Textile Sensors for Personalized Feedback

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ABSTRACT

Wearable sensors provide a means of continuously monitoring a person in a natural setting. These sensors can "look in" by monitoring the wearer's health through physiological measurements and also by detecting their activities. Other sensors can be used to "look out" from the wearer into the environment through which he/she is moving, which may serve to detect any potential hazards or provide contextual information about the wearer's lifestyle. Wearable sensors can be harnessed to give immediate feedback to the wearer while also providing an archive of physiological data which can be logged and assessed over days, months or years. This has many applications in the field of healthcare, rehabilitation and sports performance. Here we present a number of case studies involving "smart" garments which have been developed to monitor the well-being of the wearer and to assess performance and progress, for example in training or rehabilitation scenarios.

Categories and Subject Descriptors

A.0 General

General Terms

Measurement, Performance, Design, Experimentation, Human Factors,

Keywords

Wearable sensors, physiological monitoring, body sensor networks

1. INTRODUCTION

Wearable sensors integrated into garments are adding new functionality to today's fashion. Smart garments have the ability to sense the wearer and also the environment surrounding the wearer. The advantage of using textiles as a substrate for sensor integration is that they are ubiquitous. Textiles used in garments we wear are in intimate contact with the body, and also form the interface between us and our environment. In addition, textiles exist in our surroundings e.g. home textiles such as curtains and upholstery. Therefore by developing textile based sensors there are many parameters that can be measured relating to the person and their environment. Wearable sensors to monitor a person's health give rise to a concept of personal health or pHealth. This concept means that the person can be more aware of their own well-being and can take a more active role in their health by managing their lifestyle to prevent illness. The pHealth concept emerged as a response to the unsustainable increase in healthcare costs world-wide due mainly to an epidemic of 'life-style' diseases arising from unhealthy diet and lack of exercise, such as obesity, cardiovascular disease, diabetes and chronic respiratory disease. The current global demographics show an increase in the aging population which also puts further burden on the healthcare sector. Wearable sensors may be used as a tool to gather information about the person's health and lifestyle to give a more complete picture. By continuously monitoring the wearer over time an archive of their personal health can be created which is far more desirable than the snapshot images that are currently attained with occasional clinical visits.

Sensors "looking in" to the body may be used to monitor daily activity. A simple approach is a pedometer to count the number of steps that a person has taken in a day. This may be used as a crude indicator of their level of physical activity. More sophisticated sensors can measure specific joint movements, position and speed that can be used to develop a model of kinematic movements. This may be used to assess what type of movements the person is undertaking and how well the person is performing an exercise. Sensors that measure body movements can be used for home rehabilitation based on prescribed physiotherapy exercises.

Physiological measurements are also possible with wearable sensors. Textile electrodes to measure electrocardiographs have been developed and shown to perform well compared to gold standard methods [1]. Shirts capable of monitoring vital signs have recently appeared on the market such as the Vivometics Lifeshirt [2]. Sensors pertaining to physiological measurement may be used to assess chronic illnesses such as cardiovascular disease. In others they may be used to help early detection and prevention of illness where conventional clinical visits can only provide a brief window on the physiology of the patient. Exercise is of huge importance in underpinning a healthy lifestyle, and providing incentives for people to exercise is essential for maintenance of personal health. The sports industry has identified a huge emerging market for wearable devices. The world of professional sports and athletics has seen dramatic changes in performance largely due to physiological testing and a better understanding of the effects of different training techniques on the body. Physiological testing ensures athletes stay healthy and develop personalized training strategies to keep the fine balance between over-training and reaching peak performance. At present, the vast majority of this testing is done in laboratory settings, yet wearable sensors now have the potential to allow physiological testing to be carried out in the natural setting, on the track, pitch or court. However, it is not just elite athletes who are interested in their performance - the amateur athlete and occasional gym attendee often wants to get the most from their work-out and achieve their own personal fitness goals. Products are already appearing that target this emerging market. For example, the Polar heart rate monitor helps people to train at the right intensity depending on their training plan [3]. Polar also offer the service of developing personal training plans based on the data gathered. Adidas have developed the miCoach concept [4] which also measures heart rate data and suggests various plans to help people to train for their specific goals e.g. to lose weight, run a race, de-stress or run faster. Nike and Apple have developed a sports kit which measures speed and distance while walking or running. The data can then be downloaded onto a personalized homepage. Not only does this allow the user to assess their own performance but it has led to a web community where users can compete against and challenge each other in addition to discussing training and related issues. This has led to a virtual running community with close to 2 million members [5]. The advantage of this system is that it avails of apparel and a wearable/portable device that runners are already using. In this way it requires little or no extra effort on the part of the user. This type of strategy is ideal for all wearable sensing i.e. to customize apparel and on-body devices that people routinely use and augment their functionality. In this way, a truly innocuous means of sensing can be achieved that needs no additional appliances. To do this it is necessary to integrate sensors into textiles so that they are comfortable to wear. This is a challenging task considering the rigor that our clothes go through day to day. Sensors must be robust and reliable being able to withstand stretch, pressure and varying temperatures, environmental conditions and ideally the washing machine. In this paper we present a number of prototype systems which use textile based sensors to monitor the wearer. The first uses a glove that has been developed for a clinical study in stroke rehabilitation. The second uses a shirt to monitor breathing patterns. This is used to provide feedback on breathing technique and encourage patients to perform their breathing exercises. The third is a smart insole which is being developed to investigate running technique. Before presenting the individual prototypes an overview of the textile sensor integration strategies is given in the next section.

2. FUNCTIONALISED FABRICS

In order to monitor the body in a natural way there is a need for integrated sensors that are comfortable, wearable and straightforward to use. A complete system that incorporates wearable sensors and body sensor networks within a textile will require a number of functionalities to be added to the textile structure, including conductivity, sensing, actuation, data transmission and computation. Data transmission is essential between components and also wireless connectivity is often desirable. This is possible in a garment through flexible polymer or textile antennas. [6, 7] Conductivity may be added through conductive threads, fibres or coatings. Stainless steel or silver threads are available in different thicknesses, both as 100% metallic fibres, or blended with other textiles such as nylon, giving rise to a variety of yarns with different properties. [8] There are also polymers which have inherently conductive properties which can be coated onto yarns or fabrics. These materials can be used to create sensors with piezo-resistive properties. Coating a stretchable fabric with a conducting polymer converts the fabric into a strain gauge, as the resistance depends on the degree to which it is stretched [9]. Coating a compressible textile such as polyurethane foam in the same manner produces a pressure sensor [10]. In these cases the textile itself becomes the sensor – thereby making use of the structures/materials that are already in place, but improving on them by giving additional functionality. Ideally the sensor should retain its sensitivity over the lifetime of the garment and through numerous wash cycles. Making the fabric itself the sensor can augment garment functionality while still maintaining the normal tactile properties of the garment. Textile based sensors which are compatible with textile manufacturing processes are essential for such technology to become accessible. This may involve screen printing of thermochromic dyes, knitting conductive yarns or weaving of plastic optical fibres [11]. The interconnection of the sensors to a microcontroller or wireless device still remains an issue as it is at this point where a textile sensor must be connected to more conventional electronics. Flexible circuit boards and batteries [12, 13] are a possible solution and a sewable microcontroller (Lilypad Arduino) has recently been developed which allows conductive threads to be stitched to the pins of the microcontroller [14]. Recent studies have reported textile based transistors using organic field effect transistors which would allow fully computational electronic textiles [7, 15]. Smart nanotextiles are being developed to overcome the shortcomings of interconnections with conventional silicon and metal components which are incompatible with the soft textile substrate[16]. By integrating technology at the nanoscale level the tactile and mechanical properties of the textile may be preserved, retaining the wearable flexible necessary characteristics that we expect from our clothing. Through nanoscale manipulation intelligent textiles are given new functionalities including self-cleaning, sensing, actuating and communication [16]. Nanotechnology allows the incorporation of new functionalities at various stages of production – at fiber spinning level, during yarn/fabric formations or at the finishing stage. Nanocoatings are being widely applied at present by the textile industry to improve textile performance by adding antimicrobial and self-cleaning effects. Other applications under development involve the use of conductive materials such as graphite nanofibers and carbon nanotubes to bring conductivity and anti-static behaviour to the textile [17].

The prototypes presented in the following sections make use of piezoresistive textile sensors. The glove and the shirt use a carbon-loaded elastomer which can be coated onto textiles. The insole makes use of a conducting polymer based felt which acts as a pressure sensor. Bekinox stainless steel thread is used to connect the sensors while conventional components and microcontrollers are used for signal conditioning and data acquisition.

3. CASE STUDIES

3.1 Rehabilitation Glove

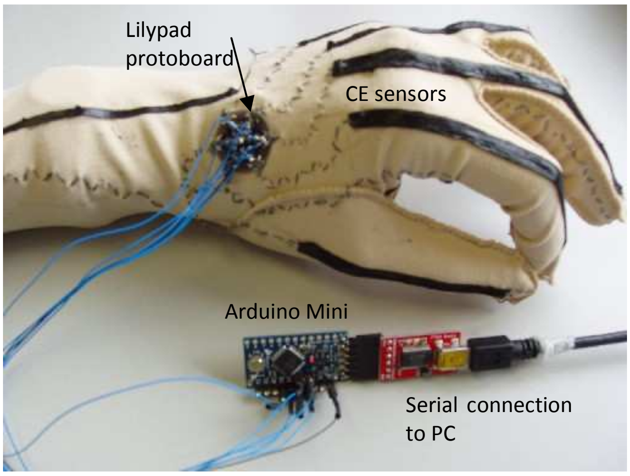

Figure 1 Sensorised glove for stroke rehabilitation

A sensorised glove has been developed for rehabilitation applications to monitor the ability of patients to perform finger extension movements during stroke rehabilitation. An oedema glove, which is typically worn by patients following a stroke to reduce swelling of the hand, has been modified to integrate bend/stretch sensors to measure finger movement, as shown in Figure 1. The glove is made from a lycra and spandex material, which fits to the hand closely with light compression. Movement of the fingers causes the fabric to stretch and regions of the finger and thumb of the glove have been coated with a sensing element , a carbon-loaded elastomer which is commercially available from WACKER Ltd (Elastosil LR 3162 A/B). This approach has been demonstrated in the University of Pisa for measuring body kinematics [18]. This glove has been developed for rehabilitation applications based on the Fugel-Meyer Assessment of motor recovery after stroke. This assesses various motor functions and scores them based on performance where 0 = cannot perform, 1 = performs partially, 2 = performs fully. The advantage of this sensor is that it is comfortable to wear and is integrated into a garment that is already being used by many patients. It is important that the sensor does not constrain or enhance the natural movement of the joints. The sensor's performance has been compared to a commercial bend sensor (Spectra symbol Flex sensor 4.6″) which is a more rigid structure. The two sensors are shown side by side in Figure 2. However, the CE sensor has the advantage of being much more flexible and can be made in any dimension or form while the flex sensor is available at a specific length. Figure 3 shows the response of the sensors positioned on the fingers of a glove during three stages of finger extension. Both sensors achieve a similar response although there is some latency with the CE sensor due to the nature of the material.

The elastomer is a two part compound that is mixed together thoroughly before being cured. The substance was coated onto the fingers and thumb of an oedema glove. The glove was then placed in an oven at 80ºC for 2 hours. Conductive thread was used to connect the sensors to a Lilypad protoboard. This is a circular prototype board (2cm diameter) which allows interconnection by embroidering with thread and also allows wires and components to be soldered. An Arduino Mini microcontroller is used to collect the data using an analog input, sampled at 10Hz. This microcontroller has been chosen for its small size. While it does not have wireless connectivity built in, it is possible to connect a BlueSMiRF modem which works as a (RX/TX) pipe through which a serial data stream can be passed seamlessly at baud rate of 9600bps to a laptop up to 30m away.

Figure 2 (top) CE sensor coated onto stretch knit fabric, (bottom) commercial bend sensor

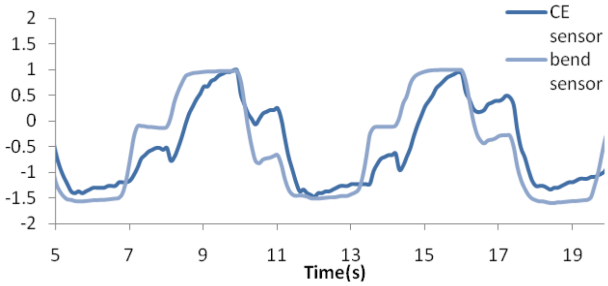

Figure 3 Performance of CE sensor compared to a commercial bend sensor during finger flexion/extension movements

Monitoring joint flexion as demonstrated here with the rehabilitation glove has the potential to automatically assess the patient's performance. A user interface designed for home use on the home PC is currently being developed to determine the position of the user's hand and to present this as visual feedback to the user. The program saves this in an animation format which can then be sent to the therapist who can play back and assess the patient's performance remotely. Figure 4 illustrates the application of this system in a clinical context. The system will be evaluated in forthcoming clinical trials with stroke patients.

Figure 4 System architecture of the stroke rehabilitation process using a sensorised glove

3.2 Breathing Feedback System

Breathing affects virtually every part of the body. It oxygenates the body, revitalizing organs, cells and tissues. Breathing is controlled by the autonomic nervous system and is unique as it is both a voluntary and involuntary process. Good breathing technique can have a profound effect on overall performance as athletes, singers, and yoga practitioners know. In the case of conditions such as asthma or cystic fibrosis it is important for patients to regularly exercise their lungs and improve their breathing technique. Exercising respiratory muscles can increase exercise capacity and reduce the aspects of breathlessness.

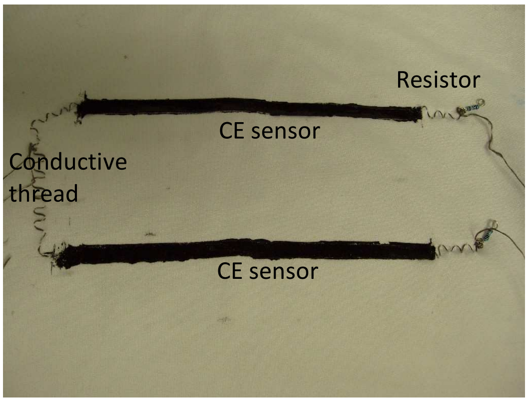

Figure 5 Carbon-elastomer sensors coated on stretch fabric connected by conductive threads. Resistor pins have been bent to allow connection by embroidery of conductive thread.

One exercise that is widely accepted is known as the Active Cycle of Breathing which uses breathing exercises to remove phlegm from the lungs. Clearing secretions from peripheral airways is the most important defence mechanism of the respiratory system. The technique involves taking 4-5 deep breaths with holding periods in-between to allow air to be transported behind obstructed areas in the lungs [19]. It is important that the patient breathes from the diaphragm and not just the thorax for the technique to be effective. For patients with cystic fibrosis this may need to be carried out three times a day. It would be of great use to develop an interactive system which would help children with cystic fibrosis to perform these exercises correctly, and to provide an incentive to perform the tasks regularly. Therefore we have developed a system which uses a wearable sensor to detect breathing patterns, records the signals and provides immediate feedback to the user. As with the stroke rehabilitation example (above), this system may be used at home, while also facilitating remote supervision by a trained therapist who can provide regular assessment updates.

Breathing rates can be measured by detecting the expansion and contraction of the ribcage, and fabric strain or pressure sensors can be used to measure this movement. Carbon-loaded elastomer sensors, as shown in Figure 5, have been used to develop a shirt to measure the expansion of the thoracic/abdominal cavity. The advantage of using these sensors is that they can be applied in any dimension to any desired position on the fabric. In order to maximize the signal quality, the sensors need to be coupled closely with the body movements, and therefore the garment needs to fit the wearer well. For greater flexibility a number or chest straps have also been developed for a universal fit during clinical trials. Data is collected using an Arduino Mini microcontroller as used for the glove discussed in Section 3.1.

The signal is filtered using a low-pass Butterworth filter and the filtered signal is cross-correlated with a reference signal to assess the performance of the user. A Flash application is used to present feedback to the user in a graphical format. The use of a Flash application makes the software easily accessible and means that the system has the potential of being accessed online where the results can be automatically logged to a user's webpage and also accessed by the therapist. The user interface presents an avatar in a picturesque setting as shown in Figure 6.

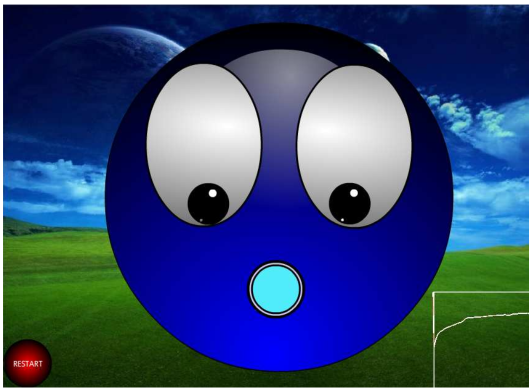

Figure 6 Graphical User interface, Avatar gives instruction and real-time feedback to the user

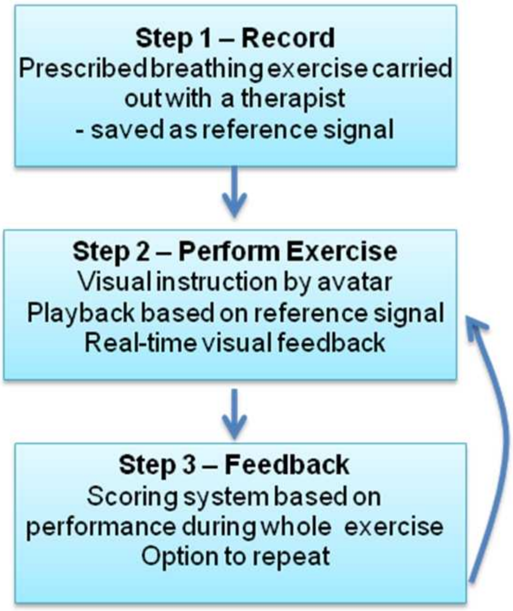

Figure 7 Breathing feedback system operation

The avatar serves to instruct the user while also giving real-time feedback of progress. The mouth of the avatar expands and contracts as the user breathes in and out. An overlay ghost image of the mouth represents the user's breathing. Therefore as they perform the exercise they must try to follow the breathing sequence as instructed by the avatar and therefore synchronise the "ghost" mouth and avatar's mouth. An overall assessment of their performance throughout the exercise is given on completion of the exercise. Rather than giving a numerical score three, four or five stars are given. The idea is that the feedback should be rewarding and encourage the user to keep performing the exercises regularly.

The sequence of the program operation is displayed in Figure 7. The first time that the exercise is performed the signal is recorded as a reference. This is designed to be performed under the supervision of the therapist so that the correct procedure is followed. The avatar is not displayed during this time, but the signal is graphed to show that everything is connected and working correctly. After this, patients may repeatedly perform the exercise in their own time.

To test the effectiveness of the avatar a breathing exercise was performed involving slow deep breathing at a rate of 8 breaths/min for 2 minutes. Breathing patterns were recorded using Sensormedics Vmax as a reference in addition to signals measured at the chest and abdomen using the textile sensors. Figure 8 and Figure 9 show the effect of the breathing exercise under the avatar's instruction. The breathing rate measured by the Sensormedics system changes from a range of 6 to 18 breaths per minute to a constant 7-8 breaths per minute once the exercise is started. Figure 9 shows an increase in amplitude in the abdominal breathing signal during the exercise as the subject is taking deep breaths and using the full lung capacity.

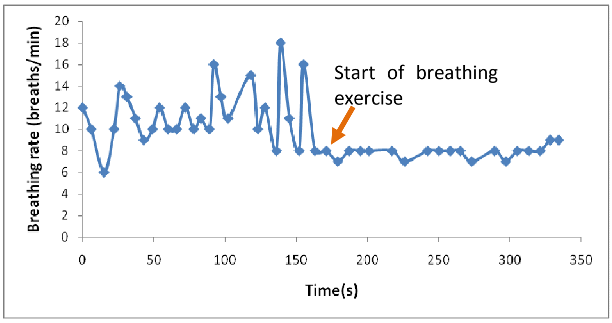

Figure 8 Breathing patterns measured using Sensormedics Vmax before and during breathing exercises using avatar instruction

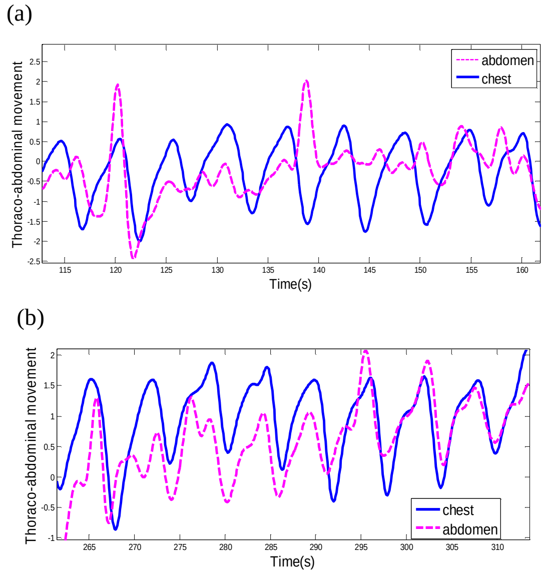

Figure 9 Breathing patterns measured from textile sensors placed at the chest and abdomen a) before breathing exercise b) during breathing exercise

3.3 Smart insole

A smart insole has been developed to detect footfalls during walking or running. The sensor used is a piezoresitive felt produced by Eeonyx (a non-woven textile coated with conducting polymer) whose resistance depends on the applied pressure. .The insole has been made by sandwiching this piezoresistive material at various locations between two layers of neoprene that have been cut into the shape of an insole. Figure 10 shows either side of one of the neoprene layers. Connection to the sensor is made using conductive thread. This is placed in the bottom bobbin case of a sewing machine while non-conductive thread is used as the upper thread. The purple, outer side of the insole has non-conductive thread stitching while the conductive thread is on the inside in contact with the sensor material. Sensors are placed at the heel and toe and at the left and right forefoot. Heel and toe sensors are important for investigating foot contact times while the forefoot sensors at each side help to determine the roll of the foot. Often runners are subject to injuries based on supination or pronation of the

Figure 10 Neoprene insole with conductive stitching for the placement of four pressure sensors

foot when the foot rolls to the outside or the inside [20]. The insole may be used for various applications to assess athletic performance. It may be used to look at how foot contact time changes throughout a track race or during long distance events. It can be used to build an archive of running history and follow the effects of different training regimes on running technique. It allows every footfall to be captured and recorded to keep track of training achieved and to help devise future training strategies. It may be used to prevent or detect injuries if an unusual pattern emerges.

Apart from sports applications, this type of wearable device may prove useful as a tool for gait analysis in rehabilitation, such as monitoring of the progression of Parkinson's disease, or activity monitoring in the elderly. The insole is comfortable to wear and can be inserted into any type of shoe. The placement and number of sensors can be adapted to the particular needs of the application.

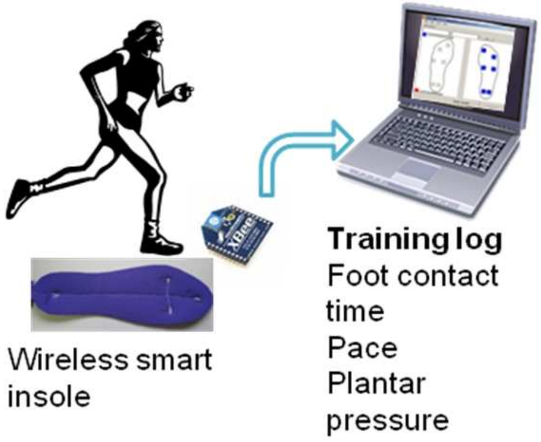

Figure 11 Smart insole to monitor running technique

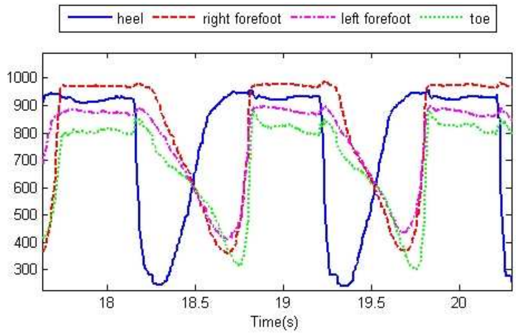

Figure 12 Response of the smart insole during walking

Data is acquired using an Xbee module (1mW chip antenna). This offers improved data acquisition performance over the Arduino platform used in the previous two examples. The Xbee is held in position by a neoprene ankle strap attached to the insole. The Xbee has 6 channels which can be conditioned as analog or digital inputs. Sampling rates up to 1kHz across all channels is possible. For the insole with four sensors each channel has been set to sample at a rate of 200Hz. An Xbee regulated USB module (Sparkfun Electronics) is used to connect a base-station receiver Xbee to a laptop which graphs the data in real-time and stores the data for analysis.

The response of the insole is shown in Figure 12 during walking. From this it is clear about the timing as each part of the foot strikes the ground. Time between steps can be estimated by measuring the time between heel strikes. Foot contact time can be estimated by measuring the time between heel strike and toe off.

4. DISCUSSION/CONCLUSIONS

Fully integrated wearable sensing technologies should be based on materials that are soft, flexible and washable, to meet the requirements of normal clothing manufacturing. Data transmission must be wireless to allow free movement of the wearer, and ideally make use of technology that is already being carried or worn by the wearer if it is not automatically built into the garment. Clearly sensor integration and signal processing are significant challenges, but one of the biggest questions is what to do with the information that is gathered. It needs to be presented to the user in a suitable feedback approach e.g. visual, tactile or auditory and the timing and frequency of this feedback is critical. This is largely application dependent and dynamic in nature, and context awareness is therefore a crucial feature in generating user feedback. The feedback should be intuitive, without overloading the wearer with too much unnecessary information. Put simply, the right information needs to be given to the wearer, at the right time. Wearable sensors can help to achieve a better understanding of personal physiology and, combined with contextual information, they can help to create a more complete archive of a person's lifestyle.

Three different systems involving textile based wearable sensors to detect body movements have been presented in this paper. Using such wearable devices, it is possible to acquire information about the person in a natural setting without intruding on their daily life. This is made possible by augmenting the functionality of the type of clothing that is commonly in use for each application. In this way it is possible to build an archive of personalized information about the wearer's activities, for example, to track progress in prescribed rehabilitation exercises or fitness training plans. By extracting digital information from the threads of our clothing it is possible to build a digital archive relating to our own body's physiology. The coming decade will clearly see a rapid expansion in the numbers of people using wearable sensors for many applications in Health and Exercise. The availability of data in archived databases opens the way to comparing activities of people on a global scale, as has been seen with the Nike plus system where thousands of people are collectively running millions of miles. It also allows for personalization of systems in addition to giving us a better understanding of our personal lifestyle and health, and how we compare to others. While this undoubtedly have many benefits in highlighting global trends, the ownership of this type of data still needs to be regulated and the privacy of individuals must be respected. Novel sensing technologies enable us to harvest large volumes of sensed information which must be used carefully and productively to benefit the whole population.

ACKNOWLEDGMENTS

We gratefully acknowledge the financial support of Science Foundation Ireland (07/CE/I1147) for this research. We are grateful to the staff at the William Stokes Unit in the Adelaide and Meath Hospital, Tallaght, Dublin 24, Ireland for their help.

REFERENCES

1. Paradiso, R., G. Loriga, and N. Taccini (2005) A wearable health care system based on knitted integrated sensors. IEEE Trans Inf Technol Biomed. 9(3):337-344.
2. Heilman, K.J. and S.W. Porges (2007) Accuracy of the LifeShirt® (Vivometrics) in the detection of cardiac rhythms. Biological Psychology. 75(3):300-305.
3. Polar http://www.polar.fi/en (accessed Jan 2010).
4. Adidas miCoach http://www.adidas.com/uk/micoach/#Start/sdf/mdf (accessed Jan 2010).
5. Nike Running http://nikerunning.nike.com/nikeos/p/nikeplus/en_US/ (accessed Jan 2010).
6. Locher, I., M. Klemm, K. T, and G. Tröster (2006) Design and Characterization of Purely Textile Patch Antennas. IEEE Transactions on Advanced Packaging. 29(4):777-788.
7. Declercq, F., H. Rogier, and C. Hertleer Permittivity and loss tangent characterization for garment antennas based on a new matrix-pencil two-line method IEEE Transactions on Antennas and Propagation. 56(8):2548-2554.
8. Post, E.R., M. Orth, P.R. Russo, and N. Gershenfield (2000) E-broidery: Design and fabrication of textile-based computing. IBM Systems Journal. 39(3&4):840-859.
9. Brady, S., S. Coyle, Y. Wu, G. Wallace, and D. Diamond.(2006) *Wireless-based monitoring of body movements using wearable sensors.* In: Proc. *MRS Spring Meeting, Symposium S*. 2006. San Francisco.
10. Brady, S., D. Diamond, and K.T. Lau (2005) Inherently conducting polymer modified polyurethane smart foam for pressure sensing. Sensors and Actuators A. 119:398-404.
11. Braddock Clarke, S. and M. O'Mahony, *Techno Textiles 2: Revolutionary Fabrics for Fashion and Design* 2006: Thames and Hudson.
12. Nishide, H. and K. Oyaizu (2008) Materials science. Toward flexible batteries. Science. 8(319):737-8.
13. Siegel, A.C., S.T. Phillips, M.D. Dickey, N.L. Zhigang Suo, and G.M. Whitesides (2010) Foldable Printed Circuit Boards on Paper Substrates. Advanced Functional Materials. 20(1):28-35.
14. Buechley, L. and M. Eisenberg (2008) The LilyPad Arduino: Toward Wearable Engineering for Everyone. IEEE Pervasive. 7(2):12-15.
15. Maccioni, M., E. Orgiu, P. Cosseddu, S. Locci, and A. Bonfiglio (2006) Towards the textile transistor: Assembly and characterization of an organic field effect transistor with a cylindrical geometry Export Applied Physics Letters. 89(14):1-3.
16. Coyle, S., Y. Wu, K. Lau, D. De Rossi, G. Wallace, and D. D (2007) Smart nanotextiles : A review of materials and applications. MRS Bulletin. 32(5):434-442
17. Qian, L. and J.P. Hinestroza (2004) Application of Nanotechnology for high performance tectiles. Journal of Textile and Apparel, Technology and Management. 4(1):1-7.
18. Carpi, F. and D. De Rossi (2005) Electroactive Polymer-Based Devices for e-Textiles in Biomedicine. IEEE Transactions on Information Technology in Biomedicine. 9(3):295-318.
19. Hristara-Papadopoulou, A. and J. Tsanakas (2007) Results of active cycle of breathing techniques and conventional physiotherapy in mucociliary clearance in children with cystic fibrosis. Hippokratia. 11(4):202-204.
20. Goldberg, D.A. and D.L. Whitesel (1983) Heel counter stabilization of the running shoe. The Journal of orthopaedic and sports physical therapy. 5(2):82-83.