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Improving sports performance with wearable computing

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Contents

1 Introduction

The wish of improving sport performance for defeating ones rivals is as old as sport competition itself. It is easy to see that this personal goal of each athlete is hard to achieve nowadays, since the standards are increasing constantly. Consequently there is a constant need for better and more in-depth training methods. Trainers cannot rely solely on their experience, but need to keep up with latest training methods and adapt them to the individual needs of each athlete. On the other hand the communication between trainer and trainee needs instruments that clarify changes and improvements of training methods.

By using ubiquitous computing technologies trainers are able to analyze movements of an athlete or even patterns of a group of athletes simultaneously. Different kinds of sensors embedded in sportswear give an overview over all kinds of measurable body functions.

But not only professional athletes are interested in efficiently improving their performance. For hobby athletes the improvement of performance is often the main motivation for doing sports.

We will give an overview of different projects on wearable computing that aim to improve sports performance and will give some ideas of some possible future projects.

2 Technology Overview

There are already a number of products on the market that fall into the category of wearable computing with the aim of improving sports performance. Most common among those are heart rate monitors in the form of a sensor strap that is worn around the upper torso and wirelessly connected to a watch. Other components included are pedometers or GPS receivers. These system are available in different degrees of sophistication. Most of these systems can be used in conjunction with a PC to plan and analyze training more efficiently. They are widely used among hobby athletes and professionals alike. Some of the most complete products in this category are the outdoor sports computers by FRWD Technologies Ltd., that record route, location, speed, distance, time, heart rate, altitude, air pressure and temperature. They are also able to display all that information in realtime in conjunction with a Symbian OS mobile phone. Another similar product is the Nike + iPod sport kit that consists of an add-on module for the iPod and a wireless sensor embedded in the shoe. It measures stride frequency, distance time and calculates burned calories and stores them in the iPod for later analysis.

Most of the systems presented in the papers of section three use some sort of sensor to detect and measure human motion. The sensors most commonly used are gyroscopes and accelerometers, sometimes in conjunction with methods already used in motion detection and analysis, like motion capturing or highspeed cameras. Gyroscopes are usually used to measure or maintain orientation, based on the principle of conservation of angular momentum. The basic component is a spinning wheel on an axle, that tends to resist changes to its orientation due to the angular momentum of the spinning wheel. So if the gyroscope is mounted in gimbals it will maintain its orientation. By mounting sensors on the gyroscope and gimbals it is possible to measure changes in orientation. One use of gyroscopes is the artificial horizon used in airplanes. Accelerometers are sensors used to measure acceleration. This is done by measuring the inertial force of a proof mass. One very common use of accelerometers is in deployment systems of car airbags. Although there are commercially available gyro sensors and accelerometers that can measure 3D orientation changes (gyroscopes) and 3D acceleration (accelerometers), most of the research teams opted to build their own 3D measuring gyro sensors or accelerometers by mounting three single axis sensors at right angles to each other for their prototype systems.

There are evidently two distinguished possibilities to approach the process of performance improvement:

1. Analysis of the motion to check the motion technique
2. the continuous check of body functions like heart rate, body temperature, etc. for an optimal training due to actual conditions.

3 Motion Detection and Analysis

In this section we will present some approaches to improve sports performance by using wearable sensors to detect and analyze human motions in sports.
To overcome some of the inherent problems in current sports measurement methods, the systems presented in this section use body mounted sensors to detect and measure human motion. Common techniques for motion analysis include motion capturing or straightforward video analysis. Problems with motion capturing are low resolution in narrow joints, such as the wrists and ankles, and the visibility of marking points. Video analysis only offers a very limited perspective, minimal movements might not be noticable, and in dynamic settings important details may be hidden from camera view. In most applications of motion capturing or video analysis these limitations are very minor, but since the research in the following papers focuses on situations that amplify these limitations the approach with body mounted was taken.

3.1 Golf Swing - Kinematical Analysis And Measurement Of Sports Form

The measurement method and system presented in this paper [7] uses a combination of 3D gyro sensors, a high speed camera and a microphone in conjunction with a rod-and-link model of the human body. The 3D gyro sensors employed measure rotation and the link model is used to estimate translation using straightforward equations. As the paper's title shows the system is applied to measuring the golf-driver swing.

To simplify the link model several assumptions are made based on the movement during a golf-driver swing. For example the right arm as well as spine and neck can be described as one rigid rod, because they actually move as one rigid rod during the swing motion.

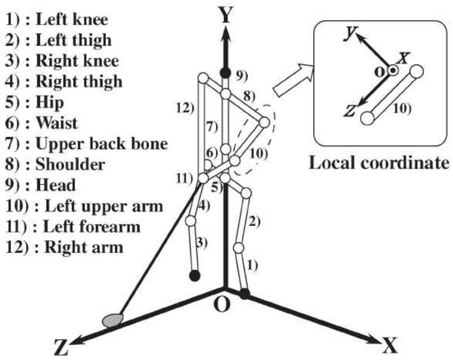

Figure 3.1: Rod-and-Link model on global coordinate system and local system for upper left arm

As figure 3.1 shows, the link model is defined on a global coordinate system with local coordinate systems for each rod.

The system needs to be calibrated for the specific user. The lengths of the body parts and the initial angles of the relevant joints are measured while the golfer is not moving. The angles around the axes of the local coordinates are measured with the 3D gyro sensors attached to the relevant body parts, e.g. knee, shoulder, wrist, etc. The 3D angular velocities measured by the gyro sensors are transfered to a PC. The microphone in the setup is used to synchronize the sensor data with the video captured by the high speed camera. The test subjects were one novice and one mid-level golfer. The rating criteria for the golf-driver swing were derived from golf training textbooks written by world-class golfers, describing the correct technique linguistically and qualitatively. One of these criteria, measured quantitavely with the system, is that from address to finish the translations of head, shoulder and waist must be minimized. The test showed that the system can verify the linguistically and qualitatively described criteria from the textbooks.

Table 3.1: Maximum displacement in meters

Body Parts		Head			Shoulder			Waist	
Axis	X	Y	Z	X	Y	Z	X	Y	Z
Middle	-0.05	0.05	-0.20	-0.14	0.03	-0.02	-0.07	0.01	-0.03
Novice	-0.09	0.27	-0.05	-0.27	0.18	-0.12	-0.07	0.02	-0.05

3.2 Sound Feedback For Powerful Karate Training

This paper [6] proposes a system for generating sound feedback during karate training to improve and simplify the learning process and to help motivate beginners. The sensor device includes a two-axis accelerometer, a sound generator and a microprocessor. The sound generator can generate music, special effects, warnings and various other types of sound.

For beginners in martial arts it is very difficult to check the correctness of their movements by themselves since the correct execution of many techniques involves very small and detailed movements. The approach with body mounted motion sensors combined with realtime sound feedback was chosen to be able to detect the correctness of the movements and to give the trainee immediate feedback.

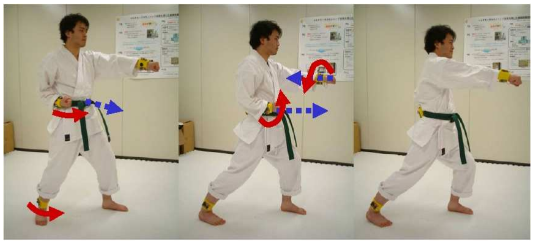

Figure 3.2: Illustration of Tsuki-movements

The test subjects were performing a basic punch, called Tsuki, which involves twists of both wrists and the waist in its correct execution (figure 3.2). The sensor and sound feedback units can be used for different training goals. For example they can help users get the correct timing of waist and wrist movements by creating a rhythm based on the users movement. An example for a different use is the unit giving a positive sound feedback if the motion is performed correctly and a different sound feedback if it is not, thus helping the user improve his technique. The experiment showed that the subjects would stay motivated and try until they got the positive sound feedback.

This system efficiently helps trainees to confirm their skills and skill improvements during training. One drawback of this system is that a user can only pay attention to a limited number of feedback units, so the training scenarios need to be quite specific.

3.3 Towards Recognizing Tai Chi - An Initial Experiment

An experiment led by a cooperation of the CSN of Hall, Austria and the ETH Zürich, Switzerland [3] analyzes to what extent wearable sensors are adequate for automatic recognition of fast and involved movements like those occurring in athletic sports. As an initial investigation Tai Chi movements were captured with wearable gyroscopes and acceleration sensors. Four different persons as test subjects and three kinds of Tai Chi movements are used to provide 60 data sets overall.

The sensor data is provided by wearable sensor boxes, containing a 3-axis accelerometer and a 3-axis gyroscope, attached to the subject's arms, legs, feet, hip, and neck (figure 3.3). The sensor placement is based on advice from a Tai Chi expert.

While two of the subjects are reputable Tai Chi experts and instructors, the other two

Figure 3.3: Test subjects wearing sensors

are Tai Chi amateurs at a roughly equal skill level. As seen in figure 3.4 the data of the accelerometers and gyroscopes shows that the peaks of the experts' signal have nearly the same length over the five measurements and the signal is smoother and more periodical than in the amateur's data. Another result of the recording is that neck and hip movements are performed much faster by the experts.

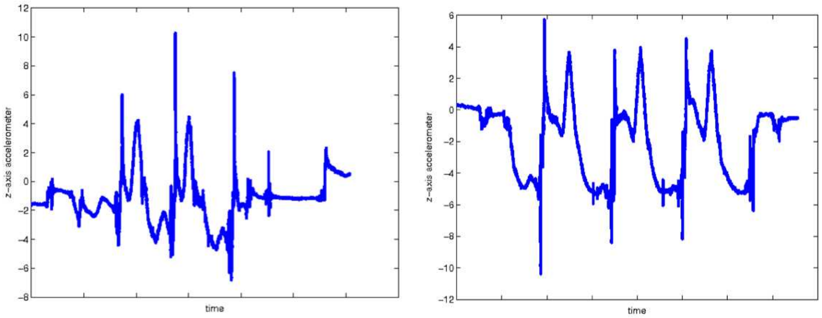

Figure 3.4: Z-axis accelerometer data of an amateur (left) and an expert (right)

This initial experiment with only four test subject shows that automated evaluation of Tai Chi seems to work. Conducting experimental trials with a larger group of test subjects of different skill levels should yield a statistically representative data set and confirm the findings of the initial experiment.

3.4 Combining Body Sensors And Visual Sensors For Motion Tracking

A project led by Doo Young Kwon at ETH Zurich, Switzerland [4] was to design a training system applicable for trainers and trainees. Unlike earlier training systems using only visual sensors to check a trainee's motion, a combination of visual and body sensors is introduced. The system is able to detect and evaluate detailed movements and it gives visual feedback on these. Figure **??** shows an overview of the system.

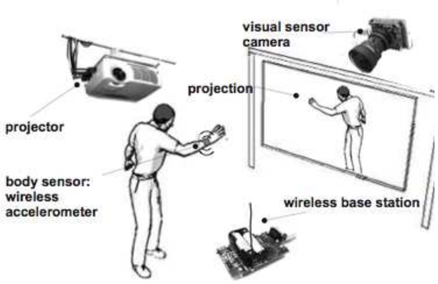

Figure 3.5: System setup overview

To assure unrestricted movement of the user, wireless body sensors are used while a camera works as the visual sensor. Accurate body sensors are able to measure tilt, movements, as well as vibrations that are not visible to the human eye. The challenge to continuously capture and process the data of the motions is met by introducing the concept of a motion chunk for the segmentation and storage of motion information.

The body sensors consist of accelerometers attached, like watches, to the wrists. To simplify the analysis of complex, sequential human motions they are divided into atomic units, static chunks (postures) and dynamic chunks (gestures). The motion chunk of an entire motion is defined as a combination of a start-static chunk, a dynamic chunk, and an end-static chunk (figure 3.6 left).

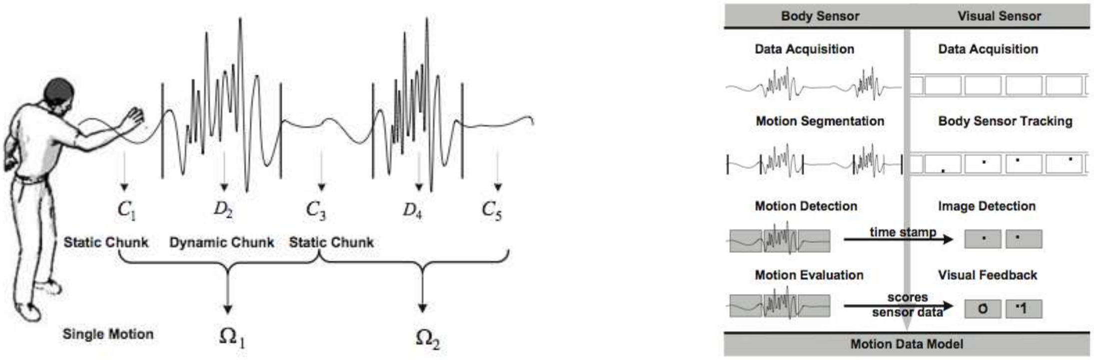

Figure 3.6: Motion sensor data segmentation (left); Data synchronization (right)

The acquired signal is segmented into a sequence of motion chunks. Within this sequence of motion chunks reference motions need to be detected and distinguished from random ones, a task performed using Hidden Markov Models (HMMs). In the next step identified motion chunks are compared to 10 different reference motion chunks in the database. For each motion a score is calculated, representing the minimum distance between actual and reference motion chunk, and displayed in real-time on the video panel (figure 3.6 right).

The motion training video on the panel acts as a reference to follow and analyze motions. Once an input motion is detected, a motion training video is generated from a data base of reference motions automatically. The training video is recorded during a trainer's performance and automatically edited to provide explanatory information. In figure 3.7 a blue circle illustrates the magnitude of acceleration by changing its size.

Figure 3.7: Generated training video screenshots

In a user test a master of Taekwondo as trainer and six trainees, three male and three female, with experience in martial arts training were engaged. While the trainer was asked to perform ten sets of five motions each (punch, outside block, upper block, inside block, down block) to test the motion evaluation methods and create reference motion data, the trainees had to complete both, a posture and a gesture training. In the posture training they trained the start and end postures of the five motions whereas the gesture training served for practicing the individual gestures between start and end postures. By measuring the average time the trainees needed to match their postures to the trainer's average roll and pitch values, the punch motion was found to be relatively easy to teach the use of the system while the outside block seemed to be the most difficult. Thus, the latter was chosen to test the gesture training. The trainees were asked to perform three sets of ten outside blocks with two hours between each set. The collected data showed that the system helps trainees to learn relatively complex martial arts postures in a short time. On the other hand the gesture training depends much more on the abilities and focus of each trainee, only trainees who focused specifically on gestures managed to improve within three sets.
Even the trainer improved his postures and found it difficult to keep the right postures during the dynamic performance. A good indicator that the training system has a sufficiently high resolution to even be used on highest skill levels.

3.5 Sensing And Monitoring Professional Skiers

One major problem of the communication between trainers and athletes is the different point of view. A trainer observes the athletes visually, while the latter are performing the technique. So it is easy to see that it is difficult to match the athlete's and the trainer's view. At this very point, combining the athlete's subjective feelings of force and movements, captured by wearable sensors, with the trainer's visual perceptions in form of video recordings, is a promising approach. [5]

Several parameters relevant to skiing were identified, like the forces under the skier's feet inside the boots, ski rotation relative to absolute world coordinates, the velocity, and also the edging angle of the ski. To measure these parameters, the following sensors were attached to a subject's body:

- Three force-sensing resistors under each of the skier's feet in the ski boots (figure 3.8 left)
- 3D gyroscope on one of the skies
- Infrared distance sensor on one of the ski boots (figure 3.8 right)
- Three 3D accelerometers fixed on skier's thigh, lower leg, and torso

The values from the sensors in the ski boots allow to infer information about front-back and left-right leanings. The gyroscopes reveal information about the ski's steering and edging maneuvers. The infrared sensor allows to calculate the edging angle distance, while the accelerometers provide information about the dynamics. Since speed measuring, meant to be done through radar, did not give compelling results in tests, it is not included in this setup.

Figure 3.8: Force-sensor placement (left); IR-sensor setup (right)

A software is used for analyzing and visualizing acquired data and associating it with video recordings to evaluate a ski run.

The system has been tested on a race course in a ski resort with a student as subject. To mark the video and data stream for synchronization, the athlete stepped with his right foot before each run. An event clearly visible on the video and also creating a clear peak on the accelerometers.

By interviewing four high level ski trainers the evaluation of the project revealed interesting aspects. The experts agreed that all sensors deliver well interpretable and useful

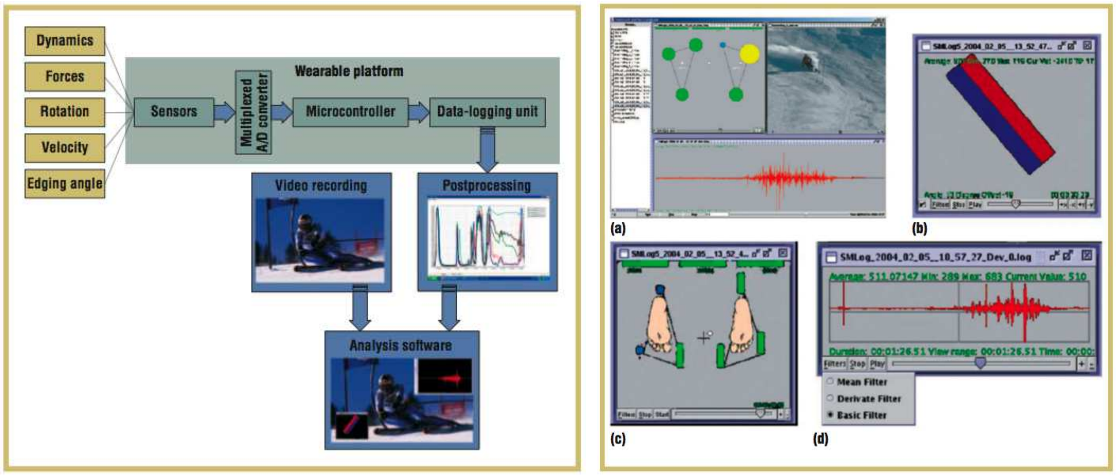

Figure 3.9: System chart (left); Visualization software: a) Screenshot, b) Rotation movement, c) Foot forces, d) Raw data plot

information, but also that there is a lack of intuitive representation. Furthermore they all agreed that the IR-distance sensor measuring the edging angle is the most valuable since it can help to detect too late or too early rotation relative to the turning at a slalom pole but also the discrimination between a slid and carved turn. Several new ideas were brought in by the trainers, such as:

- Measuring the rotation of the skier's torso, since the angle between upper and lower body is a critical parameter when initiating a turn
- Analyze the skier's hip orientation
- Visualizing the skier's back-front balance in a bird's-eye-view perspective (figure 3.9)

Overall, the hardware and software prototype is a good base for enriching trainer-athlete-communication. Due to the prototype status of the system, much room is left for improvements, e.g. measuring velocity as a desired feature in skiing. Because of the cooperation with the trainers as potential users several aspects of the data representation will be changed to be displayed in the skier's perspective. In future work there will be a further adaption to skiers' needs by doing "ski sensor training sessions" to develop a system actually used by trainers and athletes.

3.6 Conclusion Motion Detection And Analysis

As we have seen, all systems presented in this section use sensors that can be attached to various body parts or to the sports equipment. The sensors are chosen based on what they are supposed to measure and on the way that the generated data is used.

The golf system mostly needs rotational data, therefore it uses gyroscopes and infers translational data. The karate and taekwondo systems rely on accelerometers although they also need to measure rotational data, e.g. rotation of the wrist during a punch. They do not focus on the overall relation between distinct body parts, as done with the complex model in the golf system, but on the movement of single body parts. The main goal is to measure the motion itself and to determine correct execution while relations to the movement of other body parts mainly concern timing. The Tai Chi system uses both gyroscopes and accelerometers, but does not give any direct feedback. Instead the recorded data is analyzed afterwards without putting the data of different body parts into direct relation. The ski system also uses both gyroscopes and accelerometers, but does not put the collected data into direct relation either, since the measured values themselves are sufficient. Obviously an intelligent choice of sensors and sensor placement can reduce the number of needed sensors, by beeing able to infer other data from the directly measured data. As the ski system shows a big challenge is to make the systems function in their intended environments and not only under laboratory conditions. Of course, the skiing environment is pretty much an extreme: Sensors mounted on the outside have to function in a cold and possibly humid environment while the sensors inside the boots generally need to tolerate very high humidity. The systems that are primarily used for post-exercise motion analysis also use cameras, which brings up the problem of synchronizing sensor- and video-data. In the taekwondo system this is solved by directly synchronizing the sample rates of the motion sensors and the camera with time-stamping, while the ones used outdoors use either an audio cue or a well-defined motion, which is easily picked up by both the sensors and the camera. One drawback of all systems is, that they do not give the user instructional feedback on what to do differently to improve his technique.

4 Dynamic Training Support

4.1 Mobile Personal Trainer (MOPET)

At the University of Udine, Italy, a research project [1] dealt with the use of a mobile guide during fitness activities. This mobile guide, the Mobile Personal Trainer (MOPET), supplies the user with GPS-based navigation assistance on a specified fitness trail and also gives motivation support and exercise demonstrations on its screen.

MOPET is an application written for PocketPC and works on a PDA with built-in GPS. The system provides location-aware audio and visual navigation on the fitness trail. Overall the navigation module informs the user in a common way known from car navigation systems, e.g. changing the color of completed parts of the trail, audio feedback at intersections, and changing the user's position on the map based on retrieved GPS data. An view of the navigational part of the MOPET application is shown in figure 4.1.

Audio and visual feedback on the actual speed act as motivational help for the user. The application not just tells the user the average speed between predefined checkpoints, but also suggests to increase or decrease the actual speed in the next section. Information is

Figure 4.1: Navigational software component (left); Evita demonstrating an exercise (right)

given graphically by different coloration of the path and as immediate audio feedback.

An embodied virtual personal trainer, named Evita explains and demonstrates the exercises along the track. When approaching an exercise station the user's attention is caught by a sound and encouraged to look at the display. Evita demonstrates how to correctly and safely perform the given exercise in a 3D animation. Figure 4.1 shows an example of performing an exercise with rings.

As an experimental evaluation a test with twelve subjects on a trail with six fitness stations was set up. Of all test persons four engaged in frequent physical activity, one person had tried the fitness trail before, and two of them had used a PDA before. All subjects were asked to complete the fitness trail twice, once with MOPET and once without. Because users were tracked with GPS even if they were not using the personal trainer, they were asked to wear the PDA using a wristband during both sessions. For evaluation users were filmed while completing the trail and scored while doing the exercises with and without the mobile trainer. Afterwards the subjects had to fill out a questionnaire. The overall result was that MOPET is much more useful than fitness trail maps for helping users with the orientation on a trail. Subjects found it more effective than other information on the trail for learning how to correctly perform exercises. As future improvements, different kinds of motivational animations and recordings, study of the users' reactions, monitoring heart rate, improvement of navigation aids, research on better devices than PDAs, and investigating game-style approaches on motivation support will be explored.

4.2 Personalized Music System For Motivation In Sport Performance

The personalized music system presented in [8] is a training tool for non-professional endurance athletes, similar to MOPET, to help them stay motivated during training, control the training itself, and to plan training and measure training progress. The difference of this system to similar products already on the market, like the Philips-Nike MP3Run or the Nike+iPod Sport Kit, is that it actively selects or changes the played music based on the user's performance during exercise.

The system consists of a MP3-Player, a heart rate sensor and a pedometer used along with a PC. Use of the system can be separated into three distinct stages (Figure 4.2):

- Preparation stage
- Exercise stage
- Feedback stage

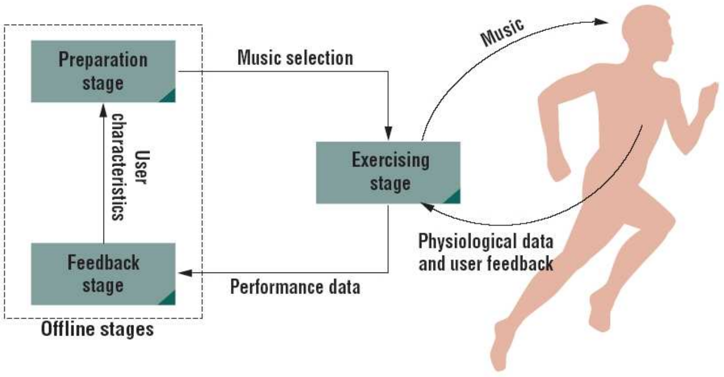

Figure 4.2: System chart

During preparation the user selects a training program and then selects music from a calculated play set. Calculation of play sets is based on several defined constraints, e.g. tempo matching the exercise, user's music tastes, etc.

When exercising the user wears the heart rate sensor, which transmits a pulse for each heart beat to the player's wireless receiver, and a pedometer to measure stride frequency. The player uses three modes to control the user's performance:

- Pace-fixing mode
- Pace-matching mode
- Pace-influencing mode

Pace-fixing mode aims to motivate the user to synchronize his steps to the music, thus helping him maintain a certain level of performance over a distance. If a song's original

tempo differs from the desired tempo it uses time stretching within bounds of -15 to +25 percent of the original tempo to avoid awkward sounding music.
Pace-matching mode aims to support the user while running at varying tempos by adjusting music playback to the user's stride frequency. As in pace-fixing mode it uses time stretching to adjust the tempo within the -15 to +25 percent bounds. Should the stride frequency increase beyond the stretching range, the player selects a new song, which includes the current songs maximum tempo and the current stride frequency. To avoid abrupt tempo changes, the player then increases the current song to its maximum tempo, switches to the new song at that tempo and then further increases the new song's tempo to match the stride frequency.
In pace-influencing mode the music speeds up or slows down to motivate the user to match his stride frequency to the music, thus making him reach a performance level specified by the training program. To achieve this it uses a for step method:

- Match the tempo to the user's stride frequency.
- Determine the heart rate goal and, from that, the needed stride frequency and tempo.
- Start the tempo change to reach the previously determined tempo.
- Wait for heart rate stabilization.

These steps are repeated until the exercise goal is reached.
In the feedback stage the user can transfer the data collected while exercising to a PC for analysis and also system learning purposes. These mainly apply to chosing fitting music for a certain exercise based on the performance data collected during previous runs of that exercise.

4.3 Conclusion Dynamic Training Support

These two systems use different approaches to support and motivate the user during exercise. Users of the MOPET system in its current form can only make full use of its functions on a fitness trail. The personalized music system is limited to supporting runners during training, in training analysis, and training planning. Though not taking the bigger part in this overview, the projects presented in this section are a lot closer to actually making it to the market. Most notably because there are already a lot of devices available that perform similar tasks for hobby users, e.g. heart rate monitors, pedometers, mp3-players, etc. The systems presented here add or combine aspects of these already existing products or elaborate on them in clever ways. Of course that also means there will be a lot of competition when trying to market them. If it was not researched by Philips, the personalized music system might be an interesting feature to be added to the Nike+iPod Sport Kit.

5 Applications For Judging

5.1 Force Sensing Body Protectors For Martial Arts

The paper by Ed H. Chi [2] describes the challenges, both, technologically and socially, in introducing new technology to a sport, in this case force sensing body protectors in taekwondo. The goal of the system developed by Chi is to support scoring decisions during a taekwondo match. To that end he installs piezoelectric sensors in taekwondo body protectors to measure the applied force and wirelessly transmit the data to a PC that scores and displays points. Since the system is supposed to support judges, not replace them, it also includes wireless scoring handsets for the judges.

In designing the system particular attention was paid to make it work reliably without significantly affecting the game. The sensors were inserted into a standard taekwondo body protector, with the wireless transmitter mounted on the back strap behind the shoulder. Because of existing rules for scoring with electronic aids the judges' handsets need to coordinate with the sensors. For a hit to score, at least two judges need to press the same scoring button within a one second window. This is handled by the scoring PC.
So the system setup is pretty simple, which facilitates making it modular and easy to use. The rest of [2] focuses on gradually introducing the system into tournaments to ensure acceptance by the taekwondo community. As a look at the current competition rules shows this approach was quite successful.

5.2 Bugged Balls For Tough Calls

The system presented in this article is basically a GPS with a very high resolution for applications in limited areas, such as a soccer field. It uses a very small radio transmitter transmitting a pulsed signal in the 2.4 Gigahertz band to receivers mounted around the soccer field. The central computer calculates the ball's 3-dimensional position from the time it takes for the pulses to travel from the transmitter to the receivers mounted around the field. The main goal, according to the developers, is to support referees on tough calls, e.g., whether the ball crossed the goal line or not. The system was tested during the 2005 U17 world cup in Peru, but it was decided that it needed further refinement to ensure complete reliability.
This application in itself is of course not really wearable computing, though it has interesting possibilities when the transmitters are put into wearables. An application suggested by the developers themselves is putting the transmitters into the shinguards of soccer players. That would enable the system to individually track each player, thus giving coaches a very usefull analysis tool and of course a lot more statistical data that can be presented to spectators. This would of course be applicable in a wide variety of team sports for post-game analysis, tactics analysis in e.g., soccer, american football, handball, basketball and volleyball, or for presentation improvement on television and screens in stadiums.

5.3 Conclusion Judging

These two systems, while not necessarily improving sports performance, aim to support judges or referees in their decisions. This can help in promoting fairness and also prevent accusations made against judges or referees for being biased. As the soccer example shows, the hardware these systems require might also be used for other innovative purposes, which might accually improve performance after all. Though, as mentioned, it is most important to consider the effects of introducing these systems into a sport and to work closely with officials and players alike, to ensure acceptance of the system.

6 Conclusion

As we have seen there are quite a few approaches to improve sports performance with wearable computing. Clearly the systems that monitor and record performance during training are the ones most likely to appear on the market in the near future. The basic systems and sensors, like MP3 players, heart rate monitoring devices, pedometers and GPS receivers are already used in a wide variety of systems, so the major innovations in the presented systems are software related. Because of the big popularity of MP3 players in general and heart rate monitors among hobby athletes, systems combining the two, with some innovative features thrown in, will likely do well in the market.

Others of the systems still have some shortcomings that need to be adressed. The ski system [5], for example, is missing a functioning way to measure speed, something rather important in downhill skiing. Using GPS and a tilt sensor might be an easy way to accomplish this. The golf system [7], while a perfect system for driving ranges or, slightly modified, for baseball batting cages, is not quite practical, because it uses different sensor placement depending on the parameters to be measured, and it needs to be calibrated for each individual user.

All of the systems have shown the importance of including the practitioners of a sport in the developement process from the very beginning. What might be seen as a good and desireable feature by an outsider may very well turn out to be unnecessary for the user. This inclusion in developement is especially important for systems that are to be used as support for judges because they will most likely need the rules to be adjusted to some degree.

For future work most of the motion analysis systems need to be improved considering ease of use and robustness, since all of the systems were prototypes mainly built to demonstrate that the systems work. The system combining motion and visual sensors from [4] is already quite easy to use and also pretty robust for a research prototype. The wireless sensor setup would certainly also benefit the tai chi system [3]. It would be interesting to see combinations of some of the systems, for example a combination of the ski system and either the taekwondo or tai chi system would be beneficial for slalom skiing because it requires precise and coordinated movements of torso and upper extremities. Challenges we see are applying modified forms or combinations of these systems in more dynamic settings that also involve complex movements, like sports that require a lot of player movement relative to an external influence, e.g. tennis, squash, track and field (high jump, pole vault), volleyball, windsurfing, olympic sailing.

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