Aggregating Multiple Body Sensors for Analysis in Sports

Alan F. Smeaton[#1, #2], Dermot Diamond[#1], Philip Kelly[#1, #2], Kieran Moran[#3], King-Tong Lau[#1], Deirdre Morris[#1], Niall Moyna[#3], Noel E. O'Connor[#1, #2] and Kirk Zhang[#1, #2]

[#1]*Adaptive Information Cluster and* [#2]*Centre for Digital Video Processing*
[#3]*School of Health and Human Performance*
Dublin City University
Glasnevin, Dublin 9, Ireland
[1]Alan.Smeaton@DCU.ie

Abstract— **Real time monitoring of the wellness of sportspersons, during their sporting activity and training, is important in order to maximise performance during the sporting event itself and during training, as well as being important for the health of the sportsperson overall. We have combined a suite of common, off-the-shelf sensors with specialist body sensing technology we are developing ourselves and constructed a software system for recording, analysing and presenting sensed data gathered from a single player during a sporting activity, a football match. We gather readings for heart rate, galvanic skin response, motion, heat flux, respiration, and location (GPS) using on-body sensors, while simultaneously tracking player activity using a combination of a playercam video and pitch-wide video recording. We have aggregated all this sensed data into a single overview of player performance and activity which can be reviewed, post-event. We are currently working on integrating other non-invasive methods for real-time on-body monitoring of sweat electrolytes and pH via a textile-based sweat sampling and analysis platform. Our work is heading in two directions; firstly from post-event data aggregation to real-time monitoring, and secondly, to convert raw sensor readings into performance indicators that are meaningful to practitioners in the field.**

I. Introduction

Sensing our environment, our whereabouts, our activities and our bodies are all part of an emergent science which holds great potential for developing useful, practical applications across a range of disciplines. There are already many sensing technologies for logging our whereabouts (GPS, UbiSense [1]), our physical activities (cameras, passive infra-red sensors) and what our bodies are doing (heart rate monitors, step counters, accelerometers), and these are commonplace and available off-the-shelf. Applications for these sensors are almost always developed in such a way that they exploit one sensor only – analysis and graphing tools for heart rate recording, location-tracking for GPS and UbiSense and software tools for managing video and image libraries.

We are pursuing two directions in our research. Firstly, we are developing novel sensors for capturing movement patterns and physiological responses, during individual and team sports. Secondly, we are investigating how a diverse range of sensors and sensor types can be combined and readings aggregated, in order to deduce a more holistic analysis of whole body movement patterns and physiological changes in response to sporting activities.

The strong interest both in developing new sensors and in using information gathered from existing sensors is part of the development of a *sensor web*, a potentially global web for gathering sensed data and allowing the development of new applications on top of that. Examples of this would be in remote sensing of the environment, where local point sensors that observe water quality or air quality can be augmented with remote sensing from satellites, for example, to give a more complete picture of what is happening in our environment on a larger scale.

Local sensor webs, also known as *body sensor networks* (BSNs) [2] involves the use of on-body sensors to gather information from the body, and from the local and immediate environment surrounding the wearer. The combined data can be combined and aggregated to create an accurate reflection of what activity the body is undertaking and the biological responses. The sensor web proposition in a local, BSN context thus provides exciting opportunities to bring innovation to personal health and well being.

For example, it may be possible to leverage sensor web technologies for next generation software coaching tools that can provide biometric and technical feedback to both elite and amateur athletes. Coaches already do this, but in a very limited way. For example, it is only possible to monitor sweat pH, a key performance indicator in the laboratory, whereas ideally coaches should be monitoring this parameter during performance. Coaches already video-tape training sessions to review tactics and technique with players afterwards, but this usually means a laborious process of either fast forwarding and rewinding a video tape or by manually 'tagging' events for slecetd viewing (e.g Dart Fish ™). By means of innovative body sensing we will support monitoring of multiple health and fitness indicators in real-time during exercise. What makes our work particularly interesting is the diversity in the range of sensing we use, as well as the development of new sensors.

In this paper we report on our work on developing BSNs for monitoring personal health, wellness and performance, particularly in sporting activities. In Section 2 we present a summary of our work on developing sensors for sweat analysis, assessing movement patterns during sport, and physiological monitoring during exercise including breathing. We also supplement these sensors with off-the-shelf sensors which we also summarise. In Section 3 we stress the importance of developing software applications which can intelligently aggregate raw sensor values. Raw sensor values are a challenging data source to manage and to exploit. The logged data values can be noisy and errorsome; can have issues of calibration and re-calibration; may be power-hungry and sometimes have limited lifetime if they require consumables such as chemical reagents for their operation; and sometimes they simply break down. Thus we need to be innovative in developing the sensors and in mining the data. To make progress towards this we have developed a system to aggregate and visualise sensor readings from a variety of sensors during a sporting event as described in Section 4. Section 5 outlines some of our planned future work.

II. Body Sensing

We have been using a combination of off-the-shelf sensors and sensors which we have built ourselves for monitoring the body during both sport and everyday activities. For outdoor field sports which involve only minor levels of physical contact such as soccer, we can track the position of the person on the field of play using a conventional handheld GPS, worn on the belt. For indoor sports such as tennis we use UbiSense [1] technology to track individual players.ubisense Both GPS and UbiSense can sample a player's location every few seconds. The GPS system stores the location on-board for subsequent download and analysis. In contrast, the UbiSense system logs and stores the location in real time. Similarly we have been using a Polar heart rate monitor [3] which samples heart rate every second and stores values on a wristwatch for subsequent download. Although these sensors provide detailed information on a player's location they do not provide information concerning the type of activity or movement patterns. Our work on soccer has involved tracking a player's activity using two video cameras, one to record activities on the field as a whole and a player-cam with which we track an individual player. The video (and audio) is recorded and subsequently analysed to determine *what* a player is doing (run, walk, tackle, pass, etc.). At the present time, the annotation of activity is performed manually but we are developing techniques to automate this.

Wearable sensors provide a non-invasive and comfortable method for continuous on-body monitoring of physiological processes such as heart and breathing rates (respiration) and these compliment the external sensors (GPS, video cameras etc.) mentioned above. The real-time analysis of data eliminates the need for laboratory sampling, and as up to 90 % of the body surface is available for sampling, multi-parameter analysis and monitoring is possible.

BIOTEX [4] is an EU funded project aiming to develop dedicated biochemical-sensing techniques to monitor body fluids via sensors distributed on a textile substrate. Initial applications exist in healthcare and assessing sports performance. As part of this work a bio-sensing textile with integrated optical detection system, used for the real-time measurement of sweat pH during exercise has been developed. Optimal athlete performance depends on balancing the contribution of aerobic and anaerobic metabolism. A change in sweat pH may signal an increased reliance on anaerobic metabolism. Knowing this information would greatly assist coaches in developing training programs and monitoring the physiological demands of competition. However, this is difficult to achieve due the lack of reliable methods for assessing pH during exercise.

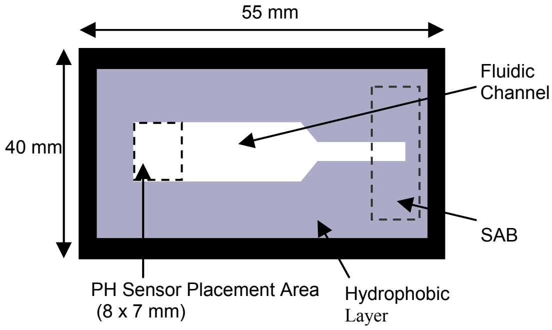

Figure 1: Fluid Handling Platform

To overcome this, a fluid-handling platform, (Figure 1), has been designed. It is based on polyamide lycra®, a material with good moisture wicking capabilities, used to draw sweat into its fluidic channel. The super absorbent material (SAB) provides a passive pumping mechanism, controlling fluid flow. On average human sweat has a pH value that lies between 5 – 7. Bromocresol purple (BCP, pKa = 6.2) is suitable for this range and is fabricated directly onto the channel by co-immobilising the dye with tetraoctyl ammonium bromide.

The optical detection of pH induced colour changes in the dye is based on the use of a paired emitter-detector LED system [5], shown in Figure 2. This is housed in a black PMMA cover, held 5 mm above the channel by a silicone gasket. The system is controlled by a Mica2dot mote [6], which transmits sensor readings from the optical detection, remotely to a base station and PC.

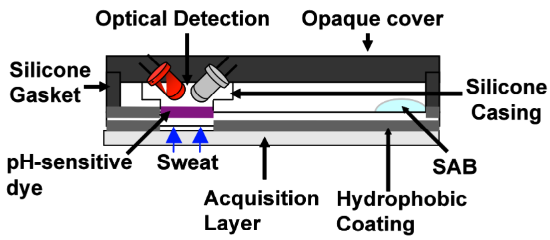

Figure 2: Optical Detection System

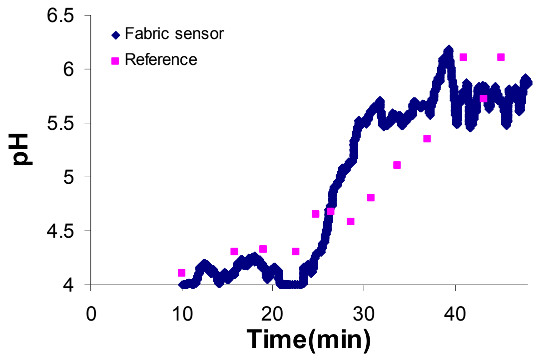

Figure 3: pH vs. time for fabric sensor and reference

The pH analysis device we have built has been calibrated from pH 4 – 8 and shows excellent repeatability. Current work is focused on implementing the sensor for the real-time measurement of pH in subjects asked to cycle for approximately 40 minutes. To reduce noise and motion artefacts, the sensor is placed in a specially designed belt, placed around the subject's waist. Initial results show an increase in sweat pH over the period of interest. This corresponds well with results obtained using a Skincheck™ pH meter [7] for reference purposes. A sample of the results are shown in Figure 3.

Our subjects have also been tested wearing a t-shirt specially designed by Foster-Miller, Inc. [8], which measures heart rate and respiration. This is used in combination with the sweat pH sensor to obtain additional information on the physiological responses of the athlete based on the combination of sensor readings. Initial results from the combined sensors are shown in Figure 4. In addition to pH, information on sweat rates, conductivity and electrolyte levels can be obtained using this textile-based platform. Investigations into the integration of such devices with the pH sensor are ongoing, with a view to conducting clinical studies in certain population groups, for example obese children and during sporting activities.

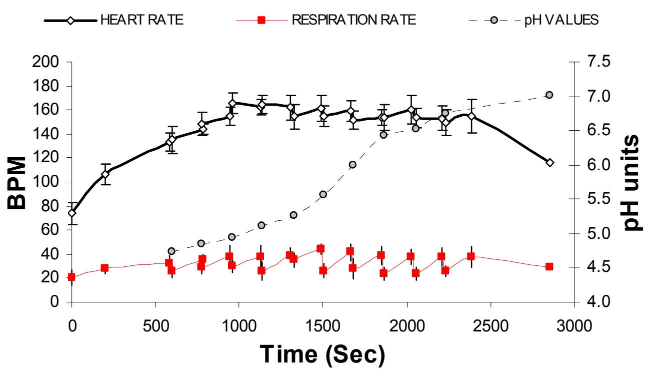

Figure 4: Change in pH during exercise compared to heart and respiration rate of a single subject

The final body sensor device we use is the SenseWear PRO2 armband produced by BodyMedia Inc. [9]. This monitors galvanic skin response (GSR), skin temperature, heat flux (loss), and acceleration using a 3-axis accelerometer. The SenseWear PRO2 armband is a small lightweight device which straps unobtrusively to the back of the upper arm. Sensors on the back of the device monitor the wearers biometric outputs. GSR is measured using electrical skin conductance (in μSiemens) between two electrodes placed on the skin and this is associated with sweat gland activity. Changes in the levels of sweat in the eccrine sweat glands have been shown to be linked to measures of emotion, arousal, and attention so GSR readings can be indicative of a wearers stress level. The rate of sampling can be varied, and we informally optimised this to capture short variations in signals. Like data from the GPS and heart rate monitor, the captured data is uploaded to a PC for analysis and further processing.

III. Aggregating Raw Sensor Data Values

As outlined in the previous section, we have a variety of on-body and external sensing devices available to measure movement patterns and physiological parameters during exercise. These devices generate a data stream of raw data values which need to be appropriately managed. What makes managing sensor values most challenging is that raw sensor values are noisy and very susceptible to noise [10]. There are issues relating to initial calibration and subsequent re-calibration due to drift. The re-calibration is challenging and expensive. Some of these sensors can be power-hungry and their battery lifetime can be limited, especially if they transmit their sensor values using wireless technology. On the other hand, there are issues of memory space if the data is logged on-board. Some sensors require a supply of consumables such as chemical reagents for their regular operation. There is therefore a real cost every time these sensors take a reading. Finally, sometimes the sensors, especially those which are new, simply break down.

It is therefore important to manage a sensor data stream to account for errorsome, uncalibrated and even missing data in such a way that minimises use for sensors where there is a real cost (in power or reagents) in taking readings. In our work we stress the importance of developing software applications which can intelligently aggregate raw sensor values to account for the above real scenario.

IV. A System for Aggregating Sensors in Soccer

We have developed a software system to aggregate and visualise sensor readings from a variety of sensors during a sporting event, namely soccer. The sensors we used in our initial experiment include a GPS for location-tracking; a heart rate monitor, a BodyMedia PRO2 armband measuring motion, GSR, skin temperature and heat flux; a Foster-Miller vest to monitor respiratory rate. A healthy physically activity male in his mid-20s wore the sensors (Figure 5) and was tracked manually on a video camera and a wide-angle camera during a lunchtime football game.

(a) (b) (c)

Figure 5: Subject wearing on-body sensors for soccer. (a) shows the Foster-Miller vest, (b) shows the BodyMedia armband and (c) shows the GPS

All sensors were logged on-board different devices and the data subsequently gathered and synchronised. We developed a web-based tool for reviewing a visualisation of the aggregated data, which is shown in Figure 6. This software tool gives a synchronised picture of the sensor readings at a fixed point during the soccer match.

The screen features the wide-angle and close up playercam video, synchronised, and shown in the windows in the middle of the screen. At the right of the screen is a layout of the pitch and the series of red dots show the location of the player (from the GPS) with the dimmed out dots showing the most recent movements of the player. The series of graphs on the bottom of the screen show the heart rate, respiration, skin temperature, galvanic skin response and heat flux. It is also possible to display other sensor readings. The user can use a slider superimposed on the graphs to move to a particular time of interest during the match and the current readings will appear on the *player analysis* section of the screen. The 2 video windows are synchronised to show what the player was actually doing at the selected time during the match.

The software tool we have built to aggregate sensor values is a first version and provides the platform for the most interesting work, sensor aggregation and event detection. The present system provides a visualisation of the aggregation of sensor readings. However, we have not yet addressed issues of consistency of event detection across sensors. For example, if the player decides to take a rest during the match and stand in the centre circle with hands on hips because he is tired then this should be reflected as a drop in heart rate and respiration and a decrease in skin conductivity due to a decrease in sweat less. Our aim is to automatically detect this as an *event* that can be monitored by the user, instead of the user having to *eyeball* the sensor readings and detect events or points of interest manually.

The software is also extensible in that future sensing technology, such as the pH sweat analysis device described earlier, can be slotted into this system, as just yet another source of sensor readings.

V. Conclusions and Future Work

The work we have described in this paper is really just a starting point to allow us to do work in sensor data value aggregation from multiple, diverse sensor types in sports-related applications. There are a number of clear practical applications which can be broadly summarised as follows:

(i) With the exception of heart rate, the evaluation of physiological responses during exercise has been limited to a controlled laboratory environment, which clearly lacks ecological validity. The provision of real time data on physiological responses and movement patterns will allow coaches to design individual conditioning programs for athletes. In addition, it will allow coaches to track changes in fitness, and monitor overreaching/overtraining.

(ii) Providing real-time automatic 'alerting' to the coach/user on when an athlete reaches a pre-determined excessive level of physiological response (e.g. heart rate or respiration rate), either momentarily or for a pre-defined extended time period, will greatly assist in optimizing performance. The coach can also, if necessary, view the corresponding video and movement (velocity) data to identify the tasks the athlete was undertaking to determine if it was an appropriate physiological response. This information could be used by the coach to design and implement an appropriate intervention. For example, an immediate response may be to remove the player from the activity/game, change the tactic or drill, or simply to get the athlete to ingest fluids. A post-event response by the coach may be to implement a (more) appropriate physical training programme to address the poor physiological response.

(iii) A coach will be able to monitor the information remotely in real-time, allowing teams/athletes to gain feedback from experts without them having to travel to the site of training.

In terms of future work, we are continuing to make the sweat pH analysis device more robust and to detect other characteristics of sweat such as electrolytic composition. This will allow us to investigate what biometric signals (HR, respiration, GSR, sweat composition, etc.) correlate with what others, and what sensors, or combination of sensors are best indicators of a person's activities.

Acknowledgments

This work was supported by Science Foundation Ireland under grant 03/IN.3/I361 and by the European Union FP6 programme as part of the BIOTEX project (016789). We also thank Foster-Miller for their support of this work.

References

[1] J. Cadman. "Deploying Commercial Location-Aware Systems." In *Proceedings of the Workshop on Location-Aware Computing (part of UbiComp 2003),* Seattle, Wa, USA, pp4-7, October 2003.
[2] B Lo, S Thiemjarus, R King, G Yang. "Body Sensor Network–A Wireless Sensor Platform for Pervasive Healthcare Monitoring." In *Proceedings of the 3rd International Conference on Pervasive Computing*, 2005.
[3] (2008) Polar Heart Rate Monitor. [Onlne]. Available http://www.polar.com/
[4] (2008) BioTex: Bio-Sensing Textile for Health Management, [Onlne]. Available http://www.biotex-eu.com/
[5] M. O'Toole, K-T Lau, B. Shazmann, R. Shepherd, P.N. Nesterenko, B. Paull and D. Diamond. "Novel integrated paired emitter-detector diode (PEDD) as a miniaturized photometric detector in HPLC." *Analyst*, vol. 131, no8, pp. 938-943, (2006).
[6] (2008) Mica2Dot Mote. [Onlne]. Available http://www.xbow.com/
[7] (2008) SkinCheck pH Meter. [Onlne]. Available http://www.skincheck.org/

[8] (2008) The Foster-Miller Vest. [Onlne]. Available http://www.foster-miller.com/

[9] (2008) BodyMedia Armband. [Onlne]. Available http://www.bodymedia.com/

[10] D.J. Cooke. "Making Sense of Sensor Data". IEEE Pervasive Computing, Col 6, No 2, pp105-108, 2007.

Figure 6: Screendump of aggregated sensors from soccer match