this value are displayed in space as a so-called iso-surface. In Figure 13b a single iso-line is drawn within the chosen layer. Having defined a grey value threshold all points belonging to the surface are calculated throughout the entire CT image stack. The stacking of CT data is called secondary reconstruction and connects the sections to a three-dimensional data set. Figure 13c shows that the stack of iso-line images forms the basis for the visualization, because these lines are used in the triangle-based graphical model of the grey value iso-surface. Figure 13d shows the surface mesh result of the so-called triangulation. Triangles are calculated between the surface points within and in between the CT sections that connect the CT sections mathematically by a regular mesh. This step is carried out by a Delaunay triangulation.

Then the mosaic of triangles is again lighted and displayed by the virtual method described above. Figure 14a schematically depicts this process. The greater the number of mosaic pieces for the reconstruction of the surface, the more realistic the result. Apart from its ability to produce an image of a vertebra that can be interactively modified by the computer – e.g. the vertebra can be rotated, and virtual tours into the vertebra are possible, so that the three-dimensional impression is enhanced – the central merit of computed tomography lies in the fact that we obtain precise three-dimensional representations of the vertebra on the basis of which we can carry out further analyses as we will see in the following sections.

3.3.3 Geometric and computational model generation

In order to carry out a computational analysis to answer a specific biomechanical question, a geometric model of the relevant parts of the anatomy has to be set up (see Figure 15 (right)). In the case of finite element simulations, the model consists of a mesh representing the underlying anatomical structures. The nature of the mesh depends on the computational task. It may combine 1D, 2D and 3D parts (see Figure 15 (left)) and may consist of different geometric primitives, such as tetrahedral, pyramids and hexahedra (deformed cubes). In a typical biomechanical application, the 3D part is usually dominating. Typically, the regions of interest or of particular complexity are represented with increasing spatial resolution, while other regions may be represented more coarsely (see Figure 16).

A geometric model of a real anatomical structure may be *generic* or *individualized*. While a generic model can be used to obtain *qualitative* results and may thus make certain simplifications, an individualized model is used for *quantitative*

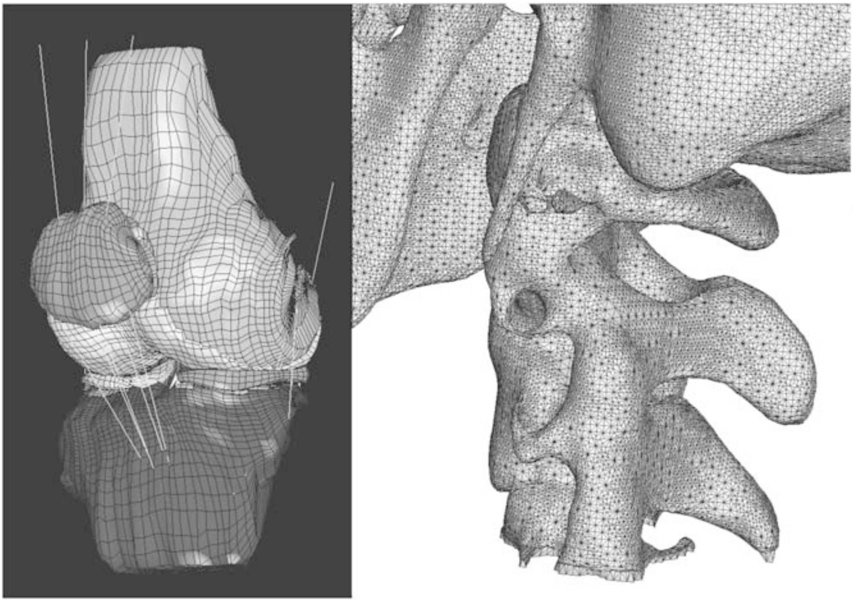

Figure 15: A model combining 1D, 2D and 3D parts (Image: c/o USFD) and a 3D mesh of a human skull (zoom).

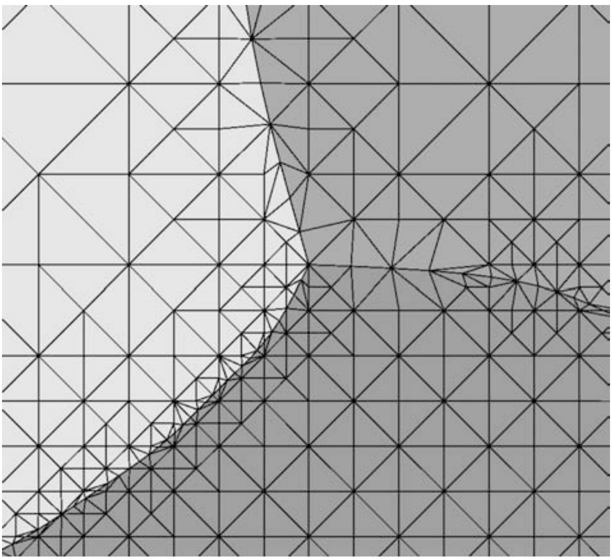

Figure 16: A mesh of a synthetic geometry with material-dependent resolution. Higher resolution is used near the interfaces, and inside the red material in the right lower part.

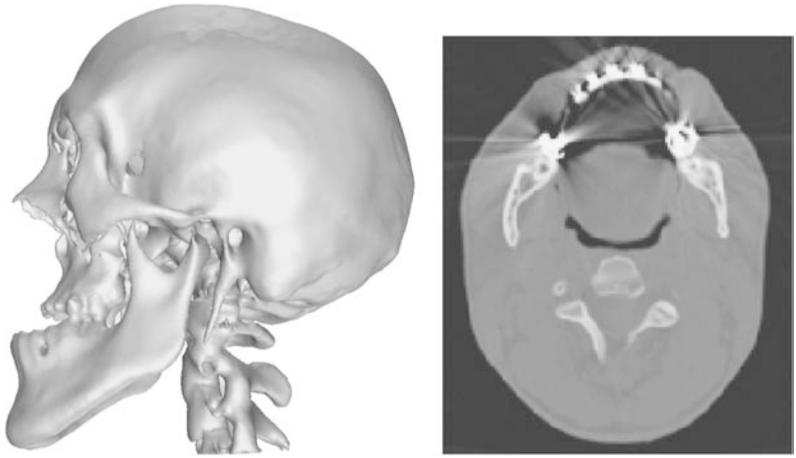

Figure 17: Left image: An isosurface of a CT image of a human skull shows a topological problem – upper and lower teeth are not separated. Right image: Metal artefacts in a CT image may severely distort the geometric information.

predictions of biomechanical quantities and must thus accurately represent the real anatomy. Today, such individualized anatomical data is given by a variety of medical imaging procedures providing a non-invasive way of measuring anatomical data.

In spite of all the progress in medical imaging in the past decades, a fundamental problem remains. In general, an image does not contain an unambiguous and accurate description of the anatomy: Thin structures may be lost, close structures may be fused erroneously (e.g. close bones in a joint) (Figure 17 left) or artefacts may distort the geometric information (Figure 17 right). This is in stark contrast to the situation in the classical field of application of computational simulation, like engineering, where the geometry generally is described in an unambiguous way by CAD data. The generation of valid individualized biomechanical models therefore often requires the input of additional data and disambiguation by a user sufficiently educated in anatomy. For instance, contact points of ligaments and bones can in general not be deduced from imaging data alone. A first step in the generation of a geometric model is the *segmentation* of the medical image, that is, a classification of regions into physiological materials, such as bone, cartilage, muscle, fat or skin.

The result may be a labelling of the image voxels or a surface-based representation (cf. Figure 14) showing an isosurface resulting from a thresholding. In the case of labelling, an additional problem is the non-smooth approximation of a smooth anatomical interface that has to be reconstructed with sufficient smoothness (depending on the application). Given a segmented image, an adequate mesh of the geometry must be produced. It has to be noted at this point that a labelled image already is a mesh consisting of voxel-shaped cells (elements); however, this is often not suitable for simulation due to inadequate smoothness or resolution (which may be either too coarse or too fine). If a mesh better adapted to the computational task is needed, additional work is needed. For generating a 3D mesh from a segmented image, the following basic approaches are popular:

1. The surface-based approach: From the surface of the structure of interest (such as in Figure 13d), a volume mesh of the interior is generated.
2. The volume-based approach: The basic voxel mesh mentioned before is successively refined into a mesh of adequate smoothness and resolution.
3. The template mesh approach: A generic, pre-fabricated template mesh is mapped to the actual geometry [13].

Each of these approaches has its unique strengths and weaknesses. The surface-based methods are in widespread use and much research has been performed in this direction. The two major representatives of this approach are the *Delaunay triangulation* and the *advancing front* algorithm. Delaunay triangulation derives a simplified mesh (i.e. triangular in 2D and tetrahedral in 3D) in a given convex domain by inserting vertices at appropriate locations and re-triangulating. While a 2D Delaunay triangulation has some nice provable properties attractive for simulation applications, most of these properties break down in 3D, and almost degenerate tetrahedra can occur and must be removed in a special post-processing step. Also, in the case of non-convex boundaries (which is the usual case), the so-called *constrained Delaunay triangulation* methods have to be used, which significantly increase the complexity of the method. In contrast, the advancing front method starts at the boundary and generates layer by layer of the mesh until the whole volume is filled, maintaining information on the current front, i.e. the boundary of the last, innermost layer, in a special data structure. Special care has to be taken at locations where different fronts meet. Both the methods have received lots of attention in meshing research [14] and most commercially available software follows one of these approaches. However, as their starting point is a surface that is not directly part of the geometry description (image), they must be complemented by an initial generation of these surfaces.

The *volumetric approach* in contrast directly uses the image as a starting point and typically builds up a hierarchical structure like a quadtree (2D) or and octree (3D) to control complexity and resolution [15]. The cells of the octree are then converted into cell types of choice, either tetrahedral or a mixture of tetrahedral, prism, pyramids and hexahedra. Finally, a smoothing of inter-material boundaries is performed, for instance by a variant of the marching tetrahedral algorithm that cuts tetrahedra crossing a material boundary (we must keep in mind that these boundaries are not always readily available in the images and must be fitted to the actual image data). This method is very robust and fast, and also flexible in terms of the type of elements generated. Some care has to be taken at the boundaries to obtain elements of good shape. The *template mesh method* sets up a master mesh on a generic representative of the anatomical structure under consideration, often involving a considerable amount of manual work [16, 17]. For each individual case, a mapping is sought from the generic case, in general by means of image registration. This mapping is used to transport the generic mesh to the individual case. A substantial advantage of this approach is that additional information not present in the images can be fitted automatically to the individual geometry, for instance 1D representations of ligaments. A drawback is the amount of work for creating the template (though one of the approaches discussed earlier can be used for that), the potentially inferior quality of the resulting mesh (due to deformations by the mapping), and a potential breakdown of the registration algorithm, if generic and individual geometries are too different. The latter is especially a problem in medicine, when the structures of interest are often diseased or pathologic.

Having generated a mesh, the next step towards a computational problem is the specification of boundary conditions. This is of course a very problem-specific task and thus few generic approaches are available. In most of the cases, a user has to manually set e.g. force values at some locations on the mesh boundary, where one must be careful to avoid mathematical singularities by choosing point forces that do not adapt to subsequent mesh refinement. Modelling boundary conditions correctly can be a quite challenging task, especially if the geometry changes (moves, deforms) over time.

Despite this problem-specific nature, at least one generic approach should be mentioned: Often, coupling a global simple model (like a multi-body model discussed before) and a detailed 3D model can be a way to consistent boundary conditions. For instance, in a study by Jones *et al* [16], a global 1D model of the blood circulation has been coupled to a local 3D model of an artery.

3.3.4 Material behaviour modelling

The choice of an appropriate material model is a crucial part of the modelling process. As briefly mentioned in Section 3.1, the numerical solution of our biomechanical model equations yields the displacement field **U**, which causes a field of internal stresses (represented by **KU**) inside of the modelled body which is in a static equilibrium with the outer forces **F** as in eqn (4) or in a dynamic equilibrium with outer and dynamic forces $\mathbf{D}^*d\mathbf{U}/dt + \mathbf{M}^*d^2\mathbf{U}/dt^2$ as in eqn (6).

Modelling material behaviour means to find a relationship that quantifies how the stresses inside a body of a given material depend on a given field of displacements. This is clearly a material-dependent relationship, since otherwise a prescribed bending of a beam would require the same outer forces for a rubber beam and a beam made out of steel. This relationship is called the material law and is represented by constitutive equations. In order to formulate the constitutive equations of a given material, a third field beside displacements and stresses is introduced, the so-called strains **E**. Each displacement field **U** produces a strain field **E** that measures how the displacements **U** change the length of infinitesimal lines inside the body. A widely used measure for those changes in length is the so-called Green-Lagrange strains

$$\mathbf{E}(\mathbf{U}) = 1/2(\nabla\mathbf{U} + (\nabla\mathbf{U})^T + \nabla\mathbf{U}(\nabla\mathbf{U})^T) \tag{9}$$

with ∇ representing the spatial gradient. Since the strains are a measure for the length changes in a body, **E(U)** vanishes for displacement fields, which describe a rigid body motion, i.e. a pure translation or rotation of the body. Clearly those motions do not alter the length of any line segments inside the moved body. Unfortunately the term $\nabla\mathbf{U}(\nabla\mathbf{U})^T$ is a non-linear term and will lead to a non-linear material law, and will therefore make eqns (4) and (6) nonlinear ones. Such equations are much harder to solve than linear ones and can easily increase the computational costs, especially the computation time, by an order of magnitude. Therefore, a linearized version of the above equation, namely

$$\mathbf{E}(\mathbf{U}) = 1/2(\nabla\mathbf{U} + (\nabla\mathbf{U})^T) \tag{10}$$

is sometimes used as a strain measure. But we have to keep in mind that such a linearization is only justified for very small displacements. In many biomechanical simulations the displacements are too large to apply linearized strain measures. Applying them to non-small, i.e. finite displacements, leads to defective simulation results.

The strains, i.e. the length changes, which are caused by a displacement field, are a purely geometric property. They do not depend on the material or any other physical property of the body under consideration. But they are widely used to model the behaviour of a material, i.e. to quantify the stresses induced by a certain displacement field applied to the physical body under consideration, and they are especially well suited to describe the displacement–stress relationship for elastic materials.

If the stresses that are induced by a displacement field in a certain material only depend on the strains that are evoked by these displacements, we call the material elastic. Roughly speaking, an elastic material remembers its unloaded shape, and returns to that shape (i.e. zero displacements) as soon as all outer loads are removed. The simplest elastic material law is the St. Venant-Kirchhoff material. Its constitutive equations read

$$\mathbf{S}(\mathbf{E}) = \frac{Ev}{(1+v)(1-2v)}\,trace(\mathbf{E})\mathbf{I} + \frac{E}{1+v}\mathbf{E} \tag{11}$$

where Young's modulus $E > 0$ and the Poisson ratio $0 < v < ½$ are material parameters and **S** are the stresses in the body and **I** is the identity mapping. This material law is linear and is used together with the linearized strain measure mentioned above to provide the common linearized elastic model. While this model is widely used since its linearity reduces the computational costs, it is crucial to keep in mind that St.Venant-Kirchhoff material models can only be used for elastic materials that are isotropic and are only exposed to small strains.

In the remainder of this section we will give a very brief overview of material laws which can be used, if the mentioned restrictions are not met and therefore the use of St.Venant-Kirchhoff materials is prohibited.

- An isotropic material has no distinct direction. The stress–strain relation is independent of spatial orientations. Only in this case the linearized material laws can be described by two material parameters, like E and ν. For a general anisotropic material 21 parameters are needed. If the stress–strain relation can be fully described by three orthogonal directions (orthotropic materials), we need nine parameters, and if the material behaviour is symmetric to one distinct direction (transversely isotropic materials) we still need six parameters. Many biological tissues show anisotropic behaviour, for instance muscles and artery walls [18].
- Most biomechanical applications do not satisfy the assumption of small strains, i.e. $|\mathbf{E}^2| \ll |\mathbf{E}|$ is not true. But linearized material laws like St.Venant-Kirchhoff yield wrong stresses for large strains, and therefore linear models are not appropriate in these cases. We will demonstrate this briefly by the following example:
  Let us consider, for instance, the displacement field, that scales the length of a given body by a factor of α, $0 < \alpha < 1$. This displacement field has the form $\mathbf{U}(\mathbf{x}) = (\alpha - 1)\mathbf{x}$ and reduces the volume of the body by a factor of α^3. The St.Venant-Kirchhoff material predicts for this displacement field constant stresses inside the body of the size
  $$\sigma = \frac{(\alpha^2 - 1)E}{2(1 + \nu)(1 - 2\nu)} \tag{12}$$
  Surprisingly this number is bounded for $\alpha \to 0$. In other words, a finite outer pressure suffices to shrink the body to any given volume. Obviously this model violates the basic principles of physics. We know that the outer forces we need to compress a certain volume of a given material by a factor of α^3 tend to infinity for $\alpha \to 0$. The linearized model is apparently useless for finite strains. Material laws, that are valid for finite strains are called hyperelastic material laws. The simplest ones look like the St.Venant-Kirchhoff material law, augmented by a term producing infinite stresses in case of infinite compression. They are called Neo-Hook material laws [19].
- Many biological tissues, especially soft tissues like tendons, muscles, skin etc., show viscous behaviour on certain time scales, like creep or relaxation. We say a material is creeping, if, loaded by a constant outer force, it shows increasing displacements over time (creep) in addition to an instantaneous response to the outer forces. The material shows relaxation, if it, exposed to a constant displacement field, shows decreasing inner stresses as a response. Both the effects are sketched in Figure 18 and can be explained by a 'vanishing memory' of the material, which is clearly a non-elastic property. For such viscoelastic materials the constitutive equations can not be expressed as $\mathbf{S} = \mathbf{S}(\mathbf{E})$, but contain time derivatives of strains and/or stresses [20].

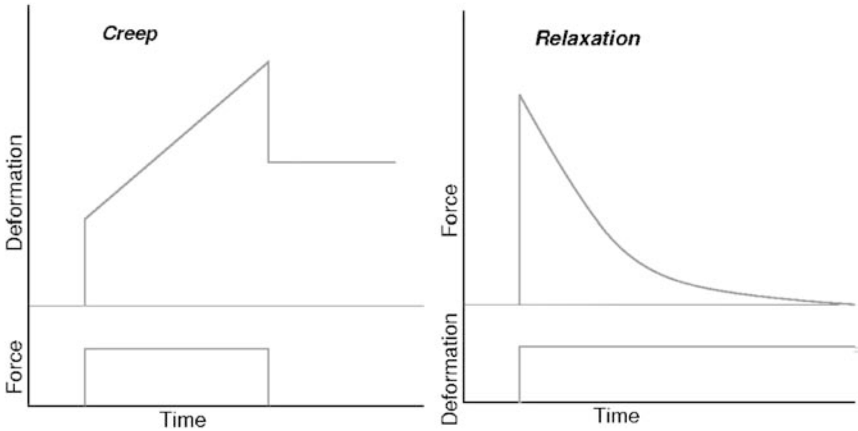

Figure 18: Sketch of viscoelastic creep (left) and relaxation (right) for an idealized viscoelastic material (Maxwell fluid).

- One of the underlying assumptions for all of the above material models is the conservation of mass. But biological tissues are living tissues that adapt to a changing environment like outer forces or other boundary conditions. For many applications these effect can be neglected, since they are small enough. But for some applications these adaptive processes, like growing or remodelling, significantly change the mechanical behaviour of the living material under consideration and have to be taken into account. For an introduction to the modelling of growth and adaptation see Ref. [21].

All material models, including the ones mentioned above, are dependent on material parameters. For example the St.Venant-Kirchhoff model needs two parameters, which are, for instance, $E = 73100\ \mathrm{N/mm^2}$ and $\nu = 0.33$ for aluminium. Material parameters are needed in modelling of biological tissues, too. But they can vary greatly from one individual to another, depending on age, sex and many other individual variables. This is an additional obstacle for accurate modelling of biomechanical materials and should be carefully taken into account. Sometimes it is sufficient to incorporate average values for these parameters given in the literature; sometimes the parameters can be deduced from the medical images, for instance bone stiffness from CT images [22]; and sometimes measurements have to be taken *in vitro* or *in vivo.*

4 Short outlook

In the future, efforts like the Virtual Physiological Human (VPH) [23] may provide a framework for developing and coupling models of different scales and body parts. The term ‘Virtual Physiological Human’ indicates a shared resource formed by a federation of disparate but integrated computer models of the mechanical, physical and biochemical functions of living human body in both physiological and pathological conditions. VPH models will be both descriptive and predictive. They comprise

- large collections of anatomical, physiological and pathological data stored in digital format,
- predictive simulations developed from these collections,
- services aimed to support the researchers in the creation and maintenance of these models and
- services aimed to empower clinical, industrial and societal users in the use of the VPH resource.

The VPH is a methodological and technological framework that once established will enable collaborative investigation of the human body as a single complex system. VPH is not 'the supermodel' that will explain all possible aspects of human physiology or pathology. It is away to share observations, to derive predictive hypotheses from them and to integrate them into a constantly improving understanding of human physiology/pathology by regarding it as a single system.

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Motion analysis in water sports

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Abstract

Historically the analysis of water based sports techniques has been isolated to the means of scientific investigation by a barrier. This barrier has been the water itself and it is only in recent years that the developments in technology have allowed a more scientific approach to the analysis of water-based activities. These activities include those within the water such as swimming and those on the water such as rowing, kayaking and sailing. This chapter will review how technology has aided the scientific analysis of water-based activities and how this technology has been used to develop the theoretical underpinnings of techniques, as well as being used as an integral tool for the performer in developing their own technique.

Keywords: kinematics, swimming, kayaking, hydrodynamics

1 Introduction

The medium of water has presented scientists over the years with problems in the design and implementation of analytical and experimental methods, which will enable an adequate evaluation of a performer's technique. For the 'dry-land' researcher, methods have been developed that allow detailed qualitative and quantitative analyses of technique to be undertaken. Such methods have been invaluable to both the sport scientist and performer in understanding key components of technique. However, as a direct consequence of the nature of the environment, many methods of biomechanical analysis have not been directly transferable. Similarly, research in these fields has not taken advantage of the opportunities that developments in technologies have presented. This has meant that it is only within the last 5–10 years that researchers have made great strides into the understanding of water-based activities, in particular, swimming and kayaking. This chapter will focus on principles of technological development in these two main water-based activities.

2 Technology in swimming research

In swimming, particularly at the elite level, the major determinant of performance is technique [1]. Improvements in performance therefore are likely to be the result of recommendations made from a detailed understanding of technique. Early assessments of technique were through observation and intuition. Up until Counsilman's 1971 paper [2] it was generally assumed (and coached) that swimmers should pull their hands directly backwards in a straight-line utilizing drag forces for propulsion. The application of film in swimming led Counsilman [2] to identify that skilled swimmers executed a 'S' shaped pull pattern in the front crawl. He inferred from this that lift forces could be generated by the hand in skilled swimming and that these forces could contribute to propulsion. As such a curved or 'S' shaped pull pattern was coached. This application of technology led to a significant change in the way swimming technique was viewed.

Over the past few years the evaluation of technique through methods or procedures that provide objective quantitative data has been at the forefront of much scientific research. Methods that have been used to evaluate swimming technique quantitatively include measures of velocity [3], acceleration [4], stroke parameters [5], power [6], the estimation of hand forces [7, 8] and swimming efficiency [9]. As technology has advanced the analysis and understanding of swimming propulsion has developed to the point where theories of propulsion commonly accepted only a decade ago are being challenged. What follows here is a brief history of how technology has shaped research and understanding of swimming technique.

2.1 The application of film

To date, arguably the most valuable tool available to the sports biomechanist has been the motion picture. Video (or cine, though rarely used) enables both qualitative and quantitative analyses to be undertaken. Certainly video has been used in almost all of the quantitative methods described above and today the use of underwater video recording is perhaps the most accessible method of technique analysis. Its use is facilitated by the fact that a frame rate of 25 Hz is sufficient to capture the swimming stroke which, compared to other sporting movements is relatively slow [10].

The quantitative assessment of swimming technique using video can essentially take two forms, two-dimensional and three-dimensional kinematic analysis. In most cases both approaches require a modification to the experimental set up because of the nature of the dual-media environment. When using standard video and digital video cameras, invariably they have to be set behind a transparent barrier of either perspex or glass (with perspex the quality of the image is reduced as a greater quantity of light is absorbed). Previous literature indicates that a variety of methods have been used for mounting and positioning cameras used in the evaluation of swimming technique.

A limited number of studies have used cameras placed on the pool-side or in some way suspended above the swimmer e.g. Ref. [11]. This method is almost exclusively reserved for quantitative assessments of variables such as average swim speed, stroke frequency and stroke length, particularly for assessments made during competition races [1].

It is reasonable to assume that kinematic measures of stroke technique which occur during the recovery phase of front crawl can adequately be measured by a pool-side camera. Such variables can also give valuable information on the overall effectiveness of a swimmer's technique. For example, stroke length is a function of the propulsive and resistive forces exerted on a swimmer [12] and has been identified as being an important factor in determining performance [1]. Of course the first two phases (block time and flight time) of the race starts can also be adequately evaluated using a pool-side camera.

Using a pool-side camera to measure underwater variables cannot be deemed sufficiently accurate. The combined effects of refraction at the water's surface and wave turbulence created by the swimmer make the following path of the hand almost impossible. The filming of the underwater stroke has been achieved by a number of different protocols. Underwater housings provide a cheap and portable method of gathering underwater video. Their widespread use in underwater photography has been well documented since the first underwater housing introduced by Louis Boutan in the 1890s, illustrated in Figure 1 [13].

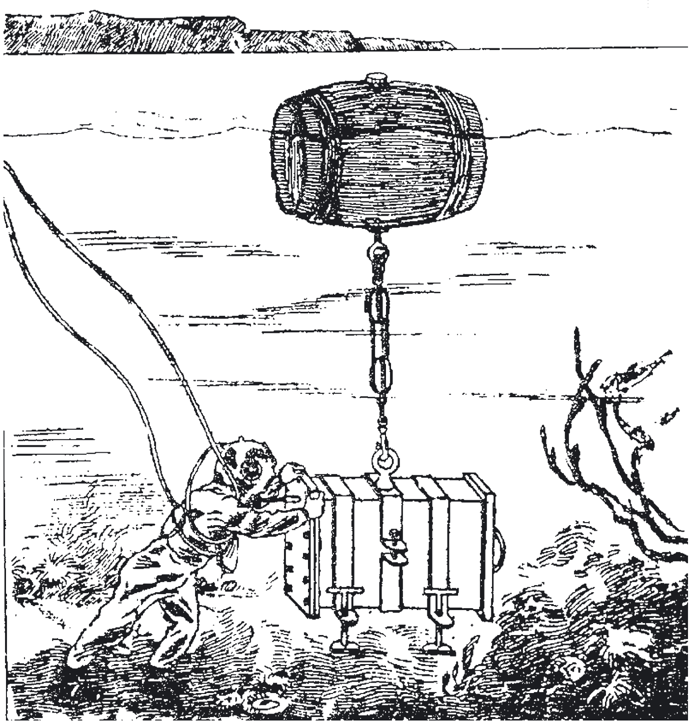

Figure 1: Illustration of the underwater housing used by Boutan in the 1890s and the method he used to manoeuvre it. (Copyright Dobbs (1962) reprinted with permission.)

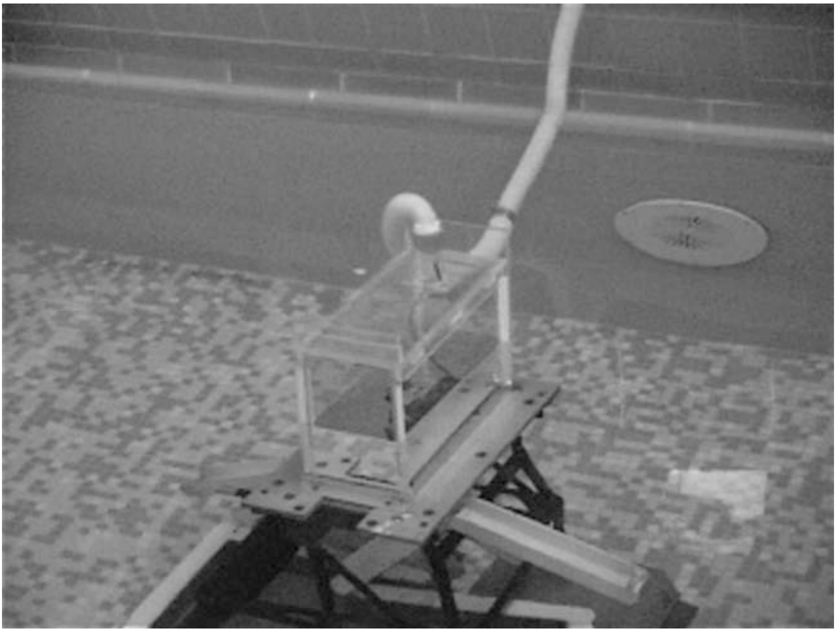

Figure 2: Illustration of the underwater housing in Lauder and Dabnichki [8].

From the literature it seems that the construction of the housing is dependent on its purpose and the size of the camera, which is placed in it. Lauder *et al* [14] used a housing constructed of perspex and fixed to the pool-side to film underwater movements in a direction towards the camera (Figure 2). Variations on this have been developed for individual purposes and, although details are rarely reported in the literature, the general construction is the same. The camera is mounted behind a glass or perspex sheet or a dome port hole. Other examples include housings that allow a panning technique to be used and housings that are fixed to run on tracks down the length of the pool. The ease with which such housings can be installed and transported has led to an increase in their use for swimming research over recent years.

Another approach makes use of underwater windows. Underwater windows were initially used for observation of swimmers' techniques. With the introduction of cinematography in swimming research there has been an increased use of underwater windows for filming rather than observation. A large number of studies have used underwater windows and many new pools, especially those used specifically for research, have underwater windows installed as part of the design. One limitation of underwater windows though, often owing to their location, is that they have a limited flexibility. Particularly for three-dimensional analyses, when ideally the windows should be positioned orthogonally to one another.

Periscope systems have also been used for filming the underwater movements of the swimmer [15]. The idea was first introduced in a presentation to the First International Symposium on Swimming by Dal Monte [16]. Hay and Gerot [17] much later presented a technical note on 'distortion-free' periscope systems for recording underwater motions of the swimmer. The basic design enabled the camera lens to be held vertically downwards, a mirror and mirror support system that reflects the image of the swimmer's movements up to the camera and a wave deflector to stop surface wave distortions caused by the swimmer's motion. Periscope systems are still in use today, however they do not directly deal with the effect of refraction at the air–water interface and it has been suggested that they severely limit the field-width [18].

The problem of refraction is not only limited to the use of periscope systems. Recordings of motion through underwater housings and underwater windows are also subject to the effects of refraction, as invariably there is an interface between the camera and object of materials with different refractive indices.

Refraction at a flat surface is readily understood on the basis of Huygens' Principle [19]. If light travels from a less dense medium to a more dense one (e.g. air to water or water to glass) its speed is reduced. The effect of this when light rays strike the interface at an angle is defined by Snell's Law as given below.
Snell's Law

$$\mathrm{Sin}\phi\ n = \mathrm{Sin}\phi'\ n \tag{1}$$

Where $n = c/v$ and $n' = c/v'$

c is the speed of light in a vacuum v and v' the speed of light in the respective mediums.

It was this relationship that McIntyre and Hay [20] used to produce their transformation equation for dual media filming. The problem is that the light rays invariably travel from water to glass (less dense to more dense) and then from glass to air (more dense to less dense), thus being refracted twice. Therefore, any transformation equation for matching underwater and 'in air' objects should take into account the refraction at each surface. Practically the effect of refraction can be corrected by assuming that the object plane is perfectly aligned with the interface between the media. Based on this assumption, it is possible to calculate object coordinates in the water with the use of two cameras. These methods have been used in photogrammetry to map underwater objects [21].

The key condition that arises from dual-media research is that the camera lens and the refracting surfaces should be perpendicular to one another. The same condition should be met for three-dimensional reconstructions using the Direct Linear Transformation (DLT) algorithm [22], where the conditions of co-linearity and co-planarity have to be met. If a flat sheet of glass (or a dome) was placed in front of the lens to form the air–water interface, it essentially becomes an element of the lens itself. Theoretically the 'outer element' can be placed such that the problem of refraction is eliminated. In practice, this is not readily achievable [23]. Therefore, by placing a video camera arbitrarily behind a sheet of glass or perspex, as in an underwater housing or behind an underwater window, a direct violation of the co-linearity assumption of the DLT algorithm occurs. The overall effect is that there is an added level of distortion to the image. If the optical system contains many refracting (or reflecting) surfaces, it should be assumed that the level of distortion increases.

Two approaches exist that could be used to correct for refraction, a mathematical approach and a physical approach. Walton [23] essentially presented the first physical method to correct for the effect of refraction where the image is viewed in both media. The solution was to place a semi-circular dome in front of the camera lens and to align the optical axis of the camera lens with the centre of curvature of the dome. The procedure then was to visually correct for refraction by changing the distance between the lens and the dome until the effect of refraction had been removed from the image. The image used for this procedure is illustrated in Figure 3 below [23] and consisted of vertically aligned 'stripes'. When the image was affected by refraction the stripes do not align but when the refraction has been corrected the stripes do align.

This is due to the dome essentially forming part of the lens as the incident node of the lens is coincident with the geometric centre of the dome. Although the author described the method for correcting for refraction he did not state if the proposed method was for correction of split media filming, i.e. above and below the water simultaneously (as indicated by the figure above) or for correcting solely underwater images where the plane glass is replaced by the domed glass. In the evaluation of the method only a written description of the tests was provided. The author indicated that the method correctly recovered valid 'three-dimensional trajectories, correct limb lengths and several kinematic variables'. Unfortunately no data or specific methods were presented in the paper, so the accuracy of the method cannot be directly compared to other research on accuracy.

Reinhardt and Walton [24] and Reinhardt [25] used the methods of Walton [23] to correct for refraction in studies determining the range on motion of space

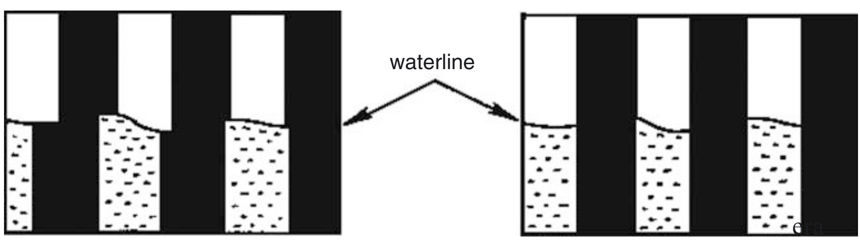

Figure 3: Views of the vertical bars before (left) and after (right) camera alignment within the housing. (Copyright Walton (1988) reprinted with permission.)

suits tested in an underwater environment. The procedure utilized ExpertVision, developed by Motion Analysis Corporation; an accuracy of ±2.5 mm was reported for a three-dimensional reconstruction of trajectories. This accuracy seems comparable with results from studies conducted in air, and the physical method of correcting for refraction is promising, particularly if incorporated into the design of underwater housings. Unfortunately the method does not account for the effect of refraction at plane glass underwater windows, which are more commonly used in underwater filming studies.

The only other study to investigate the effects of experimental set-up where filming occurs through a glass barrier is that reported by Lam *et al* [26]. These authors sought to determine the effects of various parameters relevant to test conditions on the calibration and accuracy of a video dimension analyser (VDA) used to assess strain in soft connective tissues. The set-up uses high-speed film to measure displacements on the surface of the connective tissue by digitizing markers placed on the surface. Typically soft tissue is mounted in a test apparatus and the surface of the tissue stained with parallel dye-lines. The surface is viewed through a TV monitor and an electronic dimension analyser places two 'windows' on the image. These windows are placed over two dye-lines and the apparatus scans the edges of the dye-lines when the tissue is put under strain. A timer records the time between any two edges which pass the windows. The scan time is converted to a voltage which corresponds to the distance between the two edges. Previous investigations in to the accuracy of these systems [27] had shown that the calibration of the system was linear (voltage output against linear dimension) when the media filmed through were air and glass.

Lam *et al* [26] considered three further parameters. The first was to vary the distance between the object (tissue) and the lens, the second to show the refractive effects of the glass and physiological solutions and, finally, the dynamic response of the VDA. The experiments were carried out in two groups, a series of static experiments and a series of dynamic experiments. To evaluate the first parameter, three object distances were used (175, 230, 300 mm) and the results were reported as least squares regression lines for each distance showing the slope and intercept. The refractive effects of the set-up were shown through two experiments. One used a standard object distance of 175 mm and filmed the tissue under three conditions, just the object and lens, the object, glass and lens and finally the object, glass and water. The last static test consisted of the same object distance but the angle of incidence between the lens and the object was varied (0°, 10° and 20° ± 0.5°); one other set-up of 230 mm and 10° was also reported. For the dynamic tests an Instron testing machine (Instron 1122, Canton, MA) was used to create a dimension that changed continuously with time. The experiment consisted of 10 trials of 0.1 mm simulated tissue displacements between 5.0 mm and 5.1 mm and then repeated 0.1 mm displacements up to 5.7 mm. The rate of displacement was 10 mm min^{-1}. All results were reported as best-fit regression lines giving the slope (a) and intercept (b).

The results showed that, for all parameters, increases in slope (voltage against linear dimension) occurred with increase in the size of the object. The VDA system works on the basis that the line passes through the origin, i.e. the intercept is zero. The results for all experiments showed this not to be the case. The authors undertook an error analysis to investigate how sensitive error was to the parameters of the experimental set-up based on the slope and intercept of the line, the initial length L_0 and a standard deviation of the voltage from the regressed value (VDA output). The analysis showed that the error was sensitive to camera placement and orientation as well as the media through which the object is observed. The authors suggested that one way to reduce error would be to maximize the image size on the screen, by decreasing the object distance or increasing the magnification (presumably through changing the focal length of the lens or changing the curvature of the glass barrier). Suggestions that the larger the control length as a proportion of the screen, the more accurate the results, were mediated with warnings that field width is constrained by practice. Similar recommendations for filming analysis have been made previously [28]. Unfortunately the implications of the results were not fully discussed and the reader was left to interpret the significance of the experimental set-up on error. It would appear that, for any such set-up, one should determine the error associated with that set-up before undertaking the test; something that hopefully constitutes good practice.

Refraction could restrict the experimental method that may be used to assess the accuracy of underwater filming owing to a limiting factor termed the critical angle (ϕc). The critical angle defines the maximum angle at which incident rays will be refracted. Outside ϕc all incident rays will be totally reflected. In defining the experimental set-up, therefore, the critical angle becomes important when assessing the influence of object–glass–camera distances on accuracy.

Lauder and Dabnichki [29] and Lauder *et al* [30] used a scaled down underwater environment to investigate the effect of changes to the experimental set-up, on the accuracy of two-dimensional and three-dimensional reconstructions from underwater video analysis in order to provide an assessment of physical solutions to the accuracy problem. The experimental set-up used an overhead runway to control camera (Figure 4) and calibration object (Figure 5) positioning relative to the refractive surface. In a series of experiments the researchers sought to establish the influence of experimental set-up on the level and distribution of error in underwater three-dimensional kinematic data using a scaled-down environment and the influence of the frequency of the movement on accuracy and the criteria for filtering technique that should be adopted. The main objective was to provide practical solutions to improving the accuracy of underwater kinematic data collection.

It was found that, the position of the camera and the calibration object relative to the glass interface influenced the level of error, in the reconstruction of known lengths. The results provided evidence that there was a need for an augmented calibration procedure, in order to minimize the influence of unaccounted random errors, in underwater video analysis that uses underwater windows/housings. The research highlighted that the position of the object within a calibrated volume influences the accuracy of underwater data collection. Similarly it was

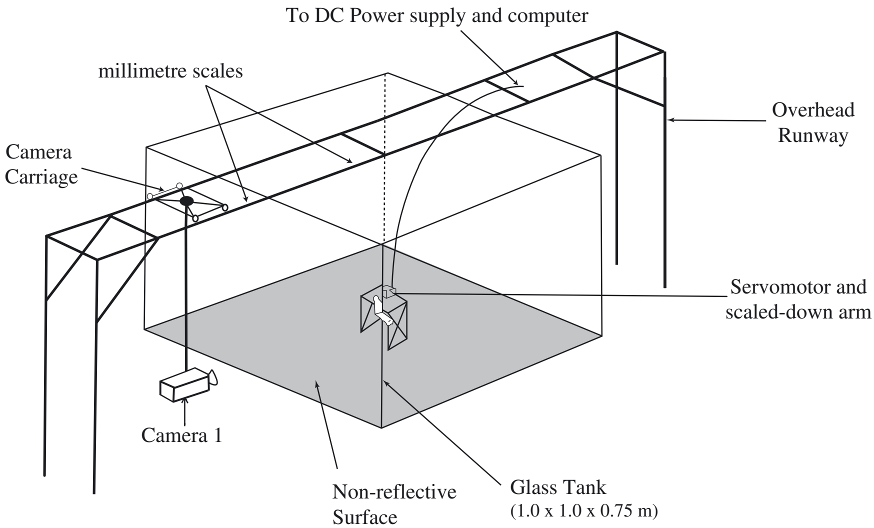

Figure 4: Experimental set-up used to evaluate error in underwater kinematic analysis [14].

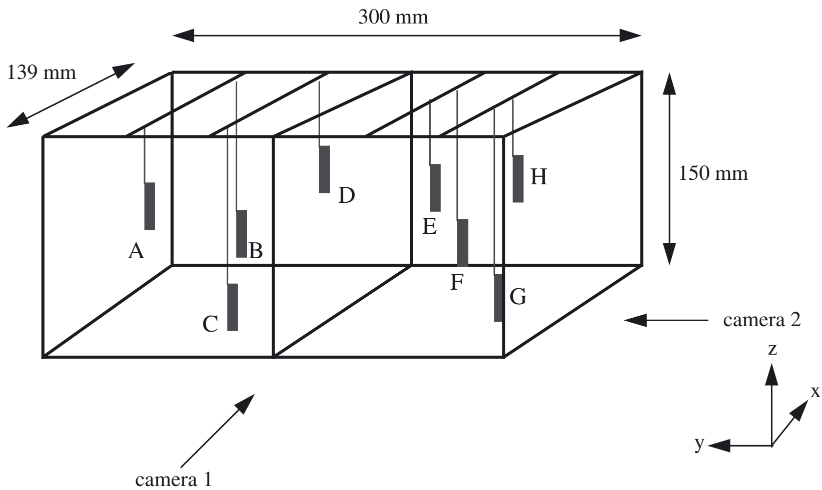

Figure 5: Illustration of calibration frame used in underwater three-dimensional analysis.

highlighted that there was an error associated with underwater filming due to turbulence. In research that used a controlled motorized rotating arm (Figure 6) with fixed rotation at different movement frequencies, it was noted that the variability in angular measurement of a dynamic movement was greatest at the fastest frequency of movement tested (1.25 Hz).

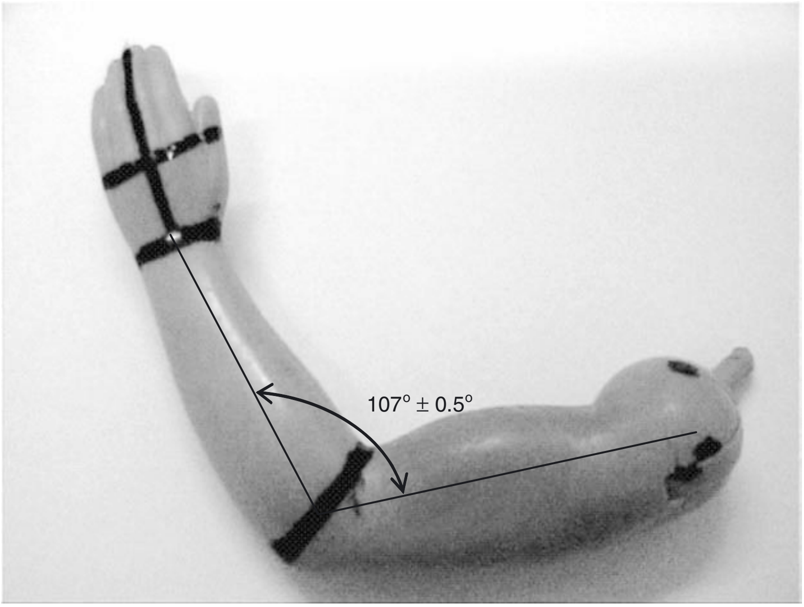

Figure 6: 1/6th scale arm (figure shown is life-size) used in Lauder *et al* [30].

Some work has also been done on data conditioning in underwater kinematic analysis. Smoothing and filtering techniques are commonly assessed by evaluating the %RMSE between the true signal and the calculated values [31]. This criterion can be employed to enable comparison of second derivative estimates across studies and can be calculated from a common formula [32].

$$\%\text{RMSE} = 100\sqrt{\frac{1/n\sum_{i=1}^{n}(Xci - Xi)^2}{1/n\sum_{i=1}^{n}(Xci)^2}} \tag{2}$$

where n is the number of data points, Xci the i th value of the criterion signal and Xi is the i th value of the estimated signal.

In the evaluation of smoothing techniques in underwater analysis Lauder *et al* [30] used five separate methods to smooth and differentiate a raw data series of angular velocity using Peak Motus 32 Software (version 2000) and Biomechanics Toolbox [33]. Due to built-in limitations of the Peak Motus Software a cut-off frequency of 3.6 Hz [34] was not possible and consequently rounded to 4 Hz. The five separate methods were:

1) A 4 Hz cut off frequency that falls within the studied range by Yu *et al* [34].
2) Second order automatic Butterworth low-pass digital filter (Bwauto).

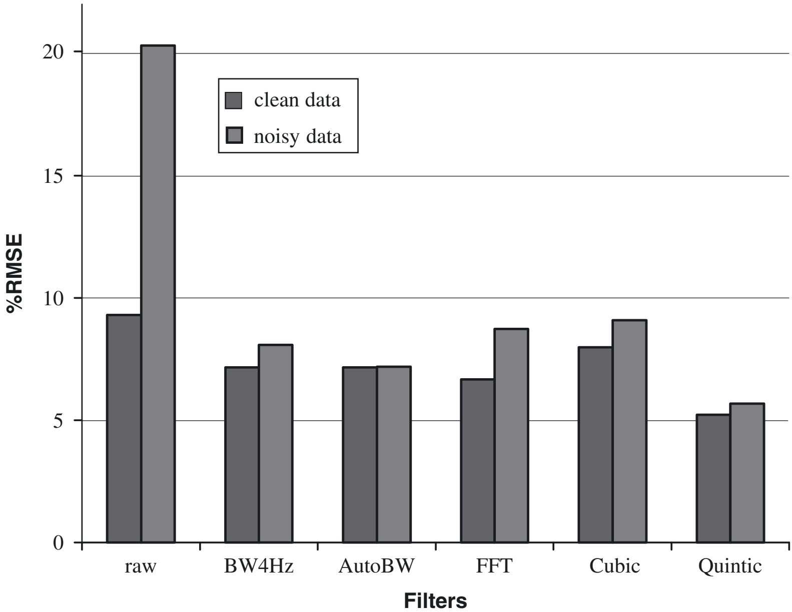

Figure 7: Comparison of the %RMSE between the true and estimated angular velocity are presented for both the clean and noisy data sets after filtration/smoothing.

3) Fast Fourier transformation (FFT) with a cut-off frequency of 6 Hz [35].
4) Cubic spline (CS) with an automatic smoothing parameter determined by the software.
5) Quintic spline (QS) with the smoothing factor determined by minimizing %RMSE of the residuals between the calculated angular velocity and the criterion angular velocity [36].

The results (Figure 7) highlight the filter that responds best in an underwater environment. In front crawl swimming the underwater arm motion is a relatively slow, cyclic action yielding non-zero accelerations at the record boundaries. The mathematical underpinning of QSs is best suited to the type of action inherent in swimming [37] especially when large deviations in the level of random noise are apparent. This finding is not surprising as QS criteria are based on a weighted combination of weighted derivatives from nil to second order. As movement in swimming is inhibited by the water resistance it yields smooth acceleration curves allowing highly accurate first order derivatives.

The generation of turbulence in the underwater stroke can be related to the frequency of the movement. The internal friction of a fluid causes a resistance to the motion of an object moving through it, which is proportional to the gradient of the velocity. Increasing velocities influence the laminar boundary layer around the front of a moving object causing a transition of the laminar flow to a turbulent one [38]. Turbulence in underwater analysis severely distorts the image of the hand. The frequency of the movement therefore, becomes an important consideration when assessing error due to the relationship between the frequency of the movement and the creation of turbulence. Lauder and Dabnichki [29] Lauder *et al* [30] demonstrated the problems associated with the reconstruction of kinematic data in underwater video analysis.

Why is it important to address refraction? Well, as technology has advanced, so have the kinematic techniques available to analyse technique. If these techniques are to be applied correctly, then the refraction problem must be addressed. More recently, Kwon [39], Kwon and Lindley [40] has addressed the issue of refraction through extensive studies that model refraction and which adopt a mathematical approach to the solution. With the development of kinematic analysis packages that have the functionality to use algorithms to correct for distortion due to refraction, the practical solutions described above appear redundant; however, the best possible image must still be available for use in the analysis of swimming technique. At present there exists no method of kinematic analysis that can reliably be used to assess technique in swimming that does not use the recorded image of the technique.

The use of the DLT algorithm in three-dimensional analysis of the swimming strokes is widespread e.g. [41]. Payton and Bartlett [42] conducted a study on the reliability of kinematic data from three-dimensional video of a swimmer's stroke, which was used to estimate propulsive force. Propulsive forces are important determinants of swimming performance and the accuracy to which they can be estimated through digitizing procedures should be considered when addressing this issue. The results from this study indicated that inter-tester differences in locating the four points used to define hand orientation produced a mean error in pitch angle and sweepback angle of 1.8° and 2.1° respectively. The propagated error in the calculated resultant force was 8%.

Lauder *et al* [14] expanded this work in a study which sought to establish the accuracy and reliability of current and newly proposed procedures for the reconstruction of hand velocity, sweepback angle and pitch angle from underwater three-dimensional video analysis. A full-scale mechanical arm capable of simulating a controlled and highly repeatable underwater phase of the front-crawl stroke was filmed and for a set of five trials. A seven-point model of the arm and hand was then digitized at 25 Hz. Hand velocity, sweepback angle and pitch angle were calculated using the procedures of Schleihauf [43], Berger *et al* [7] and a newly proposed procedure (Lauder). Statistical comparisons were made between procedures to establish their relative accuracy and reliability throughout the stroke. The mean absolute error in measurement of hand velocity between points on the hand was very small (± 0.04 and ± 0.06 m s^{-1} in the x and z directions, respectively). The mean errors in sweepback angle and pitch angle were respectively: 9.3° and 7.6° (Berger), 10.1° and 8.1° (Schleihauf) and 10.7° and 7.0° (Lauder). Agreement between procedures showed the standard error between Schleihauf and Lauder to be the least (Schleihauf and Lauder, 0.4°; Berger and

Schleihauf, 1.3°; Berger and Lauder; 1.6°). The use of four points in the reconstruction of the orientation of the hand (Schleihauf and Lauder procedures) was shown to be less sensitive to errors in the digitizing procedure. The reconstruction procedure proposed in this study (Lauder) further reduced the sensitivity to digitizing error in the reconstruction of sweepback and pitch angles in swimming. It is important to remember that all kinematic variables discussed so far have an impact on the evaluation of technique in swimming.

Propagation of errors is an important consideration in any biomechanical analysis and due to the underwater environment, measures to reduce the error are essential if technique is to be adequately described. The lack of research in the literature suggests that swimming researchers have not been as concerned with the accuracy of their methods as have researchers of 'dry land' activities [31, 44]. The explanation for this could lie with the nature of the environment. Water makes the control of variables somewhat more difficult than air. This could explain why the problem has received very little attention in the literature. Similarly, advances in technology relating to kinematic analysis, such and on-line motion analysis systems, have not addressed the analysis of the underwater stroke. Such techniques and systems have exclusively been developed to address the analysis of techniques in the laboratory. If swimming kinematic analysis is to advance, new techniques of image analysis need to be developed beyond the relatively simple, yet time consuming, manual digitization process. Recent developments in shape recognition offer some hope to this, yet this technology is developing and it will be some while before it is commonly used in 'dry-land' analysis of sports activities, yet alone applied to the underwater environment.

2.2 Other motion analysis techniques

Accelerometry provides one method of motion analysis that can be applied to swimming. As technology has become more miniaturized, opportunities to evaluate movement patters through accelerometry have arisen. Ohgi *et al* [45] presented a miniaturized accelerometer contained within a waterproofed wrist watch. The device contained two monolithic bi-axial acceleration sensors (ADX250, Analog Devices Inc.), each sensor recording accelerations up to 50 G. Recording swimming strokes, the researchers were able to distinguish phases of motion within the swimming cycle (verified through video analysis). Although the technique was shown to give reliable profiles, its main application would be in monitoring of technique profiles for an individual swimmer and therefore having a direct coaching application, particularly as wireless advances could lead to a 'real-time' logging application.

2.3 Kinetic analysis

The accuracy of kinematic data is important not only for defining or characterizing technique but also as input data for the control of mechanical and computer models. Kinematic data have been used in models, which attempt to assess the propulsive forces generated by the hand [46], forearm [7] and hand and forearm [8, 47] in swimming.

The measurement of hand forces has produced much interest in the assessment of swimming technique. Schleihauf [43] concluded that the hand was the ‘single most important contributor to propulsion in the arm stroke’. Three major methods have been established for hand force estimation. The first direct method uses pressure sensors located on the hand to estimate hand forces directly [48]. This method was shown to be ineffective due to changing conditions of hand motion and orientation during the stroke. The second method, hydrodynamic analysis, is the combination of underwater three-dimensional film of the swimmer’s technique and hydrodynamic lift and drag force coefficients for the hand obtained from laboratory experiments. The accuracy of the latter method is dependent on the accuracy of the kinematic data from the underwater three-dimensional video film and the accuracy of the drag and lift data obtained from hydrodynamic experiments using hand and arm models in static positions moving at constant velocities (quasi-static approach).

Hydrodynamic forces in swimming are dependent on two important effects associated with an immersed accelerating segment, namely vortex shedding and added-mass effects [49]. The testing protocols that have previously been used to obtain lift and drag coefficients ignore these effects, adopting the quasi-static approach. This has been shown to give different lift and drag profiles when compared to fluid conditions of unsteady flow, which are similar to those experienced in swimming [50]. Could it be then that the quasi-static assumption fails? Recently this problem has been addressed in insect flight [51] showing that extra lift from a leading edge vortex was sufficient to carry 2/3 of a Hawkmoth’s weight, while the impulse from two ring vortices left in the wake of the movement was equivalent to 1.5 times the body weight of the insect. There has been limited research on flow visualization in swimming and a study reported by Toussaint *et al* [52] suggests that vortices may exist in swimming. Toussaint *et al* [52] showed that during the upsweep of the front crawl stroke a tip vortex, very similar to the three-dimensional leading-edge vortex described by Berg and Ellington [51] for insect flight, was exhibited along the leading edge of the hand (i.e. little finger side). It was concluded that more visualization studies are needed to substantiate their findings.

Both Schleihauf [43] and Berger *et al* [7] used a quasi-static approach to obtain hydrodynamic data for an immersed hand and immersed hand–forearm respectively for modelling hydrodynamic forces in front crawl swimming. Wood [53] applied a similar approach. However, lift and drag data were obtained from wind tunnel experiments. Recently, Sanders [35] used a quasi-static approach to determine velocity and acceleration coefficients for a swimmers hand, accelerating in the direction of flow. Using an approach similar to Schleihauf [43], he produced three-dimensional surfaces describing the magnitude of the coefficients as functions of pitch angle and sweepback angle, the acceleration coefficients reported, being in the order of 6% of the velocity coefficients. Sanders concluded that the inclusion of acceleration coefficients was necessary for the accurate modelling of hand forces in swimming. Although the study begins to address the issue of unsteady flow conditions generated by an accelerating object, the reliability and the accuracy to which the kinematic parameters of velocity and acceleration can be measured, was not addressed. This must, therefore, raise questions as to the applicability of such coefficients to the accurate estimation of hand forces. These are the only studies that have published hydrodynamic force data for the hand–forearm. The relatively steady flow conditions created in these studies do not readily transfer to the flow conditions that are experienced in swimming. The hand in skilled front crawl swimming constantly changes its angle of attack and sweepback angle with respect to the water. It also accelerates, thus experiencing unsteady flow conditions. Similarly the movement of the forearm and upper arm could be expected to influence flow conditions. It would be expected, therefore, that the lift and drag profiles in swimming would be different from those obtained in the models of Schleihauf [43] and Berger *et al* [7]. These authors used force transducers positioned a distance away from the hand and arm model to measure the hydrodynamic force at the hand. This method would seem to measure a force proportional to rather than equal to the hydrodynamic force exerted by the hand on the water.

Recently, propulsive forces in swimming measured by the quasi-static approach have been compared to measures of active drag, measured by the MAD system [9, 54]. The main principle applied in these studies was that, at a constant swimming velocity, the mean propulsive force would be equal to the mean drag force acting on the body of the swimmer. The results from Berger *et al* [54] showed that the mean difference between the two measures was 5%, concluding that the kinematic approach could be used to estimate contributions of lift and drag forces to propulsive force [54]. The earlier study however [9], found that the kinematic approach was unable to estimate propelling efficiency. Berger *et al* [9] defined efficiency as the contribution of lift forces to propulsion; increased efficiency resulting from a greater contribution from lift forces to propulsion. The authors concluded that the generation of vortices in swimming may play an important role in propulsion.

To advance the knowledge in this area Lauder and Dabnichki [8] developed a direct approach to solving the problem. To obtain reliable data on propulsive forces in front crawl swimming, a mechanical model of the whole arm was developed that simulated the dynamic action of the arm in the front crawl stroke and measured the force profile throughout the stroke. The arm model was used to compare the quasi-static approach to the direct measurement of force. If the quasi-static theory was correct, then the torque profiles measured directly on the arm would be the same as the profiles calculated by the quasi-static approach.

The mechanical arm was shown to produce a controlled movement pattern, which was reliable and accurate to within $\pm 1°$ for repeated trials and $\pm 2.3°$ across different trials. The shoulder torque measurement was also shown to be reliable and accurate to within ± 1.22 N m, over a range from 0 N m to 70 N m.

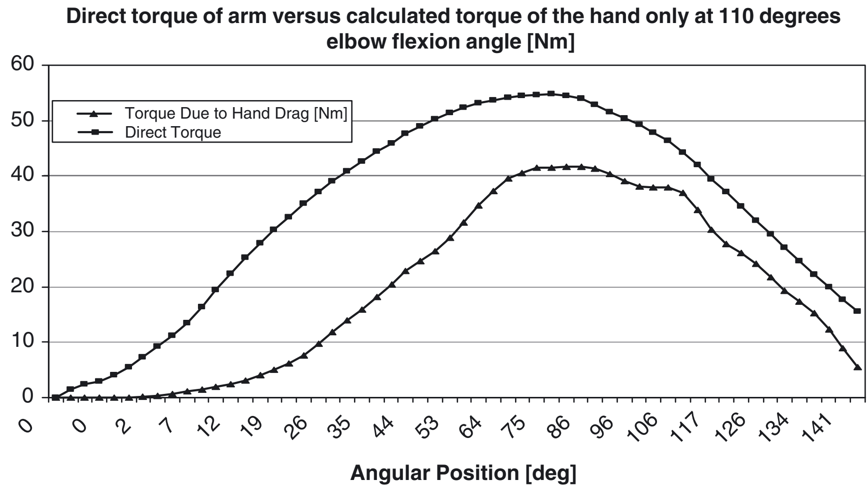

Figure 8: Direct torque versus calculated torque of the hand from Lauder and Dabnichki [8] for 110° elbow angle, illustrating the underestimation of the torque using the quasi-static approach.

Differences in torque profiles for the quasi-static approach and the direct measurement of shoulder torque (Figure 8) indicated that the quasi-static approach might greatly under estimate the hydrodynamic forces acting on the arm during swimming. The results showed that the relative contribution of the hand to the propulsive force is dependent on the arm configuration. They cast some doubt on the widely shared assumption that the swimmers' hand is always the main contributor to the propulsive force. Due to such an advance in the application of technology to the analysis of technique in swimming, the theoretical underpinnings of propulsive force estimation have been re-written.

Work has been taken further forward with the advances in computational ability. Very recently the use of Computational Fluid Dynamics (CFD) to model the propulsive forces generated by the hand and forearm has been introduced [55]. This approach offers some benefits in terms of the ability to run a number of simulations, which otherwise might be costly through experimental techniques. However, the problem of simulating unsteady flow conditions remains. Bixler and Riewald [55] replicated force coefficients for the hand and forearm that had been determined experimentally [7, 43], an important first step in the use of CFD techniques to solve the problem, but concede that simulation of unsteady flow conditions presents a greater challenge.

This challenge has been addressed in some part by Gardano and Dabnichki [47] in a paper that addresses the estimation of added mass effects due to acceleration of the arm in swimming. The authors adopted a Boundary Element Method to solve Laplace's equation resulting in a much quicker way to solving hydrodynamic problems than CFD techniques. The results showed good agreement between the calculated drag profiles and the direct drag profiles from Lauder and Dabnichki [8].

2.4 Swimming summary

In summary, motion analysis in swimming has been slow to implement the technologies that have become available to the single media researcher. There has been recent work validating and improving the application of kinematic techniques to the analysis of swimming technique, but this work has also led to the re-evaluation of the mechanisms of propulsion in swimming. Since Counsilman's observation of an 's' shaped pull pattern in 1971 through motion analysis and the subsequent theory applied to lift and drag force generation, it has been over 30 years until the technology has been applied to re-evaluate this problem. Work is on-going in this area as researchers establish the importance of added mass effects and the acceleration of the arm. The problem remains though; the barrier to research due to the environment in which the activity takes place.

3 Technology in kayaking research

3.1 Introduction

The origins of the kayak date back more than 4000 years [56]. Now a range of disciplines undertaken by paddlers is evident and include white water, slalom and flat-water. Again due to the nature of the environment, there is little technology applied to the analysis of slalom and white water kayaking, with scientific analysis usually taking the form of simple timing of phases of activity based on strokes and entry/exit from gates. The flat-water event however has received some scientific attention and will form the focus of this section.

Flat water kayaking involves many different events ranging from a 200 m sprint to a 26 mile marathon. In all events the paddler must simultaneously balance the boat while applying force to the paddle in order to propel themselves and the boat forward. Technology has been able to assist in the understanding of what makes this process efficient in two ways; through a kinematic analysis or through a kinetic analysis (in some cases, both approaches have been applied). Technological advances have allowed research to develop in the areas of kayaking technique [57–59], paddle design [58] and on-water force analysis [60].

3.2 Analysis by film

Kayak technique has been greatly influenced by the change in paddle design from a flat blade to a wing blade. The technique has had to adapt to incorporate the principles of the new blade. Kerwin *et al* [58], Sanders and Kendal [61] and Sanders and Baker [62] all identified that the blade is moved laterally away from the centre line of the boat after entering the water, as opposed to the flat blade being pulled parallel but opposite to the direction of travel.

Average boat velocity is a key determinant of success in kayaking. Kendal and Sanders [63] found that the average velocity ranged between 4.63 and 5.38 m s^{-1}. With high-speed cameras (100 Hz) it was possible to also identify that the two sides of the body did not elicit the same velocity profiles, indicating that the forces produced by the kayaker may be asymmetrical. Asymmetry in the kayak stroke has also been highlighted by Lovell and Lauder [64] in a study investigating the relationship between the incidence of injury and stroke asymmetry. Asymmetry in this instance was measured using an instrumented kayak ergometer.

An early study by Plagenhoef [57] was one of the first attempts to quantify technique. Using cine film, Plagenhoef [57] collected footage from a side-on view at film speeds from 64 to 100 frames per second. From the footage the joint centres and the absolute motion of the paddle was measured, using the cockpit and kayak lengths to establish scale. Plagenhoef [57] identified that during performance an increase in stroke rate was not the influential aspect of improving velocity and that instead it was a smooth rhythmical stroke that allowed the greatest force to be applied through the blade on to the water, resulting in a higher constant velocity.

Sanders and Kendal [61] investigated the differences in technique between elite and novice paddlers using the wing paddle. Using three-dimensional footage at 100 Hz, the trajectories of the joint centres from the hip and above and the motion of the paddle were measured. The results showed that the most important factor in determining average boat velocity and ability level was the stroke rate. They also showed that the determining factor between elite and novice paddlers was that the elite paddlers exhibited a much shorter glide and pull time than the novice paddlers. By applying a two-dimensional kinematic analysis to the stroke cycle in sprint kayaking, it was possible to show how elite paddlers produce a faster stroke rate by reducing the pull and glide phases of the stroke. Such work has also been supported by Kerwin *et al* [58] who, using a three-dimensional on-water analysis, identified that an increased paddle rate resulted in increased average boat velocity.

Technology in sprint kayak research has primarily been used as a tool to be incorporated into the coaching of race tactics [65] and kayaking technique [60]. Lauder *et al* [65] presented a simple approach to the analysis of key events in kayaking. The simplest form of notational analysis is the recording of the sequence, position and frequency of events. An 'event' is simply any object or happening of interest. Computer systems can be used to gain such information and since digital video technology and multimedia applications are now a reasonably mature technology, it is possible to develop a bespoke application to log and analyse simple notational data. For Sports Scientists, such an application is particularly useful outside the laboratory environment where speed of delivery and accuracy are two very important factors in the feedback process. In sprint kayaking (and rowing), stroke frequency and stoke length are important factors that coaches use to analyse and monitor performance. There exist simple measures of each; however there is a need, particularly at a top level, for quick and accurate measures of these factors.

The highest quality video images are obtained from equipment that conforms to the component signal standard. Such equipment is very costly and it is prohibitive to many. The availability of VHS, S-VHS and Mini DV digital video formats is widespread and cost continues to fall. Domestic video equipment provides the user with position information by using the frame interval signal on the tape to index an internal counter. This value, as it is a simple counter, resets whenever the tape is removed and is not considered a viable option for recording time. Many video recording devices, for example the Panasonic 7350 (IA-232 TC Interface), use one of the audio signal tracks to write a time code signal to the videotape. This signal is permanent, or absolute, and so can be used to find video sequences even if the tape is removed from the VCR. In a digital package the software uses the frame as the unit of time (i.e. 0.04 second increments at 25 Hz and 0.02 second increments at 50 Hz). This approach is important due to the ease of downloading digital.

The basic package developed was an integrated system, comprising various software and hardware components. The desktop VHS/S-VHS package incorporated the interfacing of a Panasonic AG-7350 through an RS232 serial port, technology that is available to most sport science laboratories. A video desktop was accomplished using a capture board utilizing the Microsoft Windows Multimedia Application Programming Interface (MMAPI). The interface allowed the full control of the VCR thus enabling a hands-free approach in identifying and recording clips.

The digital package used by the British Canoe Union Sprint Kayak Squad utilizes the IEEE 1394 interface built into the Sony range of VAIO notebook PCs and a MiniDV camcorder. Replay of video (AVI) files was achieved digitally via a custom Multimedia player designed in house. This system allowed the de-interlacing of 25 Hz video frames into separate 50 Hz fields.

The desktop VHS/S-VHS notation package had a three-tier approach. It allowed the user to identify and mark clips of interest (ten), name events (25 per clip) of interest and record the occurrence of these events (2 billion for each event) at the speed of playback desired (Figure 9). The programme then allowed the user to plot the frequency data or export the data for further analysis (Excel). Figure 10 illustrates the screen for the graphical output within the package while Figure 11 illustrates is a screen shot of the desktop package itself. The desktop package also allowed clips to be captured and stored to the hard drive for feedback purposes and for clips to be captured for two-dimensional digitization.

The digital package, used by the BCU, offered a more specific application. This package allowed any number clips to be stored (to hard drive) and accessed for analysis. There was only one event option in this package, which gave a direct measure of stroke frequency. The recording of an event was achieved by clicking anywhere on the image, this making it easy to analyse and record specific events.

Figure 12 illustrates the screen for the DV package. The graph of stroke frequency was reconstructed on the screen as the analysis progressed. Once the

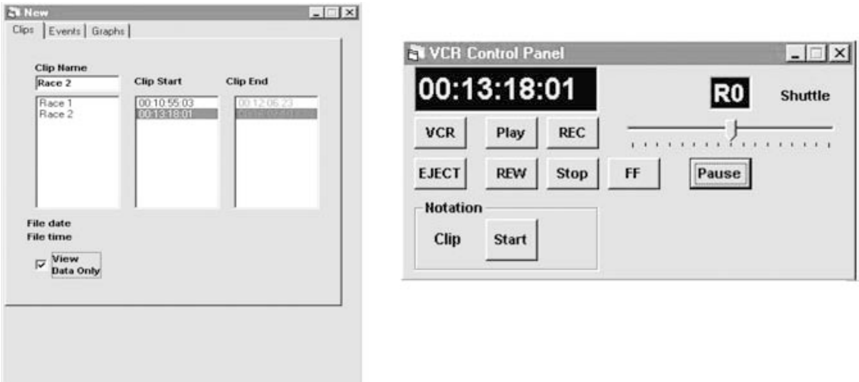

Figure 9: Control screens for notational analysis package.

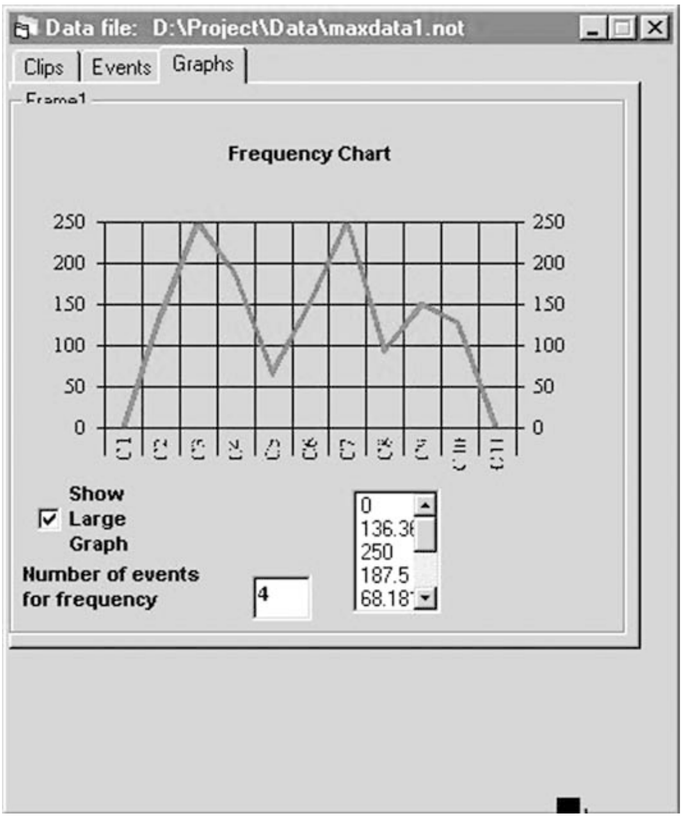

Figure 10: Example of screen window for frequency graphs.

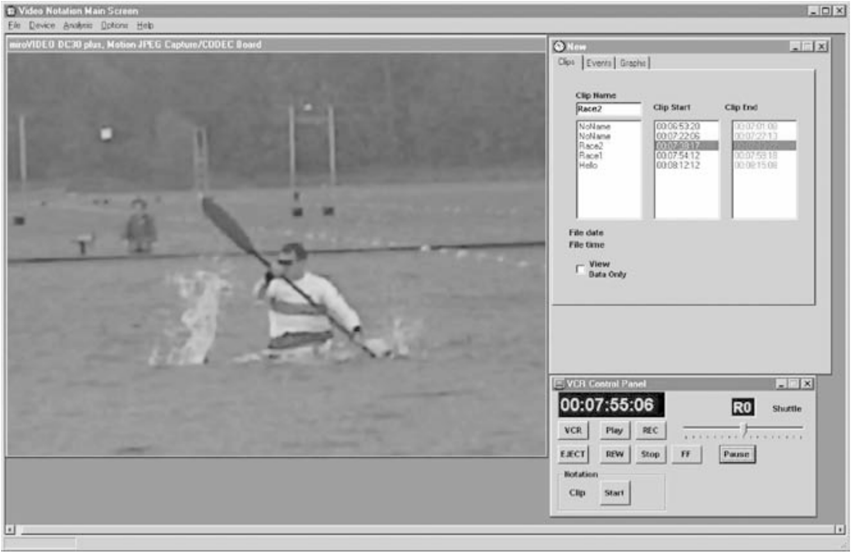

Figure 11: Screen shot of desktop package.

Figure 12: Screen shot of DV package.

analysis was complete, there was the option to change the number of samples over which stroke frequency was calculated. The data was then linked to the video clip analysed and to an athlete profile. The latter option allowed profiles of different races to be compared. Although a simple approach, many sports utilize bespoke analysis packages to gain valuable information relating to performance. As technology has progressed, so has the ability to provide real-time data relating to the event. Such advances have no-doubt contributed to a better understanding of performance by the athletes and coaches.

From a coaching perspective and in an attempt to look at the differences between male and female paddlers Baker *et al* [59] analysed ten national level paddlers (six male, four female) using a three-dimensional kinematic analysis at 50 Hz. Baker *et al* [59] analysed left and right sides looking at intra-stroke velocities, timing and displacement measures, two and three dimensional measures of the entry and exit angles, and trunk rotation (represented by shoulder rotation). The findings indicated that there was a significant difference between males and females in velocity and intra-stroke velocity resulting in a significant difference in distance covered during stroke and glide. No difference in spatial parameters however highlighted that male and female techniques were similar and therefore there was no need to coach males and females differently.

With any kinematic analysis in kayaking, perhaps the most important factor to be considered is the accuracy and reliability of the kinematic reconstruction. For two-dimensional analysis it is possible to use the kayak itself as the calibration length. It is necessary to follow two-dimensional set-up procedures [37] in order to maximize the accuracy of the two-dimensional kinematic data, but such analyses have been conducted successfully [62]. Three-dimensional analysis provides a different problem as there is a need for a calibration object in the field of view. Kerwin *et al* [58] used fixed cameras and calibration markers in the field of view, but not in the line of the kayaking action. They reported limited results, however showed their reconstruction technique to be accurate in reconstructing upper body three-dimensional profiles. Hay and Kaya [66] used a fixed camera on a motor boat that ran alongside the kayaker to elicit kinematic data. While this allows a number of strokes to be analysed, the data is limited to two-dimensional parameters. For a three-dimensional analysis a calibration frame is required. Figure 13 illustrates a floating calibration frame (5 m × 2.5 m × 1.8 m), which allows a complete stroke to be captured within the volume. The calibration frame illustrated can be positioned on the water in the area where the action will occur, a key requirement of a three-dimensional calibration set-up.

On-water kinematic analysis of techniques presents similar problems for the research as underwater kinematic analysis. The environment presents the researcher with problems of camera location and calibration techniques. Often, specialist equipment set-ups are required, particularly if three-dimensional analysis is to be undertaken. These problems can and have been overcome, but there are very few researchers working in this area, not through lack of interest, but more so through the barrier due to water.

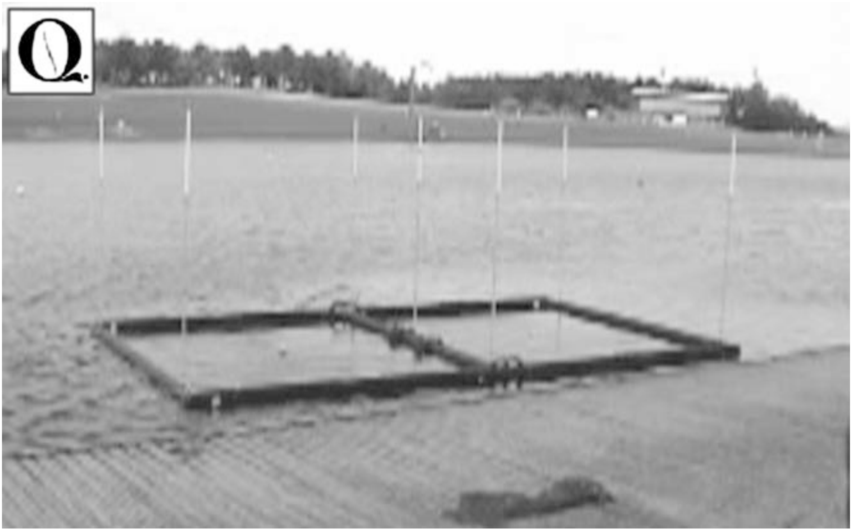

Figure 13: Illustration of a floating three-dimensional calibration frame used in kayaking research.

3.3 Kinetic analysis techniques

Asymmetry is clearly an important aspect of many water-based activities where a cyclic action is most efficient for performance. Perhaps the most direct way to analyse asymmetry is by the measurement of forces. In kayaking, the active force is delivered by the working muscles to the paddle. Efficient technique is dependent on the skill of the performer to return the propulsive force from the paddle to the boat. It is for this reason that the link between the paddle and the boat is an essential factor of performance. The force applied to the kayak has not yet been reported in the literature. Technology such as pressure mats and instrumented footplates could in theory measure this. Paddle forces however have been recorded, with instrumented paddles being used in research and applied practice.

Logan *et al* [67] investigated the force production characteristics during on-water paddling and simple land based resistance training exercises. Complete stroke profiles of eight paddlers completing trials over 100 and 1000 m were compared to force characteristics produced during a series of resistance training exercises. Although similar force traces were shown to exist, Logan *et al* [67] concluded that further analysis was required of more specific resistance exercises in order to test the strength capabilities of flat-water sprint kayakers.

Aitken and Neal [60] also investigated the forces produced during on water performance through the use of Wheatstone bridges within the shaft of the

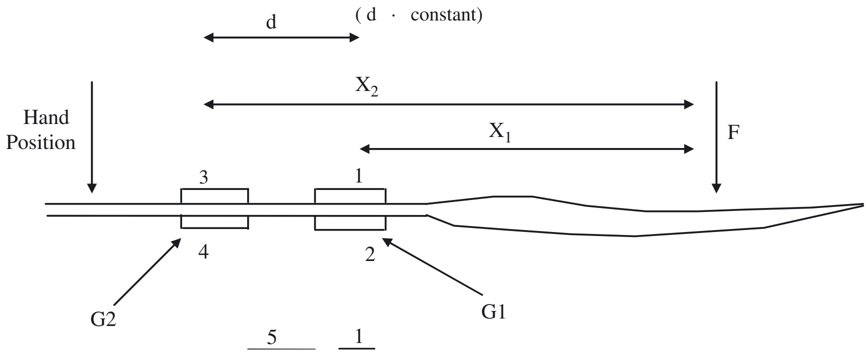

Figure 14: Arrangement of Wheatstone bridges to measure paddle forces (gauges 1 and 3 measure elongation and gauges 2 and 4 measure compression).

paddle. These were placed at each end of the paddle between the point of force application of the hand and the blade of the paddle (Figure 14) as a tool for measuring performance. Calibration was by static loading of the paddle using weights between 50 N and 300 N. Subjects' own paddles were used and each was calibrated separately. The calibrated paddles were used to record force profiles from sub-elite paddlers during a 500 m sprint race.

The instrumented paddles were used to report mean peak force, impulse, time-to-peak force and wet time of the paddle for both the right and left blades. Peak forces were in the region of 210 N for left and right sides and the data was shown to be reliable. It was reported that the instrumented paddle was a useful tool for analyzing the force characteristics and for coaching of kayak paddlers. Unfortunately such technology for on-water analysis is not real-time, so the retrospective nature of the feedback is somewhat limited. With developments in video goggles, such as those used by the Australian Institute of Sport in rowing, it may not be long before kinetic information is relayed to the performer along with video images of their technique.

3.4 Using electromyography as feedback in kayaking

Electromyography is a method of analysis where technological advances have allowed researchers to gain a clearer insight in to technique in kayaking. Tokuhara *et al* [68] attempted to identify the effects of using electromyographic feedback on kayak arm pull movement. Fourteen male paddlers were used all with 2 to 3 years paddling experience, grouped into a control group ($n = 7$) and a feedback group ($n = 7$). Each subject undertook pre testing and posting testing consisting of a seated arm pull which included trunk rotation and leg extension in an attempt to imitate paddling technique and a standing arm pull, during which the activation of the posterior aspect of the deltoid, the long head of the biceps brachii, the brachialis and the lateral head of the triceps brachii were measured. The arm pulls were all carried out through an isometric contraction in conjunction with a dynamometer for force measurement. All subjects were required to train 20 days over the 6 weeks following pre testing during which the standing and seated isometric arm pulls were carried out twice in addition to the subjects' usual training regime, with the feedback group being given continuous information of their performance throughout the training.

4 Summary

Clearly the barrier due to water presents researchers with an immovable obstruction in their quest for knowledge in water-based sports. Advances in technology do allow research to move forward in this area, but progress has been slow. There have been many challenges that have been overcome, however it is clear that there is more work to be done to explain the mechanisms that underpin movement through the medium of water and the effects that this has on the movement of the water itself and any efficiencies that might be gained from it [69].

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4. Data Acquisition/Analysis/Data Bases/IT/ Pervasive Computing

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Sensors and ubiquitous computing technologies in sports

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Abstract

Sensors and other ubiquitous computing technologies have slowly penetrated the arena of sports. As a field, ubiquitous computing has learned a great deal about sensors and how to embed them in everyday objects. Accelerometers, gyroscopes, microphones and cameras all lend themselves nicely to various applications in sports. Here we examine some examples of pervasive technology in sports and points to future directions. This article consists of two parts. First, we outline trends and implications of utilizing sensors in sports. Second, we examine technological challenges in introducing sensors in various sports, in particular paying attention to our own research case study on introducing force sensors into a martial art competition.

Keywords: sensors, ubiquitous computing, wearable computing, user interfaces, ergonomics, wireless computing, extreme sports, taekwondo, usability of wearable wireless systems

1 Introduction

The development of sports throughout history has been essential to our health and is keeping us strong physically, mentally and spiritually. Sports not only enhances our mind, body and spirit, but as a social activity, also helps us feel connected to the rest of the community. In its manifestation in the spirit of the Olympics Games, it promotes peace and increases contact between different cultures and people. The benefit and importance of sports cannot be overemphasized.

Here we focus on the application of sensors and ubiquitous computing technology to enhance sports. Recent results are quite encouraging. As a field, ubiquitous computing has learned a great deal about sensors and how to embed them in everyday objects. Accelerometers, gyroscopes, microphones and cameras all lend themselves nicely to various applications in sports. For example, accelerometers can be used to detect activities that generate unique motions, while gyroscopes can be used to measure changes in orientation. New computer vision algorithms are enabling researchers to not only analyse the motions of a single player, but also analyse the patterns of a group of players simultaneously. For example, Stephen Intille at MIT has explored the use of contextual information to track multiple football players in video clips of plays. Knowledge about the rules of football enables the disambiguation of colliding players.

One of our hopes is that technology will make sports more entertaining for players and encourage the general public to exercise more than they do currently. Certainly, the video game ‘Dance Dance Revolution’ must have had an effect on the amount of calories burned during gaming, especially since gaming is otherwise a rather sedentary activity. Indeed, if we can make couch potatoes exercise while playing video games, we might very well be creating a new research endeavour to solve obesity problems in the world.

These new results and a growing interest and demand for better technology for supporting sports activities have spawned a wide variety of new research areas. For example, a pioneering workshop at the UbiComp 2005 conference organized by Intel researchers Elizabeth Goodman, Brooke Foucault and Sunny Consolvo examined various issues of applying technology in sports.

These new technologies can deal with the possibilities of enhancing the experiences for players, spectators or judges in sports in several different ways:

(1) We need research that helps us understand how ubiquitous computing techniques could be used to change the game for the better, sense and monitor practices or matches, assist in training and enhance the experience for spectators.
(2) Technologies could be developed for a wide range of areas in sports, including single-player, multiplayer and large team sports as well as activities ranging from track and field to indoor team sports.
(3) Research and technological explorations could be conducted in a wide range of aspects in introducing pervasive technology into a sport, including reports on the challenges of integration, deployment and usage experience.

What is needed to move this forward is solid research presenting case studies and lessons learned, so that other technologists interested in this area could learn from both successes and mistakes made by other pioneers in this area.

This article consists of two parts. First, we outline trends and implications of utilizing sensors in sports. Second, we examine technological challenges in introducing sensors in various sports, in particular paying attention to our own research case study on introducing force sensors into martial art competitions.

2 Trends and implications of utilizing sensors in sports

First, we review and outline some of the trends and implications of utilizing sensors in sports [1]. Our goal is to encourage and highlight new research in this new emerging area, and to spike everyone’s interest in understanding how technology can be applied to sports.

2.1 Improving sports performance and learning

The history of sensors in sports performance studies is actually littered with success stories in the recent past. Golf clubs have been instrumental in offering a computer analysis of one's swing for example [2]. Runners have been using heart rate monitors to keep track of their training progress.

Wijnalda *et al* [3] at Philips Research in the Netherlands present a research product for personalizing music selections based on heart rate monitors and the ubiquitous MP3 players. The idea is both simple and elegant. By monitoring runners' heart rate before, during, and after exercise, a unique personal training program can be constructed automatically. The IM4Sports system helps users in selecting songs that fit a training program, and can dynamically change playback to guide the runner. During training, the tempo of the songs can be modified to suit the speed of the runner. It is obvious that this research has an immediate appeal in the market by making training programs not only more enjoyable but also more effective.

Researchers in this area continue to innovate on new ways to understand human performance in sports. For example, Dr. Joan Vickers at the University of Calgary have been examining neuro-motor psychology by understanding the gaze of the athletes while they perform specific sports skills using a helmet-mounted eyetracker [4].

There is also research into wearable sensor devices that enhance sport performance and training. Michahelles and Schiele [5] present the application of wearable sensors to downhill skiing. By embedding various sensors on the clothing and ski boots, the system reveals information about the athlete's motions, such as forces, rotations or accelerations. This presents a huge improvement in the quality of data that could only be partially obtained from video analysis previously. By working with trainers and former World Cup coaches, they are developing data visualization software that presents measured sensor data alongside reference videos.

Sports technology, of course, is not limited to enhancing performance, but potentially also to rehabilitation and prevention of injury. For example, in a recent article in *IEEE Spectrum*, high-tech prosthetics enabled double-leg amputee Oscar Pistorius to run nearly as fast as able-bodied athletes, raising the question regarding whether the Olympic Games will allow athletes with running prostheses to compete in the future [6].

It is not hard to imagine that almost any sport can benefit from both equipment enhancements and novel measurement and analysis of athletes' performance. From popular sports such as golf, baseball and basketball to extreme sports such as snowboarding, motorcross racing and rock climbing, athletes could all benefit from better understanding of their muscle movements, orientation and heart rate response.

The research question here is not to instrument everything on the human body, but rather the understanding of what are the most appropriate sensors and how they should be used. 'Appropriate' here means how to enhance players so that they want to use sensors for their own training, enable unobtrusive instrumentation so that coaches can analyse the best data available, and cooperate with judges to make good calls on the field with social acceptance.

2.2 Leisure and entertainment

In addition to enhancing performance and learning, the field of sports is closely tied to the availability of leisure time and desire for entertainment. There are two possibilities for technology in sports entertainment. First is the use of sports technology in participatory games. For example, game arcades have already incorporated various technologies into soccer balls, golf clubs, baseball bats, motorcycles and boxing gloves to make sport games more entertaining. There are also companies such as Laser Quest [7] who are creating innovative new games from laser tag equipment, such as the team mission game of protecting the queen bee. Laser tag games can be every bit as exhausting as professional sports. Fitness clubs have started to incorporate video games into their exercise equipments. For example, Life Fitness' Lifecycle had been connected to a Super Nintendo. The faster you pedal, the faster the counterpart on the video game screen goes [8]. Here the user is encouraged by the game to pedal harder.

The second possibility is to use technology to enhance spectators' enjoyment of sports. Major tournaments now measure the speed of tennis serves, for example, to satisfy spectator's curiosity of what it might be like to receive such serves. Beetz *et al* present a novel system built by Cairos Technologies and Fraunhofer IIS in Germany for tracking not only the soccer ball on the field, but also the players [9, 10]. By embedding microwave transmitters into the ball and shin guards of footballers, they are analysing game data and patterns to enhance understanding of game strategy, coaching of players and entertaining of spectators. The coin-sized transmitters broadcast signals to receivers placed on floodlight masts and sidelines. A central computer calculates the exact location from these pulsed signals, much like the way the Global Positioning Systems work. With balls and players instrumented, spectators and coaches will be able to know the speed of a shot, whether the ball passed the goal line, or who ran the fastest.

On the other hand, TV viewers rejected the use of the highlighted trails of hockey pucks during live broadcasts of National Hockey League games. These pucks were instrumented with 20 infrared emitters, and sensors around the rink picked up the infrared signals to track the puck [11]. Fans hated the trails and the pucks were eventually pulled. It has been less than clear how to design technology for spectator enjoyment. The key appears to be balancing the tradition, distraction, and satisfying spectator curiosity. Spectators enjoy the total immersion in watching live sports. Technologies should be introduced to assist in this immersion rather than to break it.

2.3 Interaction with sports authorities

Indeed, the acceptance of a technology interacts not only with spectators but also with sports governing bodies. Modifications to golf balls, clubs and other equipments are now heavily regulated by the United States Golf Association.

The so-called ‘dimple wars’ in the 1970s ignited such controversy that, for a while, people were afraid ‘old’ golf courses would become obsolete. As another example, modifications to bicycle design have been severely restricted with several new fast recumbent-type designs rejected for international competition [12]. However, after some wrangling in 1984, cycling federation officials allowed disk wheels to be used in cycling events. Other controversial technologies include the Cyclop tennis line-calling system and its acceptance by players. In most cases, sports governing bodies are reluctant to adopt new standards for equipments and new technologies. Indeed, in many cases, the rules themselves need to be changed to accommodate the new technology.

Occasionally, however, governing bodies can themselves be the catalyst for change. For example, in a recent rule change, the World Taekwondo Federation states that the number of scoring judges around the competition ring shall be reduced to two from four when the competition includes the use of new force-sensing electronic chest protectors. Interestingly enough, these new chest protectors are not yet even available on the market, so the governing organization has been one step ahead of the technologists.

As a unique challenge of working with sports technology, developers of new ubiquitous computing devices for sports would do well to learn from others who have tried to transfer new technology into sports. In extreme cases, changes to the sport equipments can actually alter the ideal body type for a sport. We need to understand how a particular technology affects the game and whether it enhances athlete performance at the expense of creative expression. Indeed, in introducing new technology into a sport, there is a fine balance between completely eliminating the human factor in competition vs. enhancing the expression of fitness and technique.

3 Technological challenges in introducing sensors in sports

As the above researches show, there will be enormous implications if these sensor technologies are adopted in sports in the future. It can help runners train better, allow coaches to understand their athletes’ performance on the football field, enable ski trainers to design better programs for learning precise muscle movements and help judges score more accurately in a Taekwondo match.

Dario Salvucci of Drexel University suggested to the author that Jean Scholtz and Sunny Consolvo’s recent work on an evaluation framework for ubiquitous computing applications [13] might be fruitful for analysing the sensors and ubiquitous computing technologies in sports. Scholtz and Consolvo’s paper suggests nine evaluation areas that are worth examining in understanding a ubiquitous computing area: *attention, adoption, trust, conceptual models, interaction, invisibility, impact, appeal* and *application robustness*.

For each of these areas, they also suggested a set of metrics for understanding how these areas might be evaluated. There are a total of 34 different metrics under these nine areas. Here we take a subset of these metrics and apply them to a variety of sports technology. We chose a subset of these metrics that are the most appropriate for sports technology. While other metrics would have been interesting to examine, space constraints in this paper would prohibit a meaningful analysis of all 34 metrics. Salvucci applied these metrics to these sports and made rough guesses at these measures, which we report there with more detail. These metrics and measurement serve as a guide rather than a conclusive evaluation of these systems.

3.1 Bowling foul-line detector

In the game of bowling, a simple foul line system has been used for detecting when a player steps over the line, which results in a beep (see Figure 1). Moreover, the system also automatically counts the pins and scores the game. An interesting bit of trivia is that, as a new start-up in Silicon Valley, Hewlett Packard tried to sell a bowling foul-line indicator as far back as 1938.

This technology is a poster child for excellent adoption of a sensor system into a sport. The systems are everywhere, and they are extremely accurate. Players understand how they work and can easily predict its behaviour. Because the beep occurs after the players have already released their ball, they require no behavioural changes and they are not distracting. Socially, they are as much part of the sport as any other part of the bowling alley. Table 1 summarizes its advantages when evaluated using the simplified framework.

3.2 Cyclops auto serve line detector for tennis

A system with very similar functionality called Cyclops has been in use at major tournaments since the 1990s. Cyclops detects whether serves are 'in' or 'long'(see Figure 2). They are not used for the detection of 'wide' serves, and are

Figure 1: Bowling Foul-Line Detector is widely accepted at various bowling alleys around the world. (http://www.korea.army.mil/pao/hwarang4/photos/22%20August/bowling.jpg)

Table 1: Three sports technologies evaluated using the framework proposed by Scholtz and Consolvo.

	Bowling foul-line detector	Tennis cyclops	Baseball QuesTech
Adoption rate/value	✓	–	–
Accuracy	✓	✓	✓
Predictability	✓	✓	✓
Aware of capability	✓	✓	✓
Distraction	✓	–	–
Behavior changes	✓	✓	✗
Social acceptance	✓	–	✗

Adopted from Salvucci's discussion slides [14].

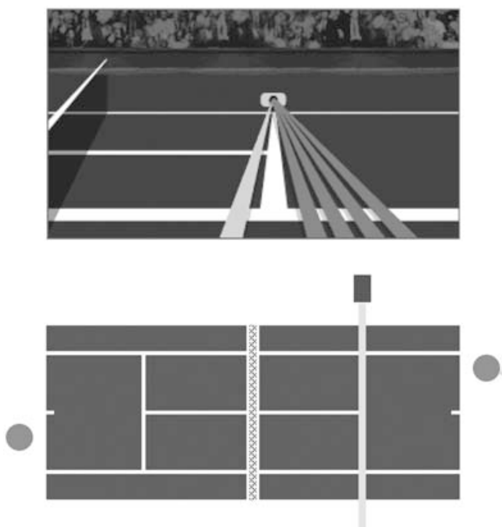

Figure 2: The tennis Cyclops system is used to call 'in' or 'long' during service for only one line on the whole court. (http://newsimg.bbc.co.uk/media/images/39180000/gif/_39180948_cyclops_298.gif)

only used for serves, and can be overruled by the umpire. Its use has created quite a stir when it was first introduced, but eventually won reluctant acceptance.

Cyclops systems are quite accurate and consistent in its detections, and it is easy to understand how it is used. Despite having these characteristics similar to those of the bowling foul-line detector, Cyclops has won only limited adoption. While the system does not directly change players' serves or the strategies of the receiving players, the problem is that it is distracting. The beep occurs just before the receiving player is about to strike the ball. This breaks both players' concentration and focus and, therefore, has won limited social acceptance. Table 1 above summarizes these points.

More ergonomic studies of the beep and its effect on players are needed, and we might yet have to find a more optimal timing for the beep. For example, ensuring the beep occurs after the receiving player has returned the ball might minimize the distraction effect.

3.3 QuesTec system for video analysis of balls/strikes in baseball

A huge dispute over the QuesTec system for video analysis of balls/strikes was at the centre of the labour negotiations between Major League Baseball and its umpires (see Figure 3). This dispute was not settled until recently [15], and is still subject to ratification. It has been installed at 10 of the 30 major league stadiums, and baseball officials have used the system to grade the performance of umpires. "If an umpire's calls disagree with the computer's more than 10 percent of the time, his performance will be considered substandard and possibly held against him in future promotion considerations and when lucrative post-season assignments are made. The umpires are, naturally, freaked out by QuesTec…." [16].

Players are just as unhappy about the system. Arizona Diamondbacks ace Curt Schilling was fined for smashing a QuesTec camera after being told umpires are "changing their strike zones to match the machine" [17]. Atlanta reliever Darren Holmes was quoted as saying that "this system is one of the worst things that has happened in baseball" [17].

Despite the fact that players and umpires understand how the system works, it has proven to be a major distraction for hitters and pitchers alike.

The reason is because QuesTec forced definitive behavioural changes. First, umpires changed their strike zones in order to conform to QuesTec's zones. Second, the pitchers, therefore, had to deliver pitches to the new zones and modify their mix of pitches. Third, the hitters must also adjust to the new strike zones and new styles of pitching. These chain effects resulted in extremely poor social acceptance of the technology.

Despite being proven as being fairly accurate and consistent, the system is only installed in some parks, and not others, resulting in further inconsistencies across the league.

We analysed the criteria for the social acceptance of sports technology by players, coaches and international sports organizations. In applying an evaluation framework for ubiquitous computing technology developed by Scholtz and

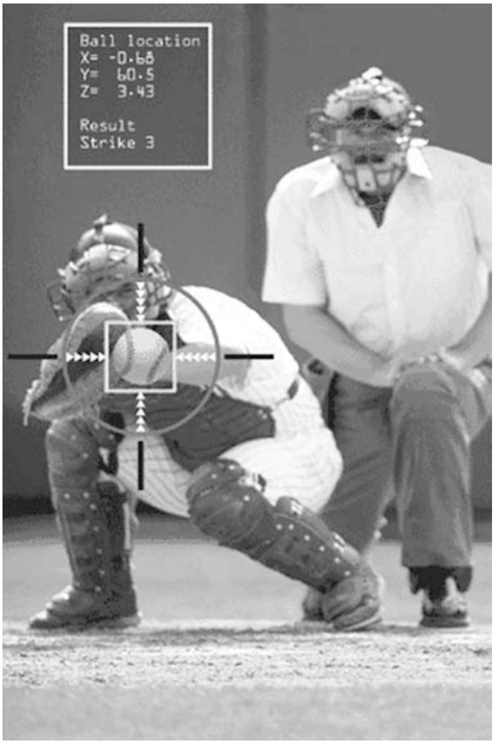

Figure 3: QuesTec video analysis system for calling balls/strikes in baseball is controversial. (http://www.isa.org/Images/InTech/2003/July/20030761.gif)

Consolvo, we note that several evaluation metrics are important, including accuracy and predictability of the technology; awareness of the technical capabilities by players, coaches and judges; the amount of behaviour changes and distraction to the players and the amount of social resistance to changes in rules or structure of the game.

Table 1 above summarizes these points.

4 Case study on force sensors in martial art competitions

Recently, we examined how force sensors could be embedded into wearable chest protectors for martial arts matches (see Figure 4). As a black belt and referee in Taekwondo myself, working with the Stanford Taekwondo Program and a Silicon Valley start-up company called Impact Measurements, we presented technical challenges in both developing the prototypes and understanding how it affects the judging of the match [18].

Figure 4: Taekwondo is an extreme full-contact sport.

Our system, called SensorHogu, uses piezoelectric force sensors on body protectors to help Taekwondo judges and referees score real tournament matches [19]. The objective is to support the judges in scoring the sparring matches accurately, while preserving the goal of merging and blending into the background of the activity.

Based on this experience, we discuss issues and roadblocks we have encountered in introducing the SensorHogu to tournament players and judges:

- First, there is the challenge of making the system work technologically without affecting the play of the game significantly.
- Second, player acceptance hinges on their perception of fairness and unobtrusiveness of the technology.
- Third, judges must be comfortable in converting to a new system of scoring.
- Lastly, rule changes are required to accommodate the use of the electronic scoring equipment. We must work with the World Taekwondo Federation (WTF) and United States Taekwondo Union (USTU) to validate and certify the equipment for tournament adoption.

Here we chronicle our experience, and then compare our experience with adoption issues that have arisen in other sports.

4.1 SensorHogu design

First, we introduce our SensorHogu design. Inducted as an official Olympic sport in 2000 Sydney Games, taekwondo has enjoyed enormous popularity in the last several decades. Because of this popularity, there has been increasing pressure to ensure fairness in judging and to make the sport more spectator-friendly.

This pressure has directly caused several changes in the rules [20], and the desire to utilize technology to ameliorate some problems inherent in judging a match. The utmost problem in achieving accurate scoring is the subjective judgment of what constitutes a valid scoring kick to the body. As defined in the rules in 2003, a scoring kick must be delivered "accurately and powerfully to the legal scoring of the body [20]." The subjective nature of this judging criterion has been a major impediment to the development of the sport, sometimes resulting in accusations of biased judges favouring players from certain countries (see, e.g. news stories at http://www.indiavarta.com/olympics/newHeadlines.asp?cat=Taekwondo: 'Never-ending protests against taekwondo judges', 'More complaints about taekwondo bias towards home team' and 'Another day of disputes in Olympic taekwondo'.).

As shown in Figure 5, the competition sport of taekwondo sparring is conducted on a square padded mat 12 metre wide on each side. The competitors,

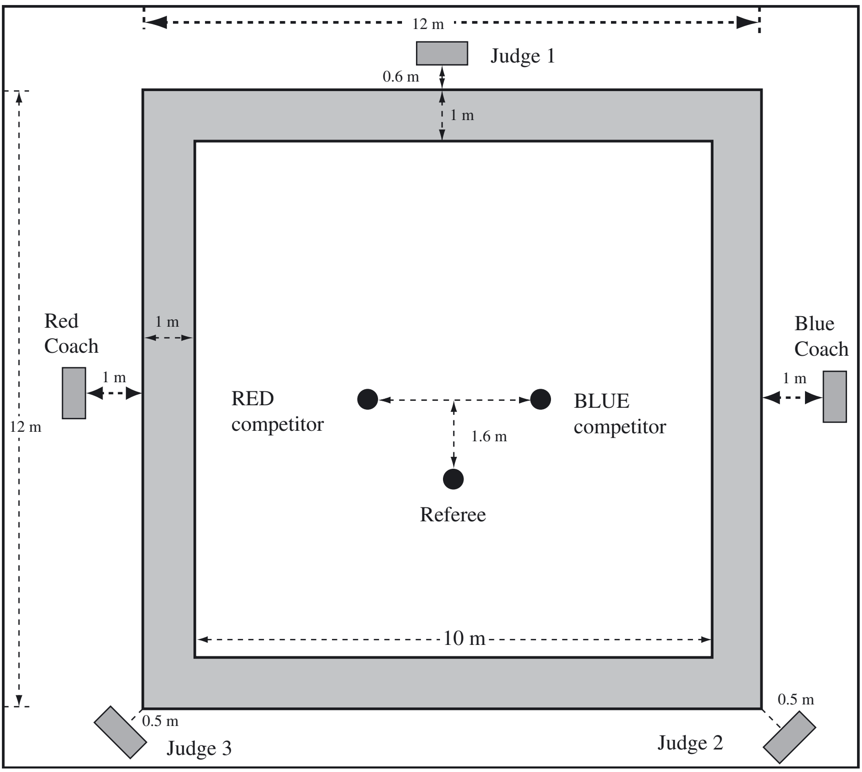

Figure 5: The competition ring of a taekwondo match consists of three judges and one referee, with 1 m attention boundary.

one wearing a blue body protector and the other red, face off against each other in a controlled environment. The competitors are moving rapidly on a large mat. There are three judges and one referee. The referee is responsible for conducting the match, while the judges are responsible for actually scoring the techniques. The judges are placed around the mat in a triangular shape, as shown in Figure 2. Existing scoring systems use wired handsets for the judges to score the points. According to existing rules for electronic scoring, a point is only awarded when at least two judges confirm it within a one-second window.

Figure 6 represents the relationships of the devices in the entire system. The system consists of a single base station that is connected to a laptop, three judges' scoring handsets and two TrueScore™ SensorHogu wireless body protectors

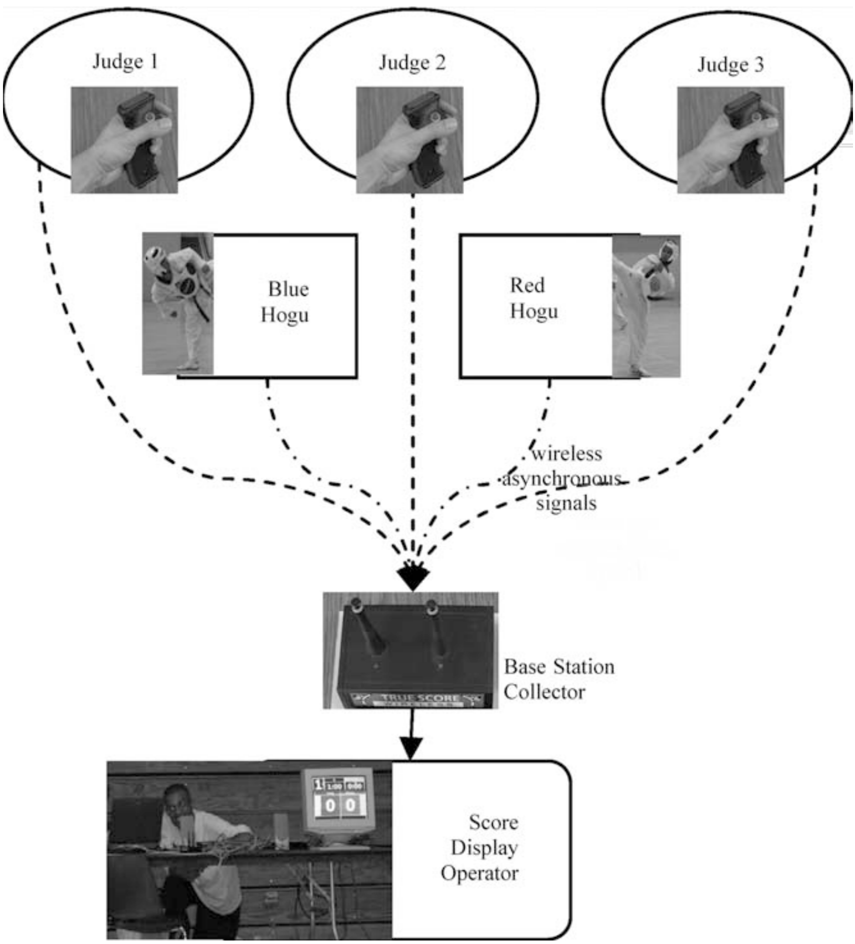

Figure 6: The overall system flowchart.

Figure 7: The SensorHogu. The wireless transmitter is taken outside of the left-shoulder protective pouch.

(Hogu is the Korean word for a body protector). SensorHogu uses piezoelectric sensors to sense the amount of force that has been delivered to a competitor's body protector, and wirelessly transmits this signal to a computer that scores and displays the point. Our hope is that the force sensors will help judges achieve greater accuracy and help eliminate controversy.

Figure 7 shows the body protector with its wireless transmitter on the upper left shoulder. For the force sensor, we needed something that is low-cost, low-powered and rugged. We did not consider employing accelerometers because of our desire to directly measure the impacting force. The most common dynamic force detector is the piezoelectric sensor. Piezo sensors' stiffness and strength make them particularly suitable in a harsh environment like a protective suit. In our application, a single long piece of piezoelectric sensor is mounted onto a plastic backing and inserted into the middle of a World Taekwondo Federation (WTF)-approved body protector. We did not instrument the facial and head area because a facial mask would obscure the player's vision, and attacks to the face are easy for the judges to score.

We developed the handset system to go along with the SensorHogus so that they all work wirelessly to the same base station. There are two handsets for each judge, one for scoring the red player on the left hand, and one for scoring the blue player on the right hand. Figure 8 shows the judge's red handset held in the left hand. As shown, there are two buttons on the handset. A trigger button scores a point for the body, and a side button scores two points for a head blow.

Figure 8: Judge's handsets are ergonomically designed to eliminate hand fatigue, because competitions often run for an entire day.

Complicating the design of the system, the events from the protector must coordinate with the scoring handsets. At least two judges must press the same button on their handsets within a one second window for the point to score.

There were numerous design goals for the SensorHogu system: easy to use, accurate, robust, secure, modular, low-cost and low-powered.

First, the system is completely wireless. In comparison, the standard foil fencing scoring system that has existed for several decades has competitors tethered [21]. The fencing system is based on electrical switches that complete a circuit when the switches touch a metal vest. The tethered set-up has limited the sport to linear forms of fencing, thus restricting the natural development of the sport. The human activity has been modified to suit the technology that was available. In comparison, SensorHogu must not only transmit contact wirelessly, but must also measure the amount of force applied.

Second, it must functions flawlessly in real time. Multiple signals from each body protector are transmitted around the same time, and the system must interpret these signals according to the rules.

Third, the whole system is designed with several criteria of robustness in mind. The devices can withstand an extremely hostile environment. It is small and secure, and can resist physical abuse and potential radio interference.

Lastly, the system is modular, low-cost and low-powered. Each device can run on two AAA-sized batteries for three or four days of competition. For modularity, each device can be individually replaced. For example, the hogu and the transmitter unit in the pouch can be replaced separately.

In summary, the SensorHogu is a novel wearable system that supports an extreme human activity. The natural next step is to test how well it works in practice and how players and judges respond to the new technology.

4.2 Players and judges trust and comfort

We believe there are two different ways to gain the trust of players and judges. First, we conducted real user testing of the system and published the results for examination [19]. Second, we performed live demonstrations at major tournaments.

The difficulty with both of these strategies is that there is a wide variety of different factors in the judgment of whether a hit is a scoring point or not. Depending on the weight division, gender and type of kicking technique used, judges modify their criterion for a point accordingly. As mentioned before, the subjective nature of the judgment of a point is one of the major reasons for the development of the SensorHogu.

For real user testing, we obtained an anatomically correct anthropomorphic dummy of a male upper torso. We outfitted the torso with the SensorHogu and asked a wide variety of taekwondo players to attack the dummy. The data were recorded and analysed for reasonable settings for the scoring threshold. The data were published in a conference paper [19]. At the same conference, we also published live footages of the system used in action, where independent judges analysed the videotapes in slow motion. For example, the analysis in Figure 9 showed that very fast kicks may falsely appear to be blocked by the arm, and the system helped in scoring these cases accurately.

For the judges' scoring handsets, we demonstrated the use of the system at a number of local tournaments first, and then gradually the system was accepted locally, nationally and internationally. Recent tournaments that used our wireless scoring handsets included US Taekwondo Union National Championships, US Junior Olympics and World University Championships. We have also demonstrated the SensorHogu scoring system at the Stanford Open 2004 tournament.

In our experience, for systems with such potentially controversial roles in determining the outcome of the matches, we must demonstrate to the players and judges the validity of the system in a wide variety of ways. Even in the large community of taekwondo practitioners, words-of-mouth reputation is extremely important for gaining the trust of players and judges.

Some details of the design played crucial roles in forming the community's opinion. For example, the handset grip is modified from industrially designed joystick grips that reduce fatigue during prolonged use. Judges really appreciated these details, as some of the earlier electronic scoring systems used cylindrical plastic handles. Players appreciated the fact that the look-and-feel of the new

Figure 9: Screenshots from the videotape of the sparring test study showing a kick to the body that would have been difficult for the judges to see clearly because of the speed.

chest protectors is exactly the same as their normal gear with little modification. We also made sure that the beep made by the system when a player scores is not distracting to the players.

Lastly, to allow the use of the SensorHogu, rule changes are necessary to use the system in tournament matches. To achieve this, we have demonstrated this technology to taekwondo officials. However, organizational changes are extremely difficult to push forward, particularly rule changes required to allow electronic scoring equipment. Fortunately, there is pressure from the Olympic committee to introduce new scoring technology in taekwondo, and we hope to introduce the system in the 2012 Olympics.

4.3 Evaluating SensorHogu technology using the framework

We were naturally concerned after understanding what happened to QuesTec systems, because like QuesTec we are trying to introduce a technology that would set the standard of the threshold the players must perform to earn a score in taekwondo. The original standard for a hit was inconsistent and poorly understood, but it was used for a long period of time and a culture of understanding had been built around the rule. Players and judges adjusted based on their own personal interpretation of the rules and the situation of the match. The inconsistencies had become part of the game. Like the QuesTec system, winning their acceptance required not only sports officials' buy-in, but also their beliefs in its accuracy and fairness. Moreover, it was important that the system does not force any unwanted behavioural changes on the part of the player or the judges. Our design mantra was 'every design is for the benefit of the players and the fairness of the game'.

At this point in the introduction of the technology, we do not know what the adoption rate will be, since it is still too early to tell. Our published data suggest that the system is consistent and fairly predictable to the judges and players, and the sensors are reliable enough to be used for fair play. Its capability is easy to understand for both players and judges. In our test matches, players performed as if the system was not there, and they have thus far not modified their behaviours or strategies while wearing the system. At this point in time, before its official introduction and sanctioning, players and judges seem to enjoy using the technology and appreciate its added value to the game. Many of these early opinions are based on reputation and inherent reliability of the system, but could change if there were to be a high-profile failure of the system. Our work is to prevent failures of this kind. Table 2 summarizes our initial evaluation of the SensorHogu system.

Interestingly enough, the audience is the third party with an indirect stake in this issue. We believe there might be value in displaying how hard someone's Hogu was hit during each encounter. This could add to the entertainment value of the system. The opaque culture of understanding on scoring thresholds would become more transparent, and easily verified.

Another interesting issue is that given that the system has no way of knowing what type of kick was used, we do not know how the system might change the kick distribution. Currently, it is not known whether judges tend to score kicks with higher degree of difficulty, even if they do not generate as much power. This is a potential area of behavioural change.

Table 2: SensorHogu evaluated against the same evaluation framework proposed by Scholtz and Consolvo. Adopted from Salvucci's discussion slides [14].

Adoption rate/value	?	– Too early to tell
Accuracy	✓	– Fairly accurate
Predictability	✓	– Fairly consistent
Aware of capability	✓	– Players/judges understand it
Distraction	✓*	– Doesn't seem distracting
Behavior changes	✓*	– Doesn't seem to affect play
Social acceptance	✓*	– Players/judges seem to enjoy it

5 Summary

As further research and discussion carry forward, more and more novel sensor technology will be introduced in different sports. As technologists, we can already see that sport is an extremely exciting field to apply our craft. Novel uses for various sensors here will further our understanding of how to embed sensors in different situations while gaining social acceptance. The benefits to players, coaches and spectators are often clear.

As our exploration with the evaluation framework above shows, there are many technological issues in adopting sensor technology in sports. Indeed, the general issue of how technology has changed the face of sports have arisen in the past, including corked baseball bats, novel special tennis rackets, special long flight golf balls and swimsuits made with low-drag material. The adoption of sensor technology is in line with prior experience with technology in general.

The broader issue is how do we want technology to augment sports and help referee sports. There are many possibilities for sensors to change various sports, such as augmenting hockey pucks with sensors and detecting pucks going over goal lines, or augmenting golf balls to better track their trajectory or augmenting footballs to better sense the last point of forward momentum. Is there a way for us to systematically understand when it works well or when it does not work too well? As the QuesTec system demonstrated, do we understand when a technology starts to 'ruin' the spirit of sports?

Researchers have envisioned a wide variety of application areas for sensors, including everyday environments such as the home or the office. Evaluators have studied the adoption of technology in these application areas, but none so far in sports. Indeed, the adoption of sensor technology in sports appears to operate on a similar set of evaluation factors when compared with other areas of ubiquitous computing. We hope this article points to future work necessary in understanding when a ubiquitous computing application has the potential for being a 'killer app'.

Besides, who can resist helping everyone be just a little healthier and better looking?

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Information technology at the Olympic Games

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Abstract

The Olympic Games are the biggest sports event worldwide. At the same time their computerized support is the most complex application of Information Technology in sports. Today there is not a single aspect of the Olympic Games, which is not supported by computer systems. The most exposed and most visible applications are sport results processing and worldwide information diffusion, however, there is a large number of other areas where computers play an important role, from events schedule planning and maintenance to the support of the Games logistics (participants' accreditation, arrival/departure, transportation, accommodation, catering, medical assistance, uniforms distribution, etc.). Software supporting all these applications consists of millions of lines of code. A huge hardware network of more than 10,000 computers and 4,000 printers attached to 900 servers (data from Athens 2004) has to be installed within a few weeks. The team which operates and supports these computer systems consists of 300–400 professionals coming from more than 30 countries and are joined by more than 2,500 local volunteers. Clearly, their opportunities to practice and work together before the Games are very limited. And all of this in an environment where there is an absolute deadline and just one chance to get it right. This paper describes the key functions of the Olympic Games computerized support, how different systems are designed and implemented and the challenges that are facing future Games organizers and their Information Technology providers.

Keywords: timing and scoring, results processing, information diffusion, scoreboards and video-boards, CIS-TV commentators system, press agencies, internet, print distribution, accreditation, transportation, uniforms, medical, volunteers, network, interfaces, security, back-up, testing, ORIS

1 Introduction

Computers are used from the first step in the Olympic Games preparations as a tool for venue construction planning and follow up, for Games event schedule planning, for the ordering of required sports and technology equipment, for ticket sales, for planning personnel who will organize the games, for defining registration and the selection of volunteers, etc.

All of these tasks, as well as detailed planning of arrivals/departures, transportation, accommodation and catering for sport delegations, media and officials are supported with appropriate software solutions.

Before the Olympic Games actually begin, data concerning all participants – athletes, media reporting from the Games, officials and games organizers – are entered into the so called "registration data bases" which are used for different purposes, mainly in the logistics areas. One of those is the "accreditation process" during which participants receive credentials (accreditation badge) that allows them to access those zones of venues, media centres and accommodation sites that correspond to their function.

Once the Games begin, computers installed at all venues process the data that are acquired from electronic interfaces with timing, scoring and the judges' devices. Within hundredths of a second, results are processed and disseminated to the huge network of computers for display on scoreboards, insertion into the live TV signal, and for the update of the Internet servers hosting Olympic web sites, relaying them in real time to servers of the major News Press Agencies, etc.

At the same time, results are updated in the Games Information data base, from where media and other users can retrieve them from the so called "INFO" work stations installed at all venues, media centres and accommodation sites. This system is also a basic source of information about athletes, their past achievements, flash quotes and a number of other data prepared and maintained by the Olympic News Service (ONS).

It is true that most of these computer applications are also used in other areas of human activities, and at some other sport events. But what makes implementing them at the Olympic Games so different and unique?

- quite a few of these computer applications are extremely "mission critical", have an absolute deadline, have worldwide visibility and have no "second chance" if something were to go wrong
- competitions at the Summer Olympic Games are organized into 38 sport disciplines at 40–50 venues, and during each of 16 days results systems support must be provided to an average of 25 of them at the same time (in parallel)
- it is difficult to find any other situation where such a large quantity of equipment – more than 10,500 workstations, 4,000 printers, 900 servers, 300 routers and 2,000 switches – located at almost 100 different locations – must be installed in a few weeks; and once the Games begin all of this hardware has to function perfectly
- there is a number of different hardware and software interfaces between computers that connect the Games with the "external world" – with timing and scoring equipment, with the computers of TV broadcasters, News Press Agencies, major Newspapers, Internet providers, etc. – and the time available to install and test these interfaces is extremely short
- all applications require a very simple and "easy to understand" users' interface, because most of the people who use or operate them have a very limited time to become familiar with them

- it is a considerable challenge to coordinate and manage the team of almost 3,000 people who operate Games IT and who come from a large number of different companies, countries and cultures, who speak different languages and who are working together for the first time.

2 Olympic Games Information Technology milestones

Computers were used for the first time at the 1960 Winter Olympic Games (WOG) held in Squaw Valley (USA) and the Summer Olympic Games (OG) held in Rome (Italy) where tabulating machines were used to calculate results at some of the events [1]. Since then, as in all other areas, the role of computers has become more and more important, following the dramatic progress in related technologies and in the computer literacy of users. A short history of the computer support at the Olympic Games follows:

- at the 1964 Innsbruck (Austria) WOG and Tokyo (Japan) OG on-line terminals were used for the first time to collect results data, and results were printed at each venue
- at the 1972 Munich (Germany) OG media used a computerized system as a source of information about athletes and historical results for the first time
- at the 1976 Montreal (Canada) OG and Innsbruck (Austria) WOG the first mainframe-based systems with an attached network of terminals supported the results processing/distribution from all venues and supported the accreditation of the participants
- at the 1980 Moscow (Soviet Union) OG the first “self-service” information retrieval terminals were installed in media centres [1]
- at the 1984 Sarajevo (Yugoslavia) WOG the software architecture that forms the basis of today’s Results Systems was first introduced. For the first time Timing and Scoring equipment from all venues were electronically interfaced with the Olympic Games computer system. The first e-mail application was available for all participants
- at the 1984 Los Angeles (USA) OG the first massive Information retrieval system with more than 1,700 terminals was installed. A complete set of back-office applications, including ticket sales, was installed on minicomputers and some of them on PCs
- at the 1988 Seoul (South Korea) OG the first de-centralized systems were used for the results processing at the venues
- at the 1992 Albertville (France) WOG, PCs were widely used for the results system interfaces for the first time. The TV commentator information system function was available remotely, and was used from TV studios hundreds of kilometres away
- at the 1992 Barcelona (Spain) OG an interactive touch screen Radio and TV Commentator Information System (CIS) was implemented for the first time
- at the 1996 Atlanta (USA) OG the first official Olympic web site on the World Wide Web was available [1]

- at the 1998 Nagano (Japan) WOG the first implementation of a Traffic Management System based on sensors installed above roads enabled real time traffic information, the adjustment of traffic signals and relayed information to drivers through interactive GPS-based equipment to inform them of the fastest way to their chosen destination [1]. Computer driven Video-On-Demand kiosks were installed at media centres, allowing the viewer to choose whatever video footage he wished to view from the Games
- at the 2000 Sydney (Australia) OG the last system implemented on mainframes worked perfectly. The huge number of visitors to the official web site was efficiently handled
- at the 2002 Salt Lake City (USA) WOG a completely new computer systems architecture was implemented, based on a network of servers that completely replaced mainframe-based systems [2]
- at the 2004 Athens (Greece) OG advanced timing and scoring technologies (such as transponders and DGPS) were fully integrated with computer driven Results Systems for the first time [3]
- at the 2006 Torino (Italy) WOG an integrated "Internet Data Feed" (IDF) provided all real time information electronically to different Internet providers and Broadcasting Companies [2]. A new sophisticated computer driven Judging System that combined interactive touch screen entry stations for judges with the video replay system was implemented at the Figure Skating competitions for the first time [3].

3 Software applications supporting Olympic Games

People and companies working at the Games Information Technology support usually break down software applications into three major groups: Results Systems, Information Diffusion System and Games Management Systems.

3.1 Results systems

Everything that happens during competitions at the Olympic Games generates a result – a rate of speed, an elapsed time, a ranking and a score. These results need to be collected, processed and distributed in real time to electronic scoreboards, TV graphics equipment and TV Commentators' monitors and relayed instantly to the world.

As mentioned in the introduction, results processing is the most visible and publicly exposed function of the Information Technology at the Olympic Games. Malfunctioning of the On Venue Results (OVR) system could cause interruption, postponement or cancellation of events. Wrongly registered or miscalculated results could have unpleasant and undeserved consequences to athletes, and bring incorrigible discredit to the Games organizer and the organizations/people operating the result systems.

For this reason the design and implementation of OVR system is the most critical aspect of the Games IT support. All systems are designed in such a way

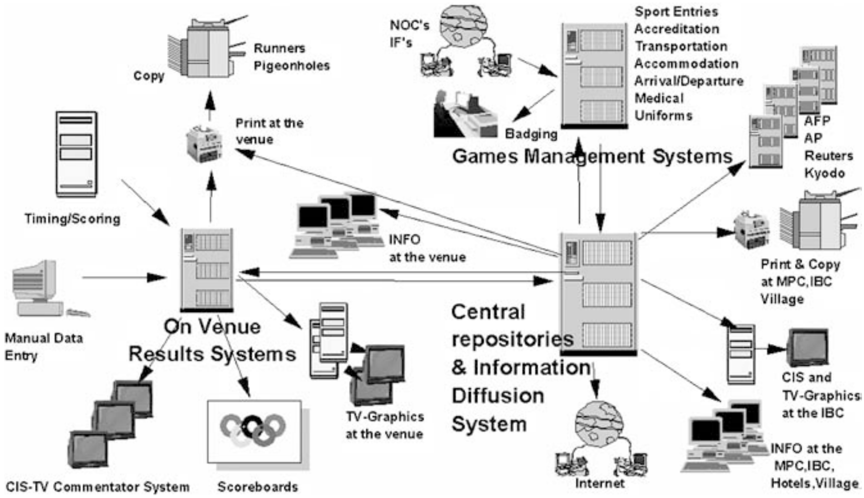

Figure 1: Systems overview.

that at least two completely independent systems are processing results in parallel. They do not share any resource, not even the power supply. In some sports where the competition could not resume if systems went down, a third independent system may even be used.

Another reason for the specific treatment of the Results System is the fact that live TV coverage strongly depends on the results service. Like most other large sports events, the Olympic Games are financed mostly from TV rights. TV Broadcasting companies are paying significant sums to the Games organizers in order to have exclusive right to broadcast Olympic competition in their countries.

In order to deliver attractive programs, these companies must provide their audiences with instant results and rankings. Who would be interested in watching the Swimming or Alpine Skiing events if the running time was not permanently displayed on the screen, or if the ranking at intermediate points and at the finish was not available instantly?

Some sports, such as Biathlon, have been transformed by the use of technology. As competitors start the race at different times, and in addition to the time achieved, a second criteria of precision in shooting determines results, live TV coverage was rather boring until the use of advanced technologies was implemented to electronically record times and shooting scores. Now, spectators know at any moment who is leading the race and how far behind other athletes are, and this sport has become one of the most televised winter sports.

3.1.1 Results acquisition

Providing audience with real time results would not be possible if computers that calculate results and rankings were not directly interfaced with timing, scoring and judges' devices. A number of these interfaces are based on very advanced technologies.

In sports where the criteria for ranking is the time an athlete took to complete a fixed distance, time is measured with extremely precise instruments. If the athlete is competing alone at that time (e.g. Alpine Skiing) it is measured with photo cells. But when there are more athletes competing together, the time is measured either with video-finish devices, or with the use of transponders (chips weighing 5 g) attached to the athletes' shoes or equipment. In sports such as Athletics, Rowing or Canoeing where more competitors are competing at the same time, the specially designed video-finish camera at the finish line operate at a speed of 2,000 frames per second, and operators and officials are able to determine the result of each athlete/boat at the computer displays to which the video-finish camera is attached [3].

In swimming, where each swimmer is competing in a separate lane, the swimmer stops the timing system by hitting the touch pad at the finish line.

In Road and Track Cycling a tape switch, with two elements of an electronic circuit which are held several millimetres apart by an extruded plastic former, is laid out on the track or road surface, and when the front wheel of the bicycle goes across the tape, the timing system will recognize it.

When it is important to precisely locate an athlete or a team, such as in Sailing, location is identified by Differential Global Positioning System (DGPS) which permanently transmits information (accurate to 1 m) by radio signal to the results system computers on shore [3].

In sports where touches of opponents have to be recorded (such as Fencing or Taekwondo), scores are registered through sensors installed in the athletes' clothing or helmet.

In Artistic Gymnastics and Figure Skating, judges enter scores using touch screens. Software requires that they immediately judge each action. They are also supported with a sophisticated computerized video system that allows them to instantly replay a video recording of athletes' performance from any point.

Specially designed "Speed guns" are already used to measure the speed of the ball in Tennis and Beach Volleyball, or the shuttle in Badminton. In Tennis the so called "Hawk's eye" video system will be used to check whether a ball is "in" or "out".

In most of the "team" or "head to head" sports in which the actions to be recorded cannot be acquired by instruments or other equipment, data are entered manually, either by Judges and Referees, or by specially trained operators. In Judo, Taekwondo and Boxing, judges award points by pressing buttons, and points are awarded if more than the required number of judges press the same button within a fixed time frame.

For scoring in Shooting and Archery, special electronic targets have been developed, with accuracy of 1/10 of a point. In some disciplines the centre ring has a diameter of only 11 mm [3].

Most of these timing and scoring technologies were developed for use for the first time at the Olympic Games, but many were first tested at smaller competitions.

3.1.2 Results processing

Algorithms for results processing that rank athletes and teams based on their achievements are defined by rules set by the International Sport Federations for each sport. Software consisting of thousands of lines of code is developed to correctly process data acquired from the fields of play, and to present results in a number of different formats suitable for presentation at scoreboards, TV screens, printed reports, electronic messages, Internet, etc.

Programming of the so called "happy path", when everything works smoothly, when there are no ties or disqualifications or other exceptions is the easiest part of the job. However programming support for many types of exceptional situations that could occur is a much more complex task. How should several athletes, who achieved exactly the same time or score, be ranked, even when results have been measured with maximum accuracy? Should results of all other athletes be re-calculated if an athlete is disqualified after the event because of doping, and in what way? Under what conditions, should a new record be recognized?

In some cases, the International Sport Federation rules are able to define the necessary procedures for all possible scenarios, but in many instances this is not the case. Those responsible for preparing the software which must be capable of automatically coping with the foreseeable exceptional situations have to analyze not only previous cases at competitions in that sport, but also discuss with Federation officials other possible eventualities. In most cases the number of lines of code for handling these exceptions is several times greater than the routine processing of the regular situations.

In order to ensure that software will efficiently and accurately process results in real time, a major effort for those people involved in the preparation of Results System software is its testing. This is done not only by the companies that develop the software, but also by several independent testing teams. One of the last tests in this process is the so called "IOC Homologation Test", during which representatives of the International Sport Federations together with experts nominated by the International Olympic Committee and some media organizations test the results system for each sport extensively. By following previously prepared test scenarios and running many different test cases, they are able to check that the system correctly processes results in all predictable situations.

3.1.3 Result System outputs

The OVR system has to calculate results in thousandths of a second, and provide several outputs in parallel:

- for spectators at the venues, results are immediately displayed on the scoreboards or video boards
- for TV audiences, results are inserted in the live TV picture via computer driven video graphical generators operated by the TV companies. At the Olympic Games, TV broadcasters from several of the richer and bigger countries do not use the results graphics provided by the Games systems. They receive the "raw data"

from which they produce their own graphics, with text translated into their languages, and the results of their athletes highlighted

- for Radio and TV Commentators reporting live from the venue results are provided at the PCs with touch screens monitors (CIS system)
- for Competition management, Federation officials and written press journalists, the OVR System provides printed result reports
- at the same time processed results are relayed to the Central Repository, from where Information Diffusion System disseminate them to remote users at the other venues, Main Press and Broadcasting centres and the whole world.

3.2 Central Repository and information diffusion

All OVR systems are connected through the internal Olympic Games communications network to servers that are used as the Central Repository of the Games information. Results are stored in the data base which is also used for many other types of data.

Prior to the Games, the Organizing Committee Olympic News Service store historical information on results of previous Olympic Games and other major sport events, athletes' biographies and other interesting facts and figures in the Central Repository servers. Before the Athens 2004 Games, the ONS prepared and uploaded more then 50,000 pages of such information in English, French and Greek [2].

During the Games, the ONS stores different news articles written at the venues by their staff – experienced journalists who prepare event previews and reviews, athletes' press conference highlights and flash quotes of winners or in the event of major surprises.

Meteorological services store information about the current weather situation and forecasts in the Central Repository servers. Transportation services also store updates in transportation schedules.

Accreditation and Sports Entries system stores data about all athletes and officials in the Central Repository servers. This data is used by the Results System together with data about other participants and organizers by a number of different applications supporting Games logistics.

Information Diffusion and retrieval Systems make information stored in the Central Repository available in two different ways.

For some pieces of information, dissemination is defined well in advance, such as for printed results reports, or results data feed to News Press Agencies. For each report the locations at which they have to be printed, or which agencies will have to receive them is defined before the Games. Once the OVR system uploads a report or message to the Central Repository, appropriate software will trigger its distribution to predetermined addresses.

In a similar way this information diffusion software broadcasts results and other data to the systems that host the official Games web site, and systems of other Internet providers who have subscribed to this service, known as "Internet Data Feed" (IDF).

Information stored in the Central Repository is also available on request. Results, background information and news can be retrieved from any of the thousands of PCs installed at all venues, media centres, Olympic villages and other accommodation sites. The application allowing this information retrieval is usually called the "INFO" system. In Athens 2004 and Torino 2006 results were also available on request from dedicated mobile phones, and for Beijing 2008 onwards distribution via mobile telecommunications will become a regular service.

An extremely important information retrieval system that is also centrally supported is the remote CIS which allows Radio and TV Commentators to have the same level of services at remote locations as those who are commenting events live from the venues. Thanks to this system, a lot of commentaries are made from the central International Broadcasting Center where most of broadcasters have their own studios. In the near future this CIS service will be available remotely at any location worldwide.

3.2.1 INFO – Intranet system of the Games

At any Olympic Games, it is not only the athletes who are under pressure but thousands of journalists are also working in tight schedules, and they need access to many different kinds of information. A journalist watching Rowing may need to know who won a Handball match on the other side of the city because he has to report for that event as well. He would also like to know what the team coach said at the Press Conference after a Basketball match. Athletes in the Olympic Village would like to learn the outcome of the draw held minutes ago at the venue. A competition manager would like to know how many athletes finally arrived at the host city in order to plan their training schedule. A TV Commentator needs some historical statistics in order to prepare for an upcoming event.

Answers to all of these questions will come from the INFO system, a highly visible, all-purpose intranet-based tool that acts as an information hub for the 200,000 accredited Games participants. This system must be designed for a very special set of customers: thousands of first-time users who need to move around the Olympic venues and use INFO.

The system has to be understood at first glance and with minimal training, and everything needs to be self-explanatory. Navigation through the different data bases should lead users quickly to the data that they need – results, sports history, athletes' biographies, news, medals, transport schedules or weather reports – in one of several languages (English and French, plus at least the local language).

The INFO system is an extremely important tool for journalists reporting from the Olympic Games, particularly, since reporting from the Games is quite different to reporting from single sport events. The International Olympic Committee limits the number of journalists from each country that can be accredited at the Games, because the number of journalists who would like to attend is far too high. As a consequence, most journalists must report on a number of sports (according to some statistics on 7–8 sports in average), and on some sports on which they have never reported before. Also very often, events in these sports overlap, and journalists must choose which event to attend. Because of this most reports are based on information retrieved from the INFO system, where the reporters are able to find not only the result, but also two other key elements for each report – the athletes' biographies or teams' profiles, and flash quotes (interviews) or press conference highlights with winners and major surprises.

According to the very precise INFO system statistics from the last summer Olympic Games in Athens 2004, the average number of INFO page views was about 400,000 a day during the 34 days of operations, with a peak of 920,000 views. There were a total 16,000,000 page views, and out of that 31% were related to results, 24% to athletes' biographies, 27% to the games schedule, 10% to news (mainly flash quotes and press conference highlights) and 8% to all other information [2].

At the end of the Athens 2004 Games there were tens of thousands of pieces of information stored in the INFO section of the Central Repositories – more than 11,000 athletes' biographies, more then 12,000 result reports, more then 6,000 news items, etc [2].

3.2.2 Commentator Information System (CIS)

With around 4 billion people watching the Olympic Games on television, getting results to broadcasters across the world is vital. CIS is a browser-based application that displays results on touch-screen PCs at the venue broadcast sites in a fraction of a second, so that they can be instantaneously dispatched across the globe.

By touching an intuitive screen icon on a touch-screen display, radio and TV commentators and producers have instant access to information in their choice of official languages. The wealth of information stored on the system includes live scores and results, together with different up to the second statistics and analysis enabling commentators to provide their audience with accurate and real time information.

CIS provides information on progress throughout the event, details of times and/or scores in the event and how individual athletes or teams stand in comparison to other competitors at that time. It also gives information on the weather conditions affecting the competition, medal standings, flash quotes, etc.

In Athens 2004 there were 1,500 CIS terminals installed at the venues and the International Broadcast Centre. The application supported more then 300 sport specific screens. OVR systems sent 477,000 messages to the CIS system during the 16 days of competition, with a peak of 47,000 a day.

3.2.3 Information retrieval from the mobile telecommunications

The first regular information retrieval service from dedicated mobile phones was available in Athens 2004. Much better and improved services were provided during the WOG in Torino 2006. There were more then 2,000 subscribers to the so called Wireless Olympic Works (WOW) system who were able to access a subset of the INFO data base, and to receive SMS messages with results of pre-selected events. Performances were reasonable, but only when the file size of data to be downloaded was not too large. According to the Beijing 2008 Olympic Games organizers, a similar system, but with improved functionality and performances will be available, primarily for the media reporting from Games.

3.2.4 Internet Data Feed (IDF)

Since the first official Olympic web site was introduced at the Atlanta 1996 Olympic Games, diffusion of results and other information through the Internet has become more and more important. From 300 million hits and 10 million users in Atlanta 1996 [1], the number of hits rose to several billions and the number of users to hundreds of millions in 2004 and 2006 [2]. Furthermore, Olympic results and news are not only available at the official Games web site, but also from a number of other media organizations, International Sport Federations and National Olympic Committees who also provide this information on their own web sites.

In order to allow quick and reliable update of web sites, the Games Information Diffusion System broadcasts the IDF to the servers of all Internet providers who have subscribed to this service.

The IDF is designed in such a way that data sent from the Results System to the Central Repositories and to the central CIS application, together with selected INFO data base updates, is transformed into XTML pages or downloadable PDFs, and then broadcast. All users receive the same feed, and select the data that they need.

3.2.5 World News Press Agencies Results Feed (WNPA Results Feed)

Major World News Press Agencies – Agence France Press, Associated Press, DPA, EFE, Kyodo, PA, Reuters, SID and others, are some of the most demanding and sensitive users of Games information. They were the first users who insisted on the direct results data feed. Each of them provides news service to thousands of clients worldwide – mainly different media organizations – and all of them require information as soon as possible. Since the 1976 Montreal Olympic Games, the Organizing Committees' (OCs) computer systems provide these results electronically, through the WNPA Results Feed.

Today the systems providing this feed are specially designed in order to be as reliable as possible, and are isolated from all other systems and their potential malfunctioning. Software routes and tracks the delivery of messages, and allows the re-sending of messages on request.

The content of messages, their structure, and timing of delivery are defined by the International Olympic Committee WNPA Working Group, in which all major agencies are represented by their editors and technical experts. All agencies are interested that these feed specifications are as stable as possible and that they do not change from Games to Games, to remain compatible with the agencies' receiving software.

During the Athens 2004 Olympic Games, press agencies received 25,000 WNPA messages with a peak of 2,200 per day [2].

3.2.6 Printed results distribution

Although it is clear that an increasing number of users are computer literate enough to easily retrieve information from INFO, CIS or the Internet and that the modern video-boards installed at the venues provide a lot of information – still a lot of users require or just prefer printed reports.

Competition officials require printed Start Lists in order to be able to check that all athletes are at the start, in the correct lane or track, etc. Journalists and TV Commentators like to manually record results on the Start Lists, and to make notes on the paper report which they use either while commenting on the event or while writing their reports.

It is true that the number of printed and copied reports is reduced from Games to Games. In Atlanta the organizer produced and distributed approximately 90 million copies of printed reports, and in Athens this number was reduced to some 55 million. It remains a challenge for all future organizers to reduce this number significantly.

During the Athens 2004 Games the Venue Results Systems produced 11.270 different printed reports, PDFs of which were sent to the Central Repository. The peak was 979 on one day [2]. Once received at the Central Repositories servers, PRD (Print Distribution) software distributed them to those locations and printers which were defined for each output before the Games in the appropriate distribution tables. There were approximately 300 dedicated printers installed for Results reports. PRD software, like other diffusion systems, route and track outputs delivery, and on request will re-send missed reports.

4 Games management applications

Computer systems supporting behind the scenes logistics ranging from accreditation and accommodation to staffing and transportation are not as exposed as the functions described above. However, this does not imply that those application areas are less important to the Games organizers, because it would be practically impossible to prepare and host the Olympic Games of today's magnitude without these systems.

4.1 Registration and accreditation systems

All Olympic Games participants (approximately 200,000 persons at the Summer Olympic Games and approximately 100,000 at the Winter Games) are registered in the computer system data bases. Half of these are the so called "Olympic Family" that consists of teams (athletes, trainers, coaches, medical and technical support teams), officials who manage and officiate competitions, media (written press and agencies journalists, photographers, TV producers, commentators and technicians), protocol and marketing guests. The other half are Games organizers including paid staff, volunteers helping them in a number of areas, providers of different services, etc.

The scope of data stored in the systems varies depending on each participant's function and the requirements of other computer applications supporting the Games logistics. For teams and media, data is provided by their National

Olympic Committees. Data on other members of the Olympic Family are provided by their respective organizations or the IOC. Information about organizers is mostly received from other computer applications – like staffing, volunteer registration and selection, etc. Because of the security background checks now required by law enforcements agencies, the deadline for provision of these data is usually half a year before the Games.

Once data are entered in the system they are used by number of other computer applications, allowing people in charge of different functions, such as organization of arrival/departure, transportation and accommodation, to plan their services in details.

A few weeks before the Games accreditation documents – photo ID badges which ensure that only eligible participants can attend and participate in the Games – are issued. These ID badges have either a bar code or a chip that allows people and/or scanning equipment to check if a person is authorized to access any particular area within the Olympic venues and sites.

For people coming from other countries ID badges are sent to their National Olympic Committees or the organizations who registered them, since an Olympic Games accreditation is equivalent to granting a visa for the duration of the Games. Once the participant arrives in the host city, after a check of his/her identity, the ID Badge is validated and activated and can be used, also for free access to public transportation.

Without adequate computer system support it would be very difficult to organize the process of producing some 200,000 ID Badges, their distribution and validation in such a short time, particularly during the peak few days before the start of the Games when more then 15,000 ID badges must be issued and/or validated during a single day. A network of hundreds of PCs is installed in the Accreditation centres, and a number of them are connected to the special equipment that produces the ID Badges.

4.2 Sport entries and qualification system

This system collects and manages the official entries of qualified and eligible athletes and teams to the Olympic Games.

The overall objectives are:

- ensuring that only eligible athletes are formally ‘entered’ to participate at the Games
- ensuring that each individual is qualified in accordance with the rules of International Sport Federations
- ensuring that all athletes are confirmed by their respective National Olympic Committees to represent their nation

For most athletes, qualifying for the Olympic Games is their best achievement, and accurately representing the official qualifying achievements is critical to fair competition.

This system maintains the criteria for qualifying individual competitors, pairs, relays or teams based on the minimum and maximum qualification standards for any event, types of qualification and quotas, combining around 1,000 different criteria across all the sports. It is usually activated 2 years before the Games. Before the Athens 2004 Olympic Games more then 16,000 athletes were registered in this system, and by the end 10,500 of them have participated at the Games in 301 events in 37 sport disciplines [2].

Information about athletes used during the Games by the Results and INFO systems is a combination of data from this system and from the accreditation system.

4.3 Protocol System

The Protocol System assists organizers in the coordination, scheduling and provision of appropriate services for a few thousand VIPs, including their registration, organization of VIP events and other VIP arrangements.

4.4 Arrival and departure system

This system gathers expected arrivals and departures data for the Olympic Family and provides the information to the groups responsible for managing the travel arrangements as well as the welcome greetings for the delegations.

4.5 Accommodation system

Planning accommodation for tens of thousands of Games participants, allocation of rooms at Olympic Villages and hotels is supported by this system, which has most of the functionality of a typical Hotel Reservation System.

4.6 Transportation system

The transportation system computerized support provides for the programming, planning and scheduling of transport services and fleet management for the Olympic Family. The system allocates the available transportation resources according to the service levels established for each athlete and group. At least it must schedule and dispatch a fleet consisting of 2,000–3,000 buses/minivans and 3,000–4,000 personal vehicles in order to transport 40,000–50,000 persons from their accommodation sites to the competition and training venues, media centres and other Games locations [2]. The Games schedule is different every day, and a number of people will make decisions as to where they must/wish to go on the next day very late in the evening because this may depend on draws or results of the previous day, etc. In such an environment proper dispatching of the fleet is essential, and would be practically impossible without appropriate computer systems support.

4.7 Medical encounters system

This system gathers information relative to the different levels of healthcare, generates reports for the medical management organizations (IOC Medical Commission, Department of Health and others) and provides an on-line summary of each case history.

4.8 Volunteers registration, selection and assignment

Volunteers are non-paid members of the OC staff. Regardless of the size of a host city and of the OC budget, it would be very difficult to recruit and hire the required number of people who have the necessary skills (languages, computer literacy, etc.) for the limited period of time (20–30 days). For the Summer Olympic Games the number of people required for the tasks of computer operators, translators, teams and VIP hostesses, drivers, access controllers, etc. exceeds 50 thousand. For this reason all Games organizers are forced to attract local people to volunteer for these positions, and often to use their holidays or vacation for this purpose. After a campaign to attract people to apply for these jobs, it is necessary to register all candidates, and organize their training and selection. In Sydney and Athens there were more than 200,000 candidates, and in Beijing they expect many more. An application that supports this area helps organizers to select and assign people with the required skills to the best positions, considering several parameters, such as home address (in order to minimize needs for transportation), special skills, etc.

4.9 Uniforms planning and distribution

This application is responsible for the planning, ordering and distribution of uniforms and accessories for the Games workforce (paid staff and volunteers), competition officials, etc. There are typically 15–20 different types and/or colors of uniforms depending on the functional area and/or status of a person. The total number of uniforms to be provided at the summer Olympic Games is about 70,000–80,000 [2].

5 Requirements definitions

As in all other computer applications, a thorough understanding of user requirements is the key to success. What (and when) results information is required by athletes, coaches, officials and competition management? What result information needs to be displayed on a scoreboard or in the TV picture that will allow even those people who are watching this type of competition for the first time in their life to understand it? What level of detail is needed in printed reports? What information should be distributed to a written press journalist and when? What should be available in the INFO system and on the Internet and when?

Content and presentation of results information is mostly based on tradition, and event organizers usually rely on the companies providing the IT services to define these. Today, when a number of users expect to receive information electronically, problems caused by lack of standards have become more serious, as users of data feeds have to reprogram their ‘receiving’ software every time a different format is used.

Unfortunately very few International Sport Federations or other user groups have any documented requirements for these results services, or any standards. Some of the few professionally developed and maintained documents and standards are those that have been developed by the International Olympic Committee.

In order to ensure smooth operations of the Olympic Games Information Technology and to properly manage user expectations, in 1994 the IOC launched the Olympic Results and Information Services (ORIS) project with the objective of identifying and documenting the user requirements.

Key deliverables of the project are the ORIS documents that provide a precise definition of all outputs (printed reports, scoreboards, Information retrieval system, etc.) together with information about ‘who’, ‘when’, ‘where’ and ‘how’ these are required. Documents also include procedures defining who is responsible for preparation, collation and processing of data, when this must be done, who must check and approve outputs before public release, etc.

ORIS documents were developed for all 38 summer and 15 winter sports/disciplines that are on the program of the Olympic Games. For each sport, an ORIS Working Group was established. The IOC invited representatives of the International Federations, experienced journalists and media researchers to provide input. They worked together with the ORIS Project team that is made up of IT experts who are experienced in the development and implementation of Olympic IT Systems.

Thanks to the contribution of more than 210 sport officials, 180 media experts and 110 IT specialists coming from more than 40 countries, the first version of ORIS was developed between 1994 and 1999 and was used at the Nagano 1998 winter, and Sydney 2000 summer Olympic Games.

The ORIS Project team continues to update documents, due to the permanent development of sports (new events, improved formats and rules), changes in user’s expectations due to increased computer literacy, and developments in information technology itself. Updated versions were produced for Salt Lake City 2002, Athens 2004, Torino 2006, Beijing 2008, and update process for Vancouver 2010 is almost completed.

A number of International Sport Federations have begun to use the same ORIS documents for definition of the IT requirements for their World Championships and other events.

6 Systems architecture

There are two key factors that have major impact on the Olympic Games computer systems architecture: the first one is that systems providing results and information diffusion must be fault-free, and the second one is maximum security.

The most critical services are isolated in a separate computer network which must provide both a high level of availability and of data integrity. It is completely independent from the outside environment, and does not share any resource with any other system or service, including the telecommunication network.

All the other non mission critical applications, such as OC internal e-mail, payroll, document management, etc. are grouped on another network in which services are of a lower standard.

Designers of the computer network supporting vital functions take considerable care about several aspects which are collectively known as 'Business Continuity':

a) redundancy of equipment, network infrastructures, systems and applications assuring that there are no single points of failure, and allowing fail-over to redundant architectural elements upon failure of a primary element;
b) back-up and restore functionality allowing quick restart of processing from some point in time when systems stored the content of data bases, and using the log of all transactions after that;
c) disaster and recovery solutions: partial or complete networks can be restarted from another location in the case of complete failure or catastrophic disaster of the primary systems.

OVR systems are designed in such a way that they could work alone without being connected to the Games network. They should at any moment satisfy all basic requirements of the users at the venue. All hardware components of these systems are duplicated or triplicated, fail-over switches between them are automated as much as possible, but should still be able to be manually operated when required. All input data coming from timing and scoring devices is stored in parallel in at least two different servers. Two fully separated configurations are attached to different power supplies, etc.

For support of the Central Repositories and Information Diffusion System there are two main data centres installed. The primary data centre hosts all servers and the central data communication equipment for normal operations, and the secondary one acts as a back-up data centre in case of emergencies.

All file servers use clusters for redundancy. Applications and processes are assigned to either node in the cluster thereby distributing the workload during normal operation. Processes fail-over to the other clustered node upon failure.

Monitoring of all systems is organized at a neutral location usually called the Technology Operations Centre (TOC), from where experts using different data base and network monitoring tools control operations, manage configuration and distribute software.

It is also equally important that all system components and all interfaces are based on stable and proven technologies. The Olympic Games operations are so risky that there is no room for testing of prototypes or '0' versions of any hardware or software component. Some previous organizers have paid a very high price for attempting to implement completely new and unproven solutions.

7 Security

In addition to running fault-free systems, the other key challenge faced by Games organizers is system security. A system open to the world could potentially be a huge security risk. It is necessary to prevent any attacks from viruses or hackers during the Olympic Games either from inside or outside the Games network. During the 16 days of competition in Athens, more than five million IT security alerts were recorded, of which just 425 were serious and 20 critical [2]. Intrusions included accredited people attempting to disconnect INFO work stations in order to connect personal laptops to access the Internet.

The first step is complete isolation of the Games network from the outside world, particularly the Internet. After that it is necessary to prevent unauthorized access within the network. At all work stations located in public areas, all inputs except the keyboard are physically disconnected to prevent anyone from being able to insert or attach his/her equipment (diskettes, CD-ROM, memory sticks, modem, etc.). Additionally, the screens and keyboards on the work stations in public areas will remain blocked until the application takes over and privilege password and special codes are added so that at the least attempt to re-configure a machine will be automatically reloaded. All servers and workstations are equipped with the full range of security systems such as anti-virus software, firewalls and Intrusion Detection System (IDS).

All interfaces with systems for broadcasters, new press agencies and Internet providers are designed in such a way that all traffic is strictly monitored and controlled. The IDS is heavily used to monitor known patterns with the addition of custom made rules to monitor anomalous network traffic that does not match the well known traffic pattern.

The location of the main and back-up computer centres is top secret, and very few people know where they are.

8 Software and testing

Software for the Games computer systems is a combination of the standard operating systems, data base/data communications, browser and monitoring packages, combined with propriety software solutions developed by companies that are partners of the IOC and OCs.

Propriety software alone consists of millions of lines of code, and more then 250 developers work on its development.

Software development usually starts 3–5 years before the Games, as most of the systems must support the Games Management Systems during the planning phase, and be ready to be implemented at Test Events that are organized a year before the Games.

Until Barcelona 1992 and Lillehammer 1994, integration of all solutions was managed by a team of the OC's experts, but since computer systems have become so huge and complex solutions, this task was subcontracted to a large company specialized in systems integration (IBM 1996-2000, Atos Origin from 2002). The same company is in charge of development and implementation of Information Diffusion and Games Management Systems, and a long-term IOC partner for Timing & Scoring and OVR system is Swiss Timing. The IOC has signed long-term contracts with these companies, in order to benefit from their experience, and to allow smooth transfer of solutions that can be reused.

The most complex tasks in Games software preparation are testing and rehearsals. All those people who have worked on the IT projects for the Games know very well that the key to successful operations is simply testing, testing and testing, followed by rehearsals.

After the development teams of different companies have completed the code and performed 'unit' tests, software is installed in the special 'Integration Testing Laboratory' usually located in the host city of the Games.

In the Integration Lab typical hardware configurations are installed, allowing the testing of solutions for each sport and function. For that purposed in the Athens 2004 Games Integration Lab more then 400 workstations and more then 40 servers were installed [2].

Specialized teams integrate programs into Games configuration and test integrated modules using hundreds of previously prepared scenarios.

Once this phase is completed, a set of volume and stress tests begun that should ensure that the expected performance of the complete system will be achieved.

The last step in testing are the so called 'Homologation tests', where representatives of International Sport Federations and media, together with the IOC delegated experts (ORIS Team) check that the systems deliver the functionality specified in the ORIS requirements documents, and that the systems are capable of handling all exceptional situations that can be anticipated.

Two to three months before the Games are due to begin Games operations are rehearsed. At least, two 3–4 days of rehearsals are organized. During them the complete IT team simulates operations during the most critical days of the Games. In addition to the regular situations, testing scenarios includes a lot of incidents and mishaps that might occur during the Games, ranging from power outages to the cancellation of events and their re-scheduling.

9 Hardware

The hardware platform that will satisfy the architecture and security requirements is usually provided by sponsors and/or partners of the IOC and OCs of each Games. Because the network of systems has such a complex architecture which must support many different applications, it is not possible to use hardware from just one manufacturer, as was the case 10 years ago. Today sponsors and partners are usually supplying equipment that is installed in the public areas (PCs, Printers), while all behind the scenes hardware is purchased or rented from specialized companies.

The quantities of equipment used at the Games are extremely impressive. Following are data about the computer equipment used at the last two Olympic Games [2]:

	Athens 2004 (Summer Games)	Torino 2006 (Winter Games)
Servers	900	385
Work stations	10,500	4,700
For results systems	4,000	1,800
For INFO retrieval system	2,500	800
For Commentator Information System	1,800	950
Printers	4,000	700
Routers	300	140
Switches	2,000	800

10 Installation

Installing the above mentioned quantities of equipment during a period of 5–6 weeks is a real challenge. Installation planning starts a few years before the Games, when it is necessary to identify the space required and locations of equipment at venues that will be built or renovated. At this stage very few people have a clear idea of how the computer system will be designed, of how much equipment will be required at each location or of how they will be connected. Planning is usually based on experiences of previous Games organizers.

Once the final computer systems configuration is defined, which usually happens 2 years before the Games, detailed planning of installation and related logistics begins.

At the summer Olympic Games computers are installed at more than 60 locations. Some of these are newly built venues (and construction is usually late) and installations planning must include considerable amounts of contingency time. At a number of other locations – e.g. hotels, airports and convention centres – installation can not be begun too far in advance, as these facilities must continue to function normally before the Games.

Once installation starts, approximately 500–600 ‘boxes’ (servers, PCs, printers, routers, etc.) have to be installed per day. If just one venue or site is not ready, these numbers of pieces of equipment to be installed on the following days is increased. Work by the technicians from the different hardware suppliers must be perfectly coordinated, because in most cases installation of different equipment can not be done in parallel, but in some technologically determined sequence.

Since the Atlanta 1996 Olympic Games, when the quantities of PCs to be installed entered the thousands, Games technology suppliers began to organize a so called ‘PC Factory’. This is the facility dedicated for storage, assembly and configuration of workstations and servers. In the first step, devices are configured according to their function and final location. After that, through a central server, the necessary operating system is transferred to the computers in a consistent and reliable manner. After the equipment is properly configured and verified, it is packaged and shipped to the venues. This process enhances the information network's stability because it loads each computer with an identical version of the appropriate operating system. In Athens 2004 the PC Factory was a 5,500 square metre storage area and a 500 square metre configuration facility, with the capacity to configure and ship 500 units a day [2].

11 Future challenges

By accurately analyzing user's requirements, future organizers can learn a lot about the design and implementation of computer systems at future Olympic Games.

- Sport officials expect that computer and other technologies will further improve the accuracy and precision of results measuring, and will develop new tools that will assure fair and impartial judgment of athletes' achievements.
- Games organizers would like computer applications that support the Games logistics to be fully integrated and more automated.
- Media, particularly written press journalists, would like to connect their own laptops to the Games systems in order to retrieve and download information that they require to prepare their reports – results, news, biographies, etc. Connection should be wireless allowing them to work at any location of the venues and other sites.
- Newspapers and other media organizations would like to have access to the INFO content from their offices worldwide.
- TV Broadcasters would like to have the CIS services available remotely, in their countries.
- A lot of media users would like to have real time access to the video footage of events, allowing them to replay actions which they have missed, or that they would like to analyze again.
- TV audiences are no longer satisfied with the concept of 'one broadcast fits all', and people would like to choose which event they actually want to see at a particular moment.

Most of these demands are already affordable from a technology point of view or will be available in the near future. The expected convergence of different technologies (Internet, TV Broadcasting and Telecommunications) will allow most of these requirements to be met.

The massive distribution of audiovisual content has gone hand-in-hand with the so called digital convergence. Thanks to the large band-width (ADSL or cable) and the improved quality and efficiency of some compression codes, on-line distribution of audiovisual content is now a reality. At the same time, the mobility and interoperability of various networks and devices can lead to new forms of interaction.

Having a technology solution does not mean that it will be implemented. There are lots of other barriers and obstacles preventing Olympic Games organizers from using some of these new developments in technology.

The first group of reasons is a complex mixture of budget, marketing and legal constraints. For some of the new technologies it is difficult to justify their temporary installation, or the investments in required infrastructure are too high without any end-user after the Games. Sometimes a loyal long-term sponsor is not capable of providing the state-of-the-art solution. The physical and legal content protection mechanisms which tie content to a particular source or platform are a huge barrier to the possible benefits of convergence of Internet and Broadcasting technologies.

The second reason is the fact that people need some time to become familiar with new technologies and solutions. Is the period of 16 days of the Olympic Games long enough for such a heterogeneous group of people as the Olympic Family to learn how to use these new tools?

However, we certainly expect that a further increase in computer literacy of users together with new developments in the computer and telecommunication industries will allow future Olympic Games organizers to improve the level of computer services. We hope that the use of computers will contribute to more accurate and fair judging of the athletes' performance, and that information from the Games will reach all parts of the globe in the most efficient way possible.

References

[1] Media kit, "IBM at the Olympic Games" distributed at the Sydney 2000 Olympic Games.
[2] Atos Origin Olympic Media kits distributed at the Athens 2004 Games and Torino 2006 Winter Olympic Games.
[3] Swiss Timing (SWATCH, OMEGA), Press kits distributed at the Sydney 2000 and Athens 2004 Olympic Games.

5. Education

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Multimedia in sport – between illusion and realism

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Abstract

Multimedia has much to offer to sport and sport science. However, research and experience clearly show that multimedia is not a panacea for all the unsolved problems of information, communication, research and education. In this contribution we discuss the advantages and disadvantages of multimedia. Existing experience and future potentials are promising, but multimedia requires deliberate use and continuous critical reflection.

Keywords: multimedia, research, education, learning, e-learning, e-research

1 Introduction

In 1995, the term 'multimedia' was elected 'word of the year' by the Society of German Language. The reason for this was that this term was the main focus of public discussion on modern information technologies. Literally, 'multimedia' means 'many means'. In order to demonstrate the technological innovation this term refers to a technological or electronic system that allows users to independently produce, use, manipulate, store, communicate or combine different time-dependent and time-independent media like texts, pictures, videos and audios [1]. Multimedia systems show several features that offer unique options for many applications in science and practice of sport: interactivity, flexibility, ubiquity, authenticity, multimodality and multicodality are only a small sample of buzzwords indicating the new and fascinating potentials of multimedia, particularly for learning. Therefore, the vision of multimedia is to improve information, communication, research and education and to solve at least some of the so-far-unsolved problems in these areas.

Although there is no doubt about the potential surplus values of multimedia learning, existing experiences and research results have been inconsistent. There seem to exist critical factors having a strong influence on the effects and efficiency of multimedia. Therefore, the question arises whether the potentials of multimedia are illusions or realism. In this contribution we adopt an intermediate position: We are going to show that in order to exploit the potentials of multimedia for information, communication, research and education, the complex interaction of users (students, teachers, researchers), media, task and context (social, technical) need to be considered. An interdisciplinary understanding of multimedia is required to deal with these complex interdependencies appropriately. Multimedia cannot serve as a substitute but rather as a complement of traditional forms of information and communication. Here we put strong emphasis on multimedia as an educational tool, but we also deal with research (see also Ref. [2]).

As a first step, we introduce different types of multimedia systems regarding learning. Based on these distinctions we discuss the pros and cons of multimedia learning in a dialectic way leading to a synthesis. Then we deal with scientific basics of multimedia learning and take a look into the future of multimedia learning. Finally, we discuss the potentials of multimedia as a research tool.

2 Types of multimedia learning systems

There are several types of multimedia learning systems (MLS). One possible way to classify MLS is illustrated in Figure 1.

In learning programs interaction is controlled by the software system, whereas in learning environments learners exercise control. *Learning programs* can have a fixed or adaptive structure. The different subtypes can be characterized as follows:

- KIOSK systems allow for animated change of pages or browsing. Users are allowed to follow only pre-structured (especially linear) paths.
- Drill-and-practice systems are based on learning models of behaviourism. The systems continuously present tasks to be solved. These systems are particularly appropriate for exercising and establishing routine skills.

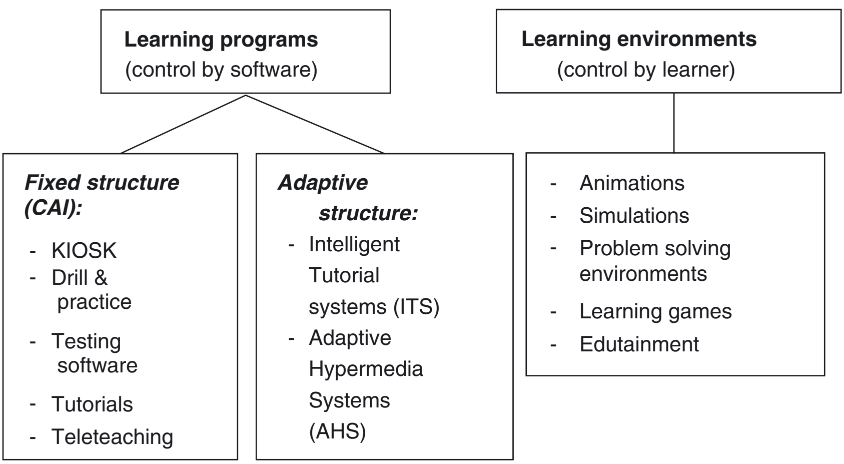

Figure 1: Types of MLS [3].

- Testing software also presents tasks in order to assess selected characteristics of a person, e.g. attention or intelligence. Various types of tasks and questions can be applied, e.g. multiple-choice tasks, drag-and-drop tasks, correction tasks and cloze.
- Tutorials or tutorial systems perform all teaching functions. They deliver information, give tasks and provide feedback.
- Teleteaching or distance teaching means that a lecture is broadcasted in an unidirectional synchronous or asynchronous communication style from a studio or a lecture hall to different locations. Feedback to the learners is provided in an indirect and asynchronous way. Especially asynchronous distance teaching is effective [4].

Multimedia systems with *adaptive structure* can be subdivided into intelligent tutorial systems and adaptive hypermedia systems [1]. Both systems are able to adapt to the learners' characteristics.

Multimedia learning environments can also be subdivided into different categories:

- Animations are dynamic visualizations of objects and procedures that are too complex to (re)present them verbally. Animations are especially effective with sport movement. However, several aspects of perception and memory have to be considered in order to appropriately apply this type of MLS, e.g. gestalt phenomena and depth perception [5].
- Simulations are programs operating on the basis of (numerical) models. Certain parameters can be changed (e.g. angle and altitude of release and initial velocity in throwing) in order to find out how these changes affect performance (throwing width). Combining animations and simulations can be a very effective learning tool [6].
- Problem-solving environments and micro-worlds are more or less complex contexts where the learners have to solve specific tasks, e.g. operating a spaceship. This category of MLS is based on constructivist learning theory demanding maximum authenticity ('situated learning').
- Edutainment systems and learning games try to combine two aims: learning and entertainment. The idea is to enhance learning motivation by presenting stimulating environments like virtual competitions. One term that has come up recently is 'serious games'. This term means that games can be used for learning and education, i.e. for serious purposes (see Section 6.2.3).

3 Learning with multimedia – thesis and antithesis

In this part of the contribution arguments in favour of multimedia learning are confronted with counter-arguments. We shall start with the respective argument in favour of multimedia learning.

Thesis 1: Multimedia learning offers appropriately structured, non-linearly linked information

This argument is based on the fact that in general knowledge shows a non-sequential networked structure. A good example is the knowledge concerning movement corrections in sport which comprises different types of feedback, various learning theories, psychological and pedagogical aspects. By means of hypertext or hypermedia structures, multimedia offers options for an appropriate (re)presentation of this knowledge.

Antithesis 1: There is no evidence that learning is really supported by presenting complex multimedia structures

Complex knowledge structures are the result of a learning process. This does not mean that this result is appropriate for beginners who are just at the starting point of this process. Looking at didactic principles like 'from simple to complex' or 'from easy to difficult' the reverse seems to be true: beginners need to experience relieved learning conditions in order to prevent overload. Finally thesis 1 does not apply from didactical and psychological points of view. The phenomenon 'lost in hyperspace' also indicates that one can lose orientation with too complex information environments.

Thesis 2: Multimedia allows new freedom for learning – interactive and self-controlled learning, independent of space and time

When multimedia systems are available online or on storage devices, learners can activate information at any time and place they like (provided that they have the technology at hand). This allows new freedom for learning. Learners can decide on their own which and how much information they get and when and where they learn. Furthermore, interactive applications, e.g. simulations and animations, offer the autonomous testing of their ideas and assumptions.

Antithesis 2: Freedom implies responsibility – self-controlled learning requires new competences and generates new dependencies

Thesis 2 sounds very promising. On the other hand, learners must be able to control and regulate their own learning. Self-control comprises several dimensions (cognitive and meta-cognitive strategies, use of internal and external resources; [7]). When beginners have to self-control their learning they are subject to a dual-task context: They have to exercise and learn and they have to monitor their own learning process. Possibly this causes an overload that impairs learning.

One might oppose that the learning system can be designed to take the control responsibility, but this would again constrain the freedom for the learners. In addition, there are serious doubts whether machine-control can be as good as or better than human control.

Besides, multimedia learning produces new dependencies: the appropriate technological options (internet, multimedia computer, etc.) and technology-related skills have to be available in order to exploit the new freedom. Learners need to spend money for computer equipment and internet access. This might result in a 'digital divide' concerning education: the gap between humans who can afford technology and those who cannot might increase. Furthermore, new and serious 'time problems' arise with new communication technologies like e-mail [8].

Finally, when learning with multimedia freedom may not increase or even decrease because stakeholders who produce and offer multimedia content decide which and how much information is available in which form, at which time and from which location. This also holds for animations and simulations: users can manipulate and explore only the changes that are offered by the particular program.

Thesis 3: Multimedia offers various options for more authentic (re)presentation of information

Contrary to a book, multimedia claims to present information in a (more) authentic way. Text and static pictures are used in a book, whereas multimedia allows dynamic representations like audio and video. Furthermore, augmented reality (AR) or virtual reality (VR) can provide three-dimensional immersive visual information and, by means of data glove, data suit and motion platform, tactile, kinaesthetic and vestibular information. The only sensory systems that have been neglected by multimedia (so far) are the olfactory and gustatory systems. Multimedia opens up an incredible number of new options to present information. This is very attractive for sport science and education: Movements can be displayed from any perspective, using any form (stick figure, wire frame, geometric model, etc.) and colour. These options can enhance authenticity of presentations. Sounds and music are presented as audios (and not as text or score) and movements are presented as videos (and not as series of static pictures). Furthermore, artificial movements can be displayed that have never been realized by a sportsman.

Antithesis 3: Only a tiny portion of the new presentational options makes sense from a didactical point of view or is effective from a learning perspective

Do learners really need more than 16 million colours, countless presentation forms and thousands of different fonts? The opposite is true: certain combinations of colour and luminance as well as fonts are extremely detrimental to perception and learning [5]. Furthermore, (superfluous) animations tend to distract attention from the learning subject and impair focussing attention. In this respect ‘less is sometimes more’.

The numerous options that may enhance authenticity of presentations can also cause specific problems like the well-known ‘motion sickness’ when immersing into VR due to a coupling of authentic visual and acoustic information and non-authentic proprioceptive information: the visual system perceives motion, whereas the proprioceptive system does not. Particularly, being aware of the artificial nature of information might also cause a strange feeling about VR and AR.

Rützel [9] stresses that the authenticity of multimedia learning is somewhat superficial because information processing might be affected by the fact that a double interaction is required: The learner has to deal not only with the learning subject as a phenomenon, but also with the cognitive models that stand behind the multimedia presentation. If these models are not intelligible, learning becomes casual and didactics are not possible. What looks like a support at first glance might turn out as a possible learning barrier.

Finally, the variety of multimedia options cannot solve the problem that we have to know how humans perceive and learn in order to derive guidelines for an appropriate design of form and content. The inverse direction (from technology to learning) can be chosen, but this strategy requires extensive research on the interactions with human information processing and learning.

Thesis 4: Multimedia offers new forms of communication to enhance learning

In the past, face-to-face conversation was the authentic form of synchronous communication. Later the phone came up. The traditional form of asynchronous communication was the letter or post-card. Multimedia offers new forms of synchronous and asynchronous communication among learners and between learners and teachers: e-mail, chat, forum, videoconference, e-lecture, etc. Compared to the phone, synchronous communication can be more authentic and gradually comes closer to face-to-face communication. New forms of asynchronous communication shorten the time interval between the message and response. Whereas the response delay for a letter usually was some days, this delay may be only a few seconds or minutes with e-mail. This augments the communicative options and allows new forms of social interactions for learning. The gap between immediate synchronous conversation and delayed asynchronous communication is filled by new options.

Antithesis 4: Multimedia communications produce new constraints and dangers

Although the number of options for synchronous and asynchronous communication rises, there are also new constraints and dangers. Everyone knows that when having just clicked the ‘send mail’ button, the sender expects an immediate answer. An immediate answer might be prohibited by too much Spam mail or absence of the teacher because she is ill or attending a conference. When will the answer to this e-mail arrive? This can happen at any time, maybe in a minute or after some days. So we have to learn to wait [8].

Several forms of communication, e.g. chat and forum, allow users to disguise. Without any problems users can invent new identities and prevent to be like they are not. Using the new forms of communication exclusively might cause impoverishment of communication and social experience, loss of vivid and perceptual experience, disorientation and self-relatedness [9].

Thesis 5: Multimedia supports up-to-date information and worldwide propagation of information

Until a textbook appears on the market usually many months or years go by. Therefore, when the book is published the content is no more up-to-date. One might accept this problem for a basic or introductory textbook that contains approved and fail-safe knowledge. But this latency cannot be tolerated if up-to-date knowledge is to be conveyed to learners. In this regard, fast publication by means of CD-ROM, DVD or internet reduces latency considerably.

Antithesis 5: Speed reduces precision and selection of good quality might become difficult facing the vast amount of information
When new evidence has to be presented as fast as possible by means of multimedia there might not be time enough for a critical inspection and integration.

When so much information is available it may be difficult to select the appropriate information that is of high quality. Anyway it may be impossible to review all the available information. By the way, this might give rise to a new professional option: to systematically select and present the appropriate information depending on the special needs of the particular customer.

4 Learning with multimedia – a synthesis

Bearing in mind the different types of multimedia systems and the result that there is no simple argument in favour of or against multimedia learning it becomes clear that there cannot be a simple 'yes' or 'no' to the question whether multimedia enhances learning or not. Rather, we have to adopt a more specific view: on the one hand and without doubt, multimedia technology offers new options for learning, but on the other hand these new options also generate new constraints and possible dangers. One way to deal with this unsatisfactory situation is to resign and to reject multimedia learning for being 'too ambivalent'. But this would be too pessimistic. The possible surplus value of multimedia learning would be neglected. It is reasonable to ask the question: for which kind of learning and in which learning contexts are which MLS promising options? In Figure 2, a model is presented that illustrates the complex interactions of multimedia learning.

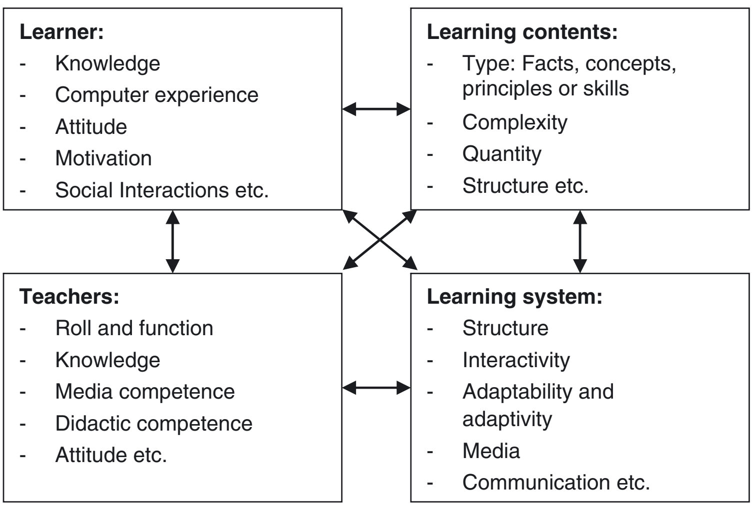

Figure 2: Complex interaction of learners, teachers, the learning content and the learning system.

Learners can have different knowledge level, computer experience, attitude, motivation, etc. Evidence shows that beginners need advice and guidance, whereas experts are able to navigate through a MLS on their own.

Teachers can take different roles, and have different knowledge level and computer experience. Furthermore, teachers' didactical competence and attitude contribute to multimedia learning.

The learning contents also play an important role in multimedia learning. Depending on different types of content, complexity, quantity and structure, the MLS has to be designed in a specific way (see Section 2).

The structure and features of the MLS is the most important factor within the complex framework of interactions. Interactivity, adaptivity, adaptability, media and communication determine the options that can be used. These options have to fit perfectly into the complex interactions of learners, teachers and learning contents.

5 Learning with multimedia – what science tells us

Many scientific areas contribute to the understanding of multimedia learning, e.g. psychology, pedagogy, computer science, sociology and physiology. In this section we focus on the perspectives of learning theory and didactics and the experimental evidence.

5.1 Learning theories and didactics concerning multimedia learning

When multimedia is applied to learning, a look at learning theory and didactic concepts is mandatory. We can find an unmanageable variety of psychological and didactical approaches that are referred to in order to substantiate multimedia learning. Kearsley [10] enumerates more than 50 different theories and concepts of learning and instruction relevant to multimedia learning. A small sample of these approaches is shown in Table 1.

Table 1: An overview of theories and concepts relevant to multimedia learning.

Theory	**Short description**
Behaviourism (Skinner)	Focus: stimulus–response relations Repeated rewards (consolidation)
Genetic epistemology (Piaget)	Focus: individual cognitive structures Development through active involvement and challenges Stimulation by social interaction
Constructivism (Bruner)	Knowledge acquisition – active-constructive process Significance of learning material Cooperative learning in real-world settings

Table 1: Continued

Theory	Short description
Multimodal memory (Engelkamp)	Modality-specific representations Conceptual representations “Do-effect” – significance of action execution
Cognitive-plausibility-hypothesis (Jonassen)	Analogy hypertext/hypermedia – organization of human knowledge Significance of networked knowledge presentation
Sociocultural theory (Vygotsky)	Age-dependency of cognitive development capacity Significance of social interaction
Anchored instruction (Bransford)	Video-based presentation of case studies Narrative structure of information presentation Generative learning (autonomous search for solutions) Embedding all required data Complex problems
Cognitive apprenticeship (Brown, Collins)	Presentation of expert problem-solving procedures Four dimensions: contents, methods, tasks and context
Problem solving (Newell, Shaw, Simon)	Starting point: problem to be solved Significance of novice–expert interaction and task context
Distributed cognition (Hutchins)	Interactions of individual, environment and cultural artefacts Significance of technology
Cognitive flexibility (Spiro)	Focus: learning in complex and ill-structured contexts Re-structuring of knowledge triggered by environmental challenges Transfer of knowledge and skills Basis of activities: multiple representation of context (different perspectives), many case studies
Situated cognition (Lave)	Context-dependency of learning (problem, action, situation, culture, etc.) Critical components: social interaction and cooperation
Goal-based scenario (Schank)	Self-motivated, goal-oriented learning – seven principles (constructivist approach)
Self-regulated learning/ metacognition (Zimmermann)	Self-control of cognitions by the individual Self-observation, self-evaluation, self-reaction

To sum it up, discussion of multimedia learning reflects three mainstreams of learning theories: behaviourism, cognitivism and constructivism. Every approach contributes considerably to the understanding of human learning. Whereas behaviourism focuses on stimulus–response relations, cognitivism (or representationalism) focuses on individuals and their mental processes. Constructivism also takes into consideration social interactions.

5.2 Experimental evidence concerning multimedia learning

Dealing with empirical evidence, the first question is how to examine multimedia learning from a scientific point of view. Bearing in mind the numerous interacting factors that influence multimedia learning, it seems to be rather hopeless to examine multimedia learning in general. Only a very specific constellation of conditions can be tested. In order to ensure internal validity a max-con-min strategy is required [11]. According to this strategy, research tries to maximize the variance caused by the treatment on the one hand and to control or minimize the unwanted variance caused by intervening variables. The experiment is the appropriate research method in order to realize a max-con-min strategy. Concerning multimedia learning experiments, the appropriate experimental design is illustrated in Table 2.

In order to compare multimedia and alternative learning two experimental groups are needed. Pre- and post-tests are required to assess initial and final learning scores. Control groups help to test for longitudinal effects that may be caused by other factors that differ from treatment (e.g. maturation or seasonal effects). Examining two control groups allows to test the effects of repeated testing.

The second question concerns the choice of the independent variable(s). Concerning multimedia learning four basic types of variables are usually assessed:

– Learning scores (LS)
– Learning time (LT) or learning rate
– Learning efficiency (LE) or learning gradient (i.e. ratio of learning gain and learning time)
– Learners' attitude

Table 2: Experimental pre-post design for analysing multimedia learning.

Group	Pre-test	Treatment phase	Post-test
Multimedia learning	×	Multimedia application	×
Alternative learning	×	Alternative method	×
Control 1	×	No treatment	×
Control 2	–	No treatment	×

However, many studies of multimedia learning suffer from poor research design [12, 13]. Instead of appropriate experimental pre-post designs with control groups often descriptive studies, case studies or studies without control groups have been performed. This lack of quality is a particular problem for adopting quantitative methods of research synthesis (meta-analyses). Nevertheless, results of these approaches are discussed in the following text. We subdivide this section into two parts: first we discuss studies dealing with cognitive learning and second we analyse studies dealing with motor learning. Although there are some commonalities of cognitive and motor learning, the main difference is that in cognitive learning the mind is the primary means to solve the task whereas the body is used for solving motor tasks. Unfortunately, meta-analyses and reviews only exist for cognitive learning in different areas. Reviews of multimedia cognitive and motor learning in sport and sport science do not exist.

5.2.1 Cognitive learning

Firstly, reviews of cognitive learning in various areas are presented and discussed. Secondly, selected studies dealing with cognitive learning in the area of sport and sport science are analysed in more detail.

Numerous qualitative reviews and meta-analyses have been published summarizing research comparing traditional to technology-supported learning (see Table 3). Meta-analyses are specific statistical techniques that allow to summarize and integrate the results of primary studies. Furthermore, meta-analyses allow to correct the results for sampling error and poor reliability. On the other hand, meta-analyses raise some problems of validity, e.g. the file drawer problem, the 'apples-and-oranges' problem or the 'garbage in – garbage out' problem. The file drawer problem means that there might be many non-significant studies that have not been published. This may cause a strong bias towards an overestimation of effect size. The 'apples-and-oranges' problem denotes the fact that the studies being integrated show particular differences that affect comparability. The 'garbage in–garbage out' problem raises the argument that studies of poor quality might be integrated leading to invalid results. Some of these problems can be overcome by adopting specific meta-analytic procedures. Therefore, meta-analyses can serve as a first overview of a specific research area. The best way to deal with the above mentioned problems is to combine several techniques of meta-analysis with a qualitative review.

Some reviews address selected aspects of technology-supported learning, e.g. interactive video [14, 15, 16], computer-assisted instruction (CAI, [17]), computer-based instruction (CBI, [18]), web-based teaching (WBT, [19, 20] distance education (DE, [4, 21]), educational simulations [6] or learners' control [22]. Furthermore, papers summarize existing reviews (e.g. Ref. [18]).

Overall, current evidence shows that multimedia learning in general has positive effects on learners' performance, learning time and attitude. The mean effect sizes (*ES*) are around $d = 0.5$, i.e. differences of means between experimental and control group are about half a standard deviation (medium or moderate effect). However, most of the meta-analyses reveal that *ES* are not homogenous.

This result is a strong indicator that there are factors that moderate multimedia learning effects. In Table 3 selected moderators are listed. They range from learners' characteristics to technical and didactic features of the learning system. Once again the complex interaction of learners, teacher, learning system, learning subject and learning environment becomes evident (see also Figure 2).

Table 3: Results of meta-analyses and reviews concerning factors influencing multimedia learning.

Moderator	**Reviewers and study**
Type of learning task, e.g. fast search through complex information	Roblyer, Castine & King [18] Dillon & Gabbard [23]
Learning subject: natural science and language – positive effects; history, sociology, etc. – no effect	Sahin [21]
Knowledge and ability level of learners	Roblyer, Castine & King [18] Dillon & Gabbard [23]
Interaction of knowledge level and system guidance: guidance – better for beginners	Steinberg [22] Dillon & Gabbard [23]
Fit of learners' characteristics and learning system	IHEP [12] Dillon & Gabbard [23]
Study duration: shorter studies – greater effects	Roblyer, Castine & King [18] Kirkpatrick & Cuban [13] Cavanaugh [24]
Group size: large and medium groups ($\geq$50 students) better than small groups ($<$50)	Sahin [21]
Study design: control group design – lower effects than one-group plans	Liao [19, 20]
Substitute vs. complement: greater effects for supplement	Roblyer, Castine & King [18]
Teacher: - greater effects of different teachers - greater effects of same teacher	 Roblyer, Castine & King [18] Liao [19]
Information presentation and interaction: - simulation better than interactive picture disc or interactive multimedia - simulation practice better than pure presentation	 Liao [19, 20] Lee [6]
Teacher role and didactic concept	Kirkpatrick & Cuban [13]
Synchronous vs. asynchronous distance education (DE): asynchronous DE – better than synchronous DE	Bernard *et al* [4]

Another interesting publication claims that most of the studies comparing traditional to technology-based learning show ‘no significant effects’. Russell [25] collected more than 350 studies finding no significant difference. Hence he coined the term ‘the no significant difference phenomenon’. On his website (URL: http://www.nosignificantdifference.org/) Russell collects all the relevant studies and publications.

Concerning cognitive learning in sport and sport science the following studies have been published comparing traditional and multimedia learning.

Kerns [26] compared traditional (TI) to CAI in teaching tennis rules and strategies. The subjects (43 undergraduate students) were instructed for eight weeks by means of either TI (8 times 50 minutes) or CAI (first tutorial: $M = 44.6$ minutes; second tutorial: $M = 53.1$ minutes). Before and after the treatment and five weeks later a written test was administered. The results show no significant difference between TI and CAI.

Everhart *et al* [27] compared traditional (TI) to CBI in learning about nutrition and physical activity. The subjects (78 high school students) were divided into two groups: one group used a multimedia program (four times within one year) whereas the other group did not. Concurrently all subjects participated in physical education (PE) class activities for one year. Before and after the treatment subjects passed a physical fitness test and completed a questionnaire on physical activity engagement. There was no significant difference between the two groups and no interaction but a tendency for better results of the TI group.

Antoniou *et al* [28] compared TI to multimedia computer-assisted instructions (MCAI) and a combination of TI and MCAI (CI) when learning basketball rules. The subjects (73 PE students; age: 18 ± 1 years) had to learn rule violations in basketball for 5 hours. The MCAI group used a multimedia program whereas the TI group was educated by an international referee. The CI group received 2.5 hours MCAI and 2.5 hours TI, respectively. Before and after the treatment students passed a written and a video test, respectively. One week later a retention test was performed. Concerning the written test, the authors found a significant interaction of measure $\times$ instruction, i.e. only the TI and CI groups showed significant learning effects. There was no superiority of the multimedia groups. Concerning the video test neither the main effect of instruction nor the interaction of measure $\times$ instruction was significant.

In general most of the studies analysing multimedia learning in sport and sport science do not find a significant difference between traditional and multimedia learning.

Overall, current evidence shows that multimedia learning *has the power* to enhance learners’ effectivity, efficiency and attitude compared to traditional learning if the various constraints are taken into account, specific constellations of conditions are present and a fit of learning system, learners’ characteristics, teachers’ characteristics and learning content is ensured. However, there is a great number of studies finding no or only little advantage of multimedia learning (e.g. Refs. [4], [25]). There is no general superiority of multimedia learning over traditional learning.

Table 4: Comparison of different media concerning LS, LT and LE, according to Hasebrook [30].

Medium	**Learning score (LS)**	**Learning time (LT)**	**Efficiency = LS/LT [%]**
Text only (= 100)	***100***	***100***	***100%***
Picture	120	120	100
Picture + audio/movie/video	130	120	108.3
Computer training program	100	70	142.9
Animated pictures	120	130	92.3
Media mix	160	140	114.3

Italics in the second row indicate, that 'text only' was set to 100 as the reference value.

Furthermore, multimedia learning shows an interesting side effect: due to high motivation and interest, learners engage more in multimedia learning [29, 30]. In Table 4 general benchmarks for learning score, learning time and LE of different media and combinations of media are presented. Except for computer training programs, all other media increase the learning time. Depending on the outcome (learning score) the LE increases or decreases compared to 'normal' text-only applications. From this perspective computer training programs seem to be the most efficient learning systems but they do not fit every learning goal and learning context. Combinations of media are also very promising whereas animated pictures may decrease learning efficiency.

5.2.2 Motor learning

Only recently a few studies on motor skill learning have been published by the research group of Vernadakis *et al* [31–33].

Vernadakis *et al* [32] compared TI to CAI when learning the setting skill in volleyball. The subjects (32 pupils; age: 12–14 years) had to learn the skill within 9 weeks. TI comprised nine 40-minute periods of direct teaching style (verbal instruction: 15 minutes; supervised physical practice: 15 minutes). The CAI received the same formal schedule (computer time: 15 minutes; unsupervised physical practice: 15 minutes). Before and after the treatments, a knowledge test and a skill test were performed. Both groups improved but there were no significant differences between TI and CAI.

Using a similar design, Vernadakis *et al* [31] compared TI, CAI and mixed instruction (MI). The subjects (48 pupils; age: 12–14 years) had to learn the shooting in basketball within ten sessions. This time the teaching periods lasted 45 minutes (verbal or computer instruction: 15 minutes; supervised and unsupervised physical practice: 15 minutes). The MI group received TI during the first five weeks and switched to CAI for another five weeks. A knowledge test and a skill test were performed before, immediately after and one week after the treatment, respectively. All three groups improved but again there were no significant group differences.

Vernadakis *et al* [33] compared TI, CAI and MI using the schedule of the first study. The subjects (48 pupils; age: 12–14 years) again had to learn the setting skill in volleyball within 10 weeks. Each session lasted 40 minutes and comprised 15 minutes of verbal or computer instruction and 15 minutes of supervised or unsupervised physical practice. Again, a knowledge test and a skill test were performed before, immediately and one week after the treatment, respectively. All groups improved skill and knowledge but there were no significant group differences.

To sum it up, there was no evidence in favour of multimedia skill learning of pupils aged from 12 to 14 years. In two studies there was a non-significant tendency towards a slight superiority of MI. Unfortunately all three studies suffer from a severe methodological problem: the CAI group does not only use MLS but practises unsupervised, i.e. without extrinsic feedback by the teacher. This is different from the TI group. Therefore there is a confounding of media and feedback effects. Furthermore, effective or net instruction time, i.e. pure teacher and pure computer instruction time (subtracting time for organization or starting the computer program), and computer experience were not controlled.

Research on multimedia skill learning is still in its beginnings. Further work has to be done in order to improve knowledge using more sophisticated research designs.

6 Learning with multimedia – a look into the future

In this section the future of multimedia as an educational tool for sport and sport science is discussed. Looking at the results of research and development projects there are two critical factors strongly influencing the success of multimedia learning: quality and sustainability. These issues will be discussed in the first part. In the second part selected possible scenarios of multimedia learning are proposed.

6.1 Quality and sustainability of multimedia learning

From the existing evidence concerning the effectivity and efficiency of multimedia learning, the conclusion can be drawn that multimedia learning is not effective in itself. Rather particular conditions have to be fulfilled in order to exploit the potentials and surplus values of multimedia learning. To ensure that multimedia is not just a mayfly, the aspects of quality management and sustainability have to be considered.

The term ‘sustainability’ means that multimedia learning is developed, implemented, used and improved in a systematic and enduring way. Sustainability pertains to five dimensions:

– Didactics and pedagogy
  The didactical and pedagogical surplus value of multimedia learning needs to be secured, e.g. by integrating multimedia learning into curricula.

- Economy
  Additional financial resources are required for developing and maintaining MLS. A continuous cost–benefit calculation and allocation of financial resources for staff and material are indispensable. Sustainability needs to be ensured by appropriate business models.
- Organization and administration
  Multimedia learning projects require an efficient project management and a systematic integration into the respective working area.
- Technology
  Both provider and user of multimedia learning have to ensure that their equipment meets the requirements of stability and security. When standards of technology change, MLS have to follow.
- Society and culture
  Multimedia learning should be compatible to learning culture. As an alternative, multimedia learning can contribute to cultural and social innovations.

Sustainability implies quality. Multimedia learning systems can only be sustainable if they are of high quality. Therefore, quality has to be continuously ensured. Quality of multimedia learning means that ‘relevant content is appropriately processed according to the respective task and presented in a way that ensures good usability’ [34], translation by J.W.).

There are numerous norms and quality standards. Some of these standards pertain to software in general (e.g. ISO norm 9241) or to learning with electronic media (e.g. LOM and SCORM).

In order to ensure that multimedia systems fulfil these requirements a systematic development process is needed (for a review: see Ref. [35]).

6.2 Scenarios of an uncertain future

Because of the complex interactions of learners, teachers, learning tasks, learning system and learning environment many combinations are possible. These combinations range from the pure online learning using multimedia exclusively to pure traditional learning using no multimedia. We present three possible scenarios: learning with multimedia as support vs. the substitute of traditional education, and serious games.

6.2.1 Multimedia as support – digital lecture hall and digital gym

Monday, May 15, 8:30 a.m. – The lecture on ‘Basics of movement science’ takes place in lecture hall S1 01/054. The students enter the lecture hall. The teacher presents the topic ‘informational support of motor learning by means of instruction and feedback’. He complements his oral presentation by a multimedia presentation that is displayed by a beamer. The presentation contains texts, pictures (photos, animated diagrams and schemes), audios (samples of sonification) and videos (sport movements). The students use digital copies of the transparencies they have downloaded from the teacher’s website. They have brought their notebook with them and may drop digital notes, e.g. a mind-map of the lecture. The teacher uses the 'digital lecture-hall', i.e. he can show also the previous transparency on the screen. Students can store these transparencies combined with their own notes on their own notebooks. The teacher can write notes onto the transparencies by using a touch-screen. These notes are also displayed on the screen and can be recorded for later access. By means of special interfaces (e.g. wireless LAN and Bluetooth), students can transfer spontaneous information to the teacher, for instance questions, comments, feedback or notes. The teacher can have a look at this information because his notebook is connected to a server. If it is necessary he can react to this information. Within the last five minutes of the lecture, the teacher tests the knowledge of the students by asking five comprehensive multiple-choice questions. The students can transmit their answers by notebook, cell phone, PDA or 'Smartphone'. The teacher immediately gets the results and has the opportunity to give immediate comments to improve understanding.

In this scenario – despite all technology – students are required to be present because the transparencies are not self-explanatory. Illness and other obstacles raise the problem that students have to get the information they missed. Reading the literature, talking to fellow students or studying the notes of fellow studies is only a poor substitute of the lecture having been presented by multimedia with high informational and didactic quality. In order to participate in the technology-based interactions with the teacher, the respective technical devices need to be available. There is no mutual communication of the students within the lecture hall because everyone is engaged in listening, dropping notes and controlling the tools for interaction and communication. Hopefully all devices work well and there is no loss of power.

Wednesday, May 17, 9:50 a.m. – The education of apparatus gymnastics for female students takes place in the gym. Today, students have to practise the flic-flac on the floor. The female teacher works with notebook and beamer. She delivers various information concerning the flic-flac: verbal cues, videos taken from different perspectives, applying different presentation speeds, demonstrations of physical guidance, information concerning the biomechanical structure of the movement and didactical information. After this phase of detailed instruction and a warm-up phase physical practice starts. The teacher adopts a coupling of video camera and notebook. The movements of the students are recorded for later analysis during the phase of reflection (errors and reasons, critical phases, didactical implications, etc.). The whole material is stored and after the lesson it will be available on the server. In this scenario the physical presence of the students is also required.

The two scenarios illustrate on the one hand the potentials of multimedia for education that have been discussed. Numerous didactical options are available that need to be chosen appropriately (which is not at all trivial!). On the other hand, the physical presence of the teacher and the students is a 'sine qua non'. This prerequisite is not always fulfilled. And even if it were the 'volatility' of present education always raises the problem that essential information may be missed or misunderstood.

6.2.2 Virtual multimedia – online course presented by a LMS

Monday, May 15, 8:30 a.m. – No student enters the lecture hall. The lecture 'Basics of movement science' is presented exclusively via internet. Students can get all the necessary information by means of a learning management system (LMS):

- The lectures have been recorded in a studio. They can be downloaded and displayed using a specific plug-in (see Figure 3).
- Further material is available: transparencies, interactive simulations and animations, videos, etc. By using this material students can confirm, transfer and deepen their knowledge and understanding.
- By means of interactive tests, students can check their knowledge. Different tasks like multiple-choice questions, cloze, drag-and-drop and assignment tasks have to be solved. With every task they get helpful comments.
- The LMS offers several options for synchronous and asynchronous communication: forum, chat rooms, videoconference and e-mail.

The options of this scenario for education are evident: Independent of space and time, the students can use the numerous offers. On the other hand, this kind of learning requires students' ability and readiness to self-control their own learning because there is no external force like time-table that guides them.

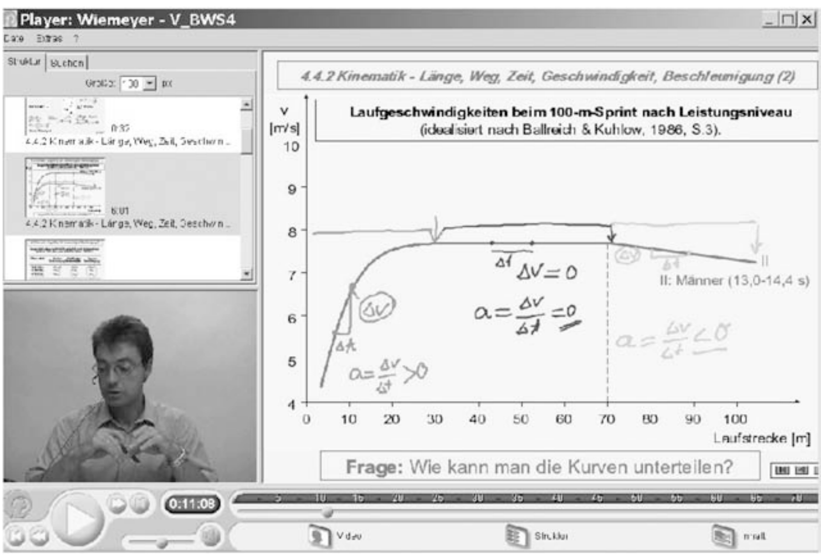

Figure 3: Example of a pre-recorded lecture with transparency navigation (top left), video (bottom left), transparency with notes (right) and control buttons (bottom).

Furthermore, financial resources for staff and technology are required in order to develop, maintain, offer and use multimedia online systems.

The scenario of a learning that takes place exclusively online is not yet used by a great number of students. Most students prefer a dual-mode or 'blended' learning strategy combining being present and using online material.

6.2.3 Playing virtual learning games – 'serious games'

Every human being is fond of playing. Games are (usually) demanding, motivating, instantaneous, open, and free of extrinsic goals and purposes. And every human being has to perform lifelong learning to adapt to the dynamically changing requirements of work, leisure, etc. Therefore, it seems reasonable to combine education and playing games. This is meant by the term 'serious games'.

VirtualTeacher – Level 1. The virtual PE teacher enters the virtual gym. In front of her, the virtual gym floor extends. The pupils stand together in groups or sit on the bench. In this lesson, the flop technique in high jump will be physically practised. The teacher has to gather the pupils, organize the practice, and give instructions and feedback. Level 1 is easy (beginner level). The pupils readily carry out instructions, organization is simple and the movement errors can easily be observed and removed. If all the tasks are solved, the final score is determined. Depending on this score, the teacher reaches level 2 or has to solve another level 1 task that is of the same difficulty as the first task but happens in a different context, e.g. teaching the crawl technique in swimming. With increasing level, the tasks gradually become more difficult and complex. Disturbances can occur, injuries require fast reactions, sport devices are missing or defect and the movement errors are more difficult to detect and correct.

The virtual PE teacher is confronted with increasingly complex and difficult tasks. Finally, if all the tasks have been solved successfully (and – as a side effect – all required competencies have been acquired) the 'high-score' may be beaten and the player may be awarded 'master of teaching PE'. And of course the player gets the respective credit points and grade. Serious games are just in their infancy. If they are applied appropriately, they may improve multimedia education due to the motivating combination of education and game. On the other hand, developing serious games of good quality is expensive. The normal budget of a commercial game project is approximately 15 million Euros.

7 Multimedia as a research tool – (still) unused potentials

So far we have discussed multimedia as an educational tool that has been the subject of research. In this section we address the option of multimedia to be used as a research tool.

Before multimedia came up, computers could only be used as devices for acquisition and processing of (predominantly numerical) data. The computer offered methods to analyse data and to present the results in an appropriate way, e.g. using diagrams.

Now, multimedia computers offer new options for research. Numerous combinations of dynamic and static media are available that can serve as research tools. These options range from new forms of dynamic and interactive instruction to complete control of experiments. In this section we present three examples of how multimedia can be used to support research: assessing the image of a movement, manipulating the visual input and instructing the learners.

7.1 Assessing the mental image of a movement

When performing experiments on motor learning, it is important to assess the current status of the internal representation, because particularly in the initial learning phase it changes constantly [36].

Conscious internal representations of movement consist of different components: visual, auditory, proprioceptive and verbal representations. Most of the existing methods to assess internal representations either use verbal or visual tests (see Figure 4).

The main disadvantage of these methods is that only the results of the test can be analysed. We developed a method that allows to record the process of reconstructing the internal representations [37], see Figure 5).

By means of the computer-assisted picture selection test much more information can be acquired compared to other procedures:

- Separate assessment of decision and movement time
- Errors and corrections
- Order of selection (e.g. primacy and recency effects in short-term memory)
- Partial and total time.

This testing program is only a first step towards a more sophisticated assessment of mental images of movement. Multimedia allows us to use dynamic presentations like audios, animations, simulations or video. One option is a multimedia program that displays synthetic movements based on the reconstructions of the users. Users only determine the key postures and the system will calculate the intermediate frames.

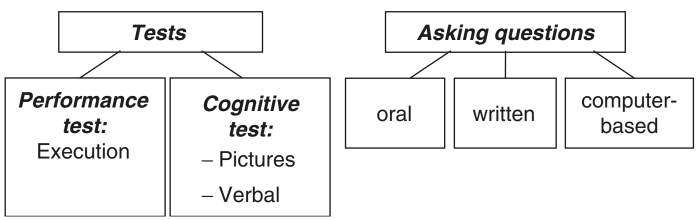

Figure 4: Options for assessing internal representations (from Ref. [36]).

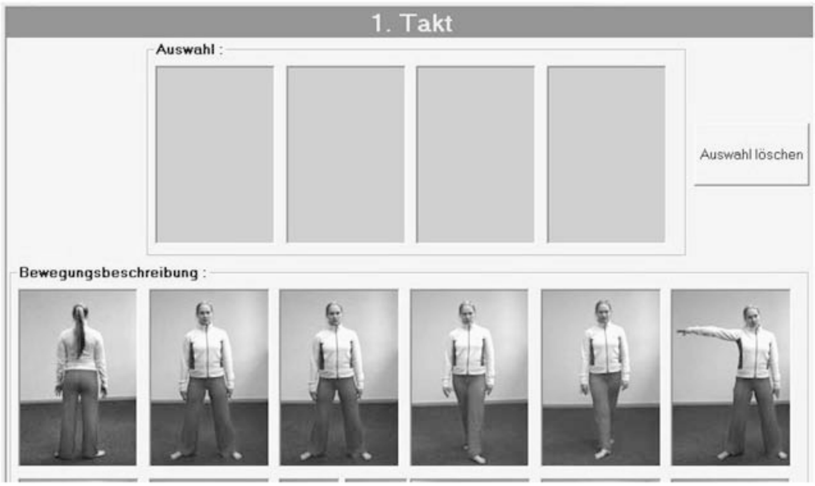

Figure 5: Computer-assisted picture selection test (from Ref. [37])

In general, multimedia has the potential to enhance practicability, objectivity and reliability of many research methods:

- Psychological tests of cognition, perception, emotion, motivation, volition, etc. can be completely performed and controlled by a multimedia system: instruction, testing procedure, feedback and evaluation.
- Multimedia features like auditory instructions or auditory feedback can complement online questionnaires to improve completion.
- Interviews can be performed by a multimedia system. The system asks questions and records the answers. Based on the progress in Natural Language Processing (NLP), a sophisticated analysis will soon be possible.

7.2 Manipulating sensory input

A further interesting research area for multimedia applications is manipulating sensory input: Virtual or Augment Reality (AR) systems, e.g. simulate sensory (especially visual) worlds. AR systems overlay real world perception with artificial stimuli. This method can be used to instruct learners and to direct their attention. Kahrs *et al* [38] have developed an AR device (head-mounted display) that illustrates the trajectory of the ball travelling to the basket to support basketball players in free-throw situations (see Figure 6).

By using VR or AR systems many issues of basic research can be addressed, e.g. focus of attention (external vs. internal) or optic flow field in relation to human motor control and learning. The great advantage of these technologies is the strict control of visual stimuli. This cannot be achieved by other techniques. One problem that has to be solved is that such sensor-based systems (still) have

Figure 6: AR application for basketball [38].

a latency of at least 50 milliseconds. For fast movements like in soccer, tennis or table tennis this latency is too long to adjust the visual image to changes of the environment fast enough. For a ball velocity of 30 metres per second, this would mean that the ball has travelled 1.5 metres before the new image is displayed. This is the reason why currently only slow changes of position and environment can be efficiently processed.

7.3 Multimedia instruction

Another purpose multimedia can be used for is instruction. Researchers can apply simple multimedia instruction or complex interactive information systems. Visual, auditory and verbal information can easily be combined and presented in an interactive way. An interesting issue that has recently been addressed is ‘sonification’, i.e. the production of multi-dimensional sound based on selected biomechanical parameters of the movement [39].

8 Conclusions

Multimedia has much to offer to research and education in sport and sport science. However, there are numerous conditions that have to be considered to really tap the full potential.

Concerning multimedia education, research has revealed many factors influencing the effects of multimedia learning. At first glance, this situation might look disappointing. On the other hand, the detailed body of knowledge helps to select particular promising combinations based on solid scientific evidence. Research on multimedia learning tells us whether or why particular combinations work and others do not. Sport and sport science have not tapped the full potential of multimedia learning yet. Particularly motor learning in sport has been investigated only in very few experiments.

Furthermore, the numerous potentials of multimedia as research tools are also very promising. Multimedia may help to enhance objectivity of instruction, perform assessments (interviews, questionnaires, tests) automatically and control experimental manipulations of perception in a more systematic way.

Finally as is the case with all technology, there is no easy way to adopt multimedia for enhancing education and research. Multimedia is neither the panacea nor the Pandora's Box – it is just a particular progress of technology opening new potentials but also posing new problems. Multimedia requires deliberate use and critical reflection. But these demands have always been the strengths of science.

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Biological Monitoring

Theory and Applications

Edited by: ***M.E. CONTI****, University of Rome 'La Sapienza', Italy*

This book provides the reader with a basic understanding of the use of bioindicators both in assessing environmental quality and as a means of support in environmental impact assessment (EIA) procedures. The book primarily deals with the applicability of these studies with regard to research results concerning the basal quality of ecosystems and from an industrial perspective, where evaluations prior to the construction of major projects (often industrial plants) are extremely important.

Environmental pollution and related human health concerns have now reached critical levels in many areas of the world. International programs for researching, monitoring and preventing the causes of these phenomena are ongoing in many countries.

There is an imperative call for reliable and cost-effective information on the basal pollution levels both for areas already involved in intense industrial activities, and for sites with industrial development potential.

Biomonitoring methods can be used as unfailing tools for the control of contaminated areas, as well as in environmental prevention studies. Human biomonitoring is now widely recognized as a tool for human exposure assessment, providing suitable and useful indications of the 'internal dose' of chemical agents.

Bioindicators, biomonitors, and biomarkers are all well-known terms among environmental scientists, although their meanings are sometimes misrepresented. Therefore, a better and full comprehension of the role of biological monitoring, and its procedures for evaluating polluting impacts on environment and health is needed. This book gives an overview of the state of the art of relevant aspects of biological monitoring for the evaluation of ecosystem quality and human health.

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Incorporating Environmental Electromagnetic Fields

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Computers in Railways XI

Computer System Design and Operation in the Railway and Other Transit Systems

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This volume features the proceedings of the Eleventh International Conference on Computer System Design and Operation in the Railway and other Transit Systems. It provides the latest information on the use of computer-based techniques, and promotes a general awareness of these throughout the business management, design, manufacture and operation of railways and other advanced passenger, freight and transit systems.

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