Physiological Tracking, Wearable Interactive Systems, and Human Performance

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ABSTRACT

Wearable devices extend the body in a real and virtual manner. The flow of information and stimuli from real-to-virtual, and virtual-to-real enable experiences to be shared across time and space. Wearable devices using textiles with embedded physiological sensors are presented in various applications involving monitoring, control and learning. The potential of interactive textiles to capture performance, accelerate learning, and connect the expertise of elite athletes and sports scientists with novices through the use of common virtual interactive models is reported. Elements of system design and the accuracy and precision required for the effective transfer of embedded knowledge over space and time is discussed.

KEYWORDS: Motion tracking, wearable devices, interactive, Emotion, smart textiles, physiological.

INDEX TERMS: H.5.2: User Interfaces, Interaction Styles, I.2.1: Applications and Expert Systems, Games.

1 INTRODUCTION

Textile and clothing innovation has moved far beyond societal needs of comfort and fashion [1]. Garments can now carry a variety of sensors to intimately interact with the human form. Textiles with embedded sensors that detect physiological function are being developed and deployed for applications in entertainment, education, sport, military and medicine [2, 3]. These wearable devices typically connect to digital infrastructure to provide a seamless flow of physiological information. Their use is enabling new methods of service provision [4]. In this paper, a generic platform for a wearable interactive system using textile sensors is discussed in terms of its various applications to monitoring, control and learning.

2 BACKGROUND

A wide variety of new and conventional materials are being investigated for textile sensors as routinely discussed elsewhere [2, 3]. Ideally, the materials are well specified to enable explicit sensor design [3] in a way that complements the greater system architecture and its usage patterns. In combining materials science with ICT technologies, our work is guided by recent engineering advances, application and implementation in various fields [3, 4], and fine art and design ideation techniques [5].

2.1 Unbounded Physiological Interaction

The goal of our work is to connect real and virtual components of individual experiences: anyone, anywhere, anytime. Our interest extends to the emotional context of engagement, to understand the emotion or feeling of the 'experience', the connectedness of multiple subjects, and subsequently how the use of technology impacts and enhances human performance in diverse settings.

2.1.1 Infrastructure and Architecture

The Commonwealth Science and Industrial Research Organisation's (CSIRO) Wearable Interactive System (WIS) combines textile sensors interfaced wirelessly with software to enable real-time tracking and interactive feedback. This interactive system can also form part of a 'Knowledge Experience Network' (KEN) using mobile devices. The KEN system facilitates capture, storage and access to performance data and audio visual communication between various distributed elements and portals. KEN is being applied in sport to improve athlete, coach and scientist interaction, accelerating performance analysis and feedback. The WIS (parts A, B & C) and KEN (parts A, B, C, & D) hardware is depicted schematically in Figure 1.

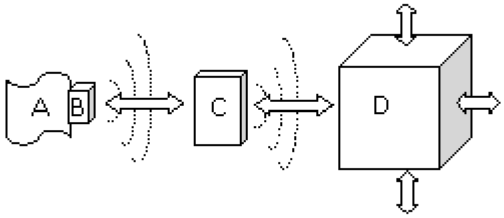

Figure 1. System architecture, A wearable sensor, B wearable electronics unit, C local computing device , D remote server.

Typically, two novel textile motion sensors [6] are combined to form a wearable control interface. The sensors can be located on various parts of the body to detect positive and negative strain, e.g. on the elbows to detect when the arm bends. To date these sensors have been used for tracking various bodily motions, e.g torso, hips, knees, shoulders, chest respiration, back, elbows and wrist [3, 5]. Other textile sensors can also be used, electrodes for monitoring bio-potentials (e.g. for heart function) [7] and pressure sensors for detecting various forces (e.g. for foot pressure) [8, 9]. The textile sensor signals are bussed via conventional garments (e.g. a shirt) to a common wireless connection point, and from there to a computer for signal analysis and output generation. Additionally, the location of a subject can be determined using imaging, global positioning systems, radio frequency, accelerometers, magnetic devices and combinations of these mounted on textiles [3]. Suitably instrumented equipment can also be integrated into the system [10].

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2.2 Real and Virtual, Balance and Transfer

Wearable devices extend the body in a real and virtual manner [11]. The flow of information and stimuli from real-to-virtual, and virtual-to-real enable experiences to be shared across time and space. The information loops created can form an integral component of device control, human learning, and mobile monitoring. Wearable devices can have mixed roles depending on the information and implementation. For example in sport, the systems and information can be used for interactive training in the field, to provide near-real-time access to data on mobile platforms that allows coaches and sports scientists to see effects of adjustments to athlete technique immediately and make more informed decisions from far away, and, assist with athlete selection and evaluation through greater access to information about individual performance in various settings over longer time periods. The key is to capture real components and connect with virtual elements in a way that emphasizes desirable natural motion and emotion. Similar approaches can be applied to medical settings [7]. The user group's acceptance of the technology platform requires the technology to complement and not distract according to their context and intent.

2.2.1 Abstraction, Approximation and Extension

A stable relationship between the real and virtual elements is an important premise for constructing interaction and control scenarios. There are a number of existing techniques and models for replicating the human form in digital space, most often relating body markers to a virtual model using image processing and standard marker locations [12]. The emergence of textile sensors for motion tracking requires the development of models for relating textile sensor information with formalised virtual knowledge and interactive functions. The customization and calibration of textile sensors to individuals can present many challenges [13].

A well designed and fitted garment with well characterized sensors can provide robust and repeatable function [3]. The accuracy and precision required of sensors is dependent on the measurement and control intent. The use of approximation and abstraction of biomechanical models and skill conceptualization can be a useful approach to achieve a balance between virtual contribution and real distraction. i.e. focusing on particular physiological movement and locating the sensors accordingly to control simple interactive functions. Figure 2 shows a two dimensional biomechanical approximation of elbow and wrist function that we have found useful in some throwing applications for the transfer of knowledge from elites to novices via virtual interactive models.

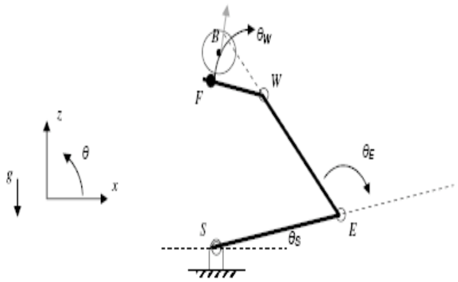

Figure 2. 2D Arm approximation.

2.2.2 Interactive Accuracy and Precision

The accuracy and precision required for the effective transfer of information between real and virtual elements is also context specific. This has implications for functional design and embodiment of hardware, firmware and software that allows information to flow to and from the client(s) and expert(s) in the architecture depicted in Figure 2.

The performance and utility of the wearable sensors we use have been reported elsewhere [3, 7, 8, 9]. Basically, when properly integrated with a host garment the sensors can have an acceptable level of accuracy and precision that is stable across a 3hr intensive session. This means useful kinematic analysis and interpretation and discrimination of different sets of actions can be achieved with these garments.

The sampling rate and system *latency*, time taken between a real motion and the output from the digital infrastructure, (e.g. PC, smart phone, network etc), and *jitter,* the variation in this delay, are important design considerations for a wearable interactive system. The *latency* and *jitter* often need to be minimized to enable realistic interactive function and for the feedback to usefully affect the user's subsequent motions. If the latency is too large a systematic slowing of a performance may result or possibly the output will not be synchronised with the user's movements. Latency is less of an issue where the feedback stimulus is not delivered as part of the task. There are various signal passing components that impact on latency and jitter, see Figure 3, these are additive within a system.

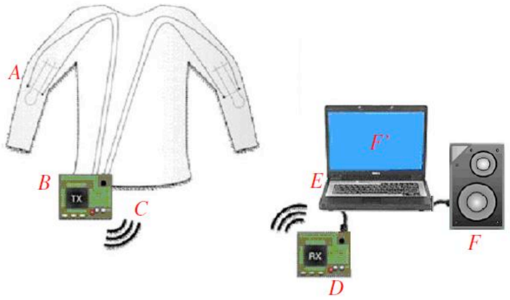

Figure 3. Key points in signal path from detection to expression.

In general the key contributions to signal latency relate to

A-B	Analogue component of motion sensing
B-C	Digitization and Broadcast
C-D	Reception and Passing to PC
D-E	Appearance in software application and processing
E-F	Output from software application

We typically use customised interactive systems with a latency of 20 +/-5ms in high performance settings, and have found latencies of 60 – 120ms acceptable for entertainment applications.

2.2.3 Engagement and Emotion

Virtual games offer an exciting way to motivate and engage subjects [14, 15]. The device interface itself also has the ability to engage [11]. Physiological measures, such as heart rate variability and bodily gestures, can provide insight into emotional state and perceptions of task [16]. Understanding and monitoring the emotional context of real and virtual settings is important in enhancing human performance, as emotions can cause a loss in self-monitoring capacity and objective observability [17].

3 RESULTS AND DISCUSSION

The following discussion describes some of our work to date exploring the potential of interactive textiles in various applications involving monitoring, control and learning.

3.1 Virtual Connection and Manipulation

A number of control and interaction scenarios are being explored using textile sensors as a generic control interface in 3D virtual environments, see Figure 4. The textile sensors are used to detect movement as discrete gestures and/or stream continuous biomechanical measures of limb motion.

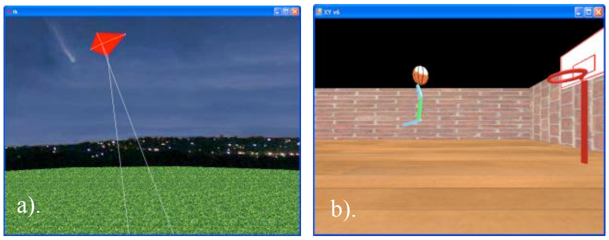

Figure 4. Screen shot of 3D Virtual Object Control, a). flying kites via discrete gestures, and, b). virtual ball throwing using biomechanics.

3.1.1 Step-wise Gesture Control of Virtual Kites

A sensor garment and step wise control model initially developed for a wearable instrument [3] was adapted for virtual 'kite flying' to explore new interfaces and flight control concepts. The kite was controlled using a gesture interpretation rule set that enables the kite to be drawn towards and pushed away from the subject and also rotated and moved in the direction the kite is facing by arm gestures as depicted in Figure 5. The control was implemented as Left and Right components representative of the left and right elbow bends, see Table 1. Where +3 is straight arm, -3 is fully flexed arm, zero is a nominal midpoint, and for example a value of '1' represents an arm bend between say 50 and 60 degrees.

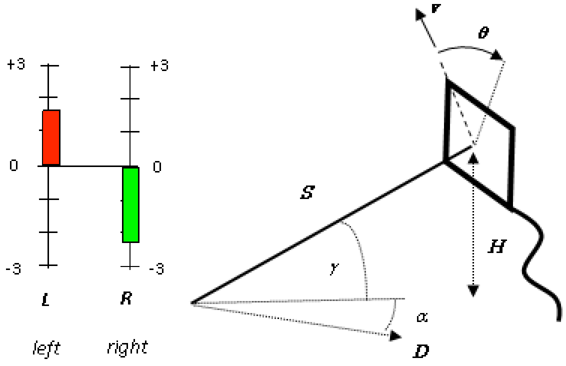

Figure 5. Step wise 3D Virtual Object control and kite flying.

Table 1. Stepwise Control Rule Set

Rule	Action
L=R = 0	No action
L=R > 0	Move away from subject, Increase S
L=R < 0	Move toward subject, decrease S
L>R	Rotate clockwise, (Increase θ, v =fn(L-R))
L<R	Rotate anticlockwise, (Decrease θ, v =fn(L-R))

The kite flying exercise established a model relating the textile sensor to a virtual object's motion such that the object could be moved in 3D by a small set of imprecise gestures. The relationship of elbow bend to L and R could be customized to suit user gesture preferences and concepts of preferred 'feel'.

3.1.2 Biomechanical Approximation and Virtual Balls

A number of control and interaction scenarios are also being explored looking at the WIS as a generic dynamic control interface. A 2D model for ball throwing [3], see Figure 2, was used in a 3D game environment to allow interactive feedback and different perspectives of ball throwing. The static inputs to the task, such as target metrics (geometry, size,centre height, location $G(x, z)$), ball size (b)), and subject metrics (shoulder location $S(x, z)$ and angle (θ_S), upper arm length (SE), forearm length (EW), hand length (WF)) were chosen to reflect a typical throw scenario. The model assumptions included: shoulder position and angle is fixed, ball is in contact with 'fingers' until release, then it obeys 2D motion equations, release point from hand is related to arm kinematics (θ_E, θ_W), which were detected using a textile with elbow and wrist sensors .

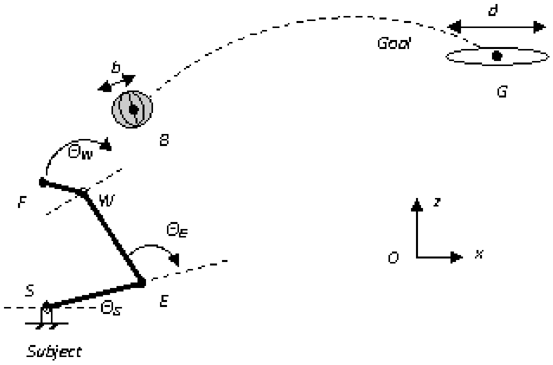

Figure 6. 2D model of arm and virtual ball throwing .

A key issue in virtual ball throwing using a textile sensor as the control interface is establishing rule conditions for the point of release and modes of contact with the arm. Whilst it is possible to fully describe the ball trajectory and interaction with complex 3D environments [18], in this case, the knowledge of typical kinematic conditions at release from previous work with throwing real balls was used to create an approximation for release.

3.1.3 Using Virtual Models to Control Real Objects

The skills developed with virtual games have potential to translate to real control and skill [15]. The use of stepwise gesture control rules allows for low precision movements. The control scenario described above for flying imaginary kites might also be useful for controlling real vehicles. For example, the kite analogy is perhaps useful for landing aircraft where the controller has little experience in flying but can relate to kite control and the control algorithm is implemented on the aircraft. Using biomechanical approximations such as that shown for ball throwing can be adapted for virtual training and may enable the rudiments of technique (e.g. promoting wrist flexion) to be grasped by multiple subjects in a fun and engaging setting.

The use of game technologies and haptic devices for skill development will form part of our future investigations.

3.2 Interactive Implementation and Intervention

In skill acquisition, often the real task is paramount and contributions from the virtual counterpart and its associated hardware, such as interactive auditory biofeedback, need to be designed to compliment learning with minimal distraction to normal session practices. Understanding how humans acquire skills to perform motor tasks is a multidisciplinary and challenging issue. It involves addressing complementary aspects of perception, cognition, motor control, decision-making, and social behaviors. Interactive devices provide additional movement stimuli. This biofeedback can act as a common reference that connects sound with technique [19], particularly in relation to the relative timing of a movement sequence. This effect can enable knowledge and skill transfer from experts to novices through the use of a common interactive model, see Figure 7.

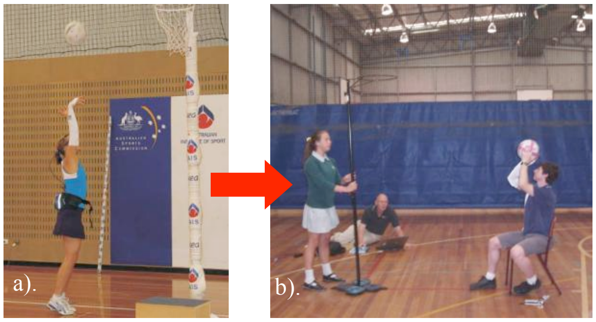

Figure 7. Using wearable devices to connect elite performance (a) with novice development (b).

3.2.1 Elite Training and Virtual Interactive Models

An interactive model for netball throwing evolved from preliminary exploratory work with elite athletes. The auditory feedback consisted of two related rhythmic audio samples. These were triggered by exceeding preset sensor values, e.g. angles which were chosen to draw attention to say the elbow and/or wrist motion. The athletes' preferences guided the choice, placement and tempo of the rhythmic audio samples. Dance beats and tempos of the order of 120bpm were pleasing to the athlete and were used as part of throwing training. The intent was not to significantly alter the athletes understanding or performance of their technique, merely to observe it, provide an auditory conceptualization, subtly prompt throw initiation, create pressure situations, and add a new interesting element to engage the athlete with routine training. As part of this, the audio was used to relate the athlete's action to a beat. The athlete was then asked to perform various throwing exercises in time with the beat. For example, to catch a ball and then throw in time with a beat that was randomly initiated on or before catching

From this work, a model evolved to provide a common reference for preferred technique for certain throwing exercises. The interactive model's first beat rhythmic audio sample was triggered during the backward 'loading' motion of the elbow, an increase in elbow displacement from less than 90 degrees to more than 90 degree, well before the release of the ball. The second beat was triggered by the forward wrist motion exceeding 15 degrees displacement in the latter part of the throw (i.e., after the first sound had triggered and near the point of release). Rhythmic audio samples were used as it was thought that this would influence the temporal aspects of a subject's throw technique. The placement of a trigger on the wrist sought to promote greater flexion of the wrist. The model is depicted for a 2m netball throw in Figure 8 where the trigger points (T1 and T2) are identified along with the audio play period for the elbow and wrist sounds.

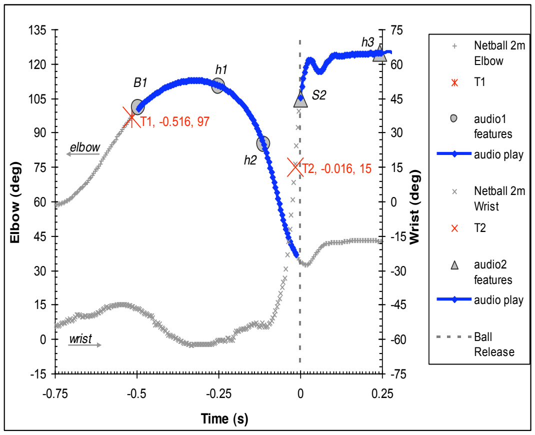

Figure 8. Interactive Model for Ball Throwing.

3.2.2 Novice Skill Development and Learning

The potential of a wearable interactive garment to provide rhythmic auditory biofeedback to augment the learning of a novice study was explored in a setting where there was no expert guidance [20]. Twenty-two secondary school children (16±1 years) in four different locations, with limited to no previous netball or basketball free throw shooting experience participated voluntarily in this study. The task was designed so that it was novel, expedited the learning process, and allowed direct comparison between the kinematic measures recorded and fed back to the subjects and their shooting performance. The interactive intervention group who received rhythmic biofeedback during training was required to perform a dual task in training, to activate both audio samples and throw a 'swish' with their throws. The control group were also asked to throw a 'swish' but only wore the sleeve for monitoring purposes, and no audio was used in testing.

The study provided preliminary evidence for a general improvement in throwing accuracy for a group of novice adolescents through the prescribed use of an interactive device without expert guidance [20]. The techniques and approach exhibited during training were quite different for the two groups. The use of biofeedback typically led to an appreciable drop in performance during the early phase of training as the subject grappled with controlling the ball throw and the audio sounding. Their performance recovered as training proceeded, see Figure 9.

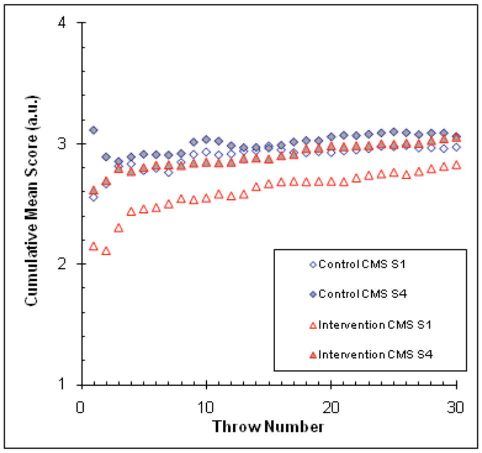

Figure 9. Cumulative mean accuracy score in early training (S1) and later training (S4) of interactive intervention and control.

Not all subjects within the interactive biofeedback intervention group responded positively and it was observed that some struggled with the dual task of throwing a ‘swish’ and activating the audio, particularly those with particularly low scores in preliminary testing (i.e. poor initial skill). This suggests that the use of interactive devices may need to be adapted to suit individual abilities and preferences.

Whilst the interactive audio triggering may have proved challenging to the intervention group, it encouraged greater movement exploration, which is associated with effective learning [21], and engagement with task as evidenced by clear articulation of task strategy. The control was observed to optimize early and were not able to articulate task strategies. Consistent with an ecological approach to practice, learning is considered to be the process of continually searching for regions of stability within a learner’s perceptual-motor workspace with variability in movement dynamics seen as a functional method of enhancing this search process [22]. The benefits of training with a dual task may also have contributed to learning and improved accuracy. Whilst there is scope for improvements to fit and function across a population, the result realised the potential of interactive textiles to significantly affect technique development, accelerate learning, and connect the expertise of elite athletes and sports scientists with novices.

3.3 Mobile Systems

The expert and client, e.g. athlete and coach, can often be physically separated making both measurement and communication difficult. Field locations can also make it difficult for specialist staff to routinely attend client training sessions and access and comment on immediate and historical data. Further issues arise as data is captured by isolated devices which may require manual data handling leading to lengthy delays between acquisition, analysis and feedback. This limits productivity and efficiency. Figure 10 shows an example of elite training where a smart textile is being used to monitor technique in the field and the performance measurement is relayed in real-time to a coach on a chase boat and shared with a sports scientist in an office.

Figure 10. Mobile Tracking KEN v1.01.

An online information storage and handling system has been developed to allow near-real time display of current performance data. The first system embodiment (KEN v1.01) had multiple wearable sensors connected via Bluetooth to a smartphone to provide real-time data acquisition. The smartphone application acquired and transmitted data to an online store in real time, with a local interface for voice communication and feedback of performance metrics. A variety of peripheral devices with variable signal flow control have been used to explore the capacity of the system and the performance of state of the art smartphones. Storing and sharing data online significantly improved accessibility, allowing coaches and scientists to analyse training and testing from any location. With a single data store, use of multiple sensor systems meant data sources were combined as a single synchronized multidimensional time-series of data. Portal interfaces, such as that shown in Figure 11, provided data visualization, control and interaction that allowed experts to filter data to see detail of effects of adjustments to client technique immediately and make more immediate informed instruction whilst mediating some of the frustration that can be present in challenging field environments. The system also provided the ability to compare individual performances with group measures.

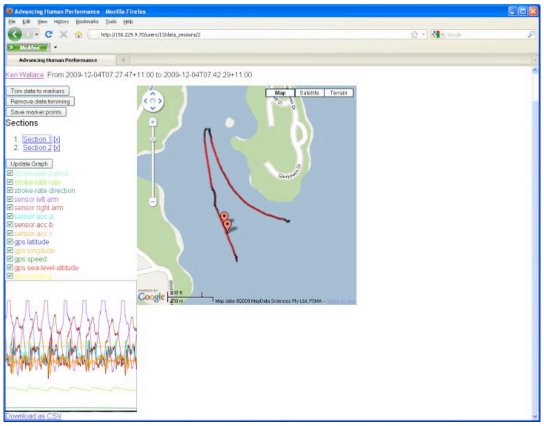

Figure 11. Virtual Interaction Portal KEN v1.01.

4 CONCLUSION

We find that wearable sensor interface stimulates creativity and ideas for new modes of control and interaction, including games. The flow of information and stimuli from real-to-virtual, and virtual-to-real enable experiences to be shared across time and space. Wearable devices using textiles with embedded physiological sensors can capture real performance, assist with accelerating learning, and connect the expertise of highly skilled individuals with novices through the use of common virtual interactive models.

REFERENCES

[1] “The Future is Textiles! Strategic Research Agenda of the European Technology Platform for the future of textiles and clothing”, The European Apparel and Textile Organisation, June, 2006.

[2] F. Carpi, and D. DeRossi, “Electroactive polymer-based devices for e-textiles in bio-medicine”, IEEE Transactions on information technology in Biomedicine, 9:3, 295-318, September, 2005.

[3] R.J.N. Helmer, M.A. Mestrovic, D. Farrow, S.R. Lucas, and W. Spratford, “Smart Textiles: Position and Motion Sensing for Sport, Entertainment and Rehabilitation”, Adv. Sci. & Tech. 60 144. 2008.

[4] JJ. Rutherford, “Wearable technology”, IEEE Engineering in Medicine and Biology Magazine, 29(3), 2010.

[5] D. Wilde, R J. N. Helmer, M. Miles, “Extending Body & Imagination: moving to move.”, Proc. ICDVRAT with ArtAbilitation Viña del Mar/Valparaíso, Chile. September 2010

[6] WO/2007/041806

[7] H. Ding, A. Sarela, R. J. N. Helmer, M. A. Mestrovic, and M. Karunanithi, “Evaluation of Ambulatory ECG Sensors for A Clinical Trial on Outpatient Cardiac Rehabilitation”, Proc. IEEE/ICME Complex Medical Engineering, Gold Coast, Australia, June, 2010.

[8] R. Cranston, L. Foley, M. Mestrovic and B. D'Arcy, "Sensing and Monitoring the Neuropathic Foot", Proc 3rd Cong. World Union Wound Healing Societies, 2008.

[9] J. McLaren, R.J.N. Helmer, S.L. Horne and I. Blanchonette, "Preliminary Development of a Wearable Device for Dynamic Pressure Measurement in Garments", Procedia Engineering 2 (2), 3041-3046, 2010.

[10] M.J. Jennings, I. Blanchonette, S.R. Lucas, S.W. Morgan, R.J.N. Helmer, and C. Yang, "Instrumentation of a Field Hockey Stick to Detect Stick and Ball Interaction during a Drag Flick", Procedia Engineering 2 (2), 2979-2984, 2010.

[11] D. Wilde, A. Cassinelli, A. Zerroug, R J N. Helmer, M. Ishikawa, "Light Arrays: a system for extended engagement", Proc. ICDVRAT with ArtAbilitation Viña del Mar/Valparaíso, Chile. September 2010

[12] B.C. Elliott, J.A. Alderson, and, E.R. Denver, "System and modelling errors in motion analysis: Implications for the measurement of the elbow angle in cricket bowling", Journal of Biomechanics, 40: pp 2679-2685, 2007.

[13] T.E. Campbell, B.J. Munro, G.G. Wallace, J.R. Steele "Can fabric sensors monitor breast motion?" Journal of Biomechanics, 40, 3056-3059, 2007.

[14] S. Berkovsky, M. Coombe, and R.J.N. Helmer "Activity interface for physical activity motivating games", Proc. 14th int. conf. on Intelligent User Interfaces, Hong Kong, China, February, 273-276, 2010.

[15] Y.A. Fery and S. Ponserre, "Enhancing the control of force in putting by video game", ERGONOMICS, 44 (12): 1025 - 1037, 2001.

[16] Smith, C.A. "Dimensions of appraisal and physiological response in emotion", J Pers Soc Psychol. Mar;56(3):339-53, 1989.

[17] Novaco, R.W., "Anger", Encyclopedia of Psychology, Oxford University Press, 2000.

[18] Okubo H., and Hubbard M., 'Dynamics of the basketball shot with application to the free throw', Journal of Sports Sciences, December 2006; 24(12): 1303 – 1314, 2006.

[19] C.H. Shea, G. Wulf, J.-H. Park and B. Gaunt, J. Motor Behavior 33, 127, 2001.

[20] R.J.N. Helmer, D. Farrow, S.R. Lucas, G.J Higgerson and I. Blanchonette, "Can Interactive Textiles Influence a Novice's Throwing Technique?", Procedia Engineering 2 (2), 2985-2990, 2010.

[21] K.M. Newell, K.M. Differing Perspectives in Motor Learning, Memory, and Control, edited by D. Goodman, R.B. Wilberg and I.M. Franks (1985). 295-317. Amsterdam: Elsevier Science.

[22] C. Handford, K. Davids, S. Bennett and C. Button, "Skill acquisition in sport: some applications of an evolving practice ecology", J. of Sports Sciences 15, pp. 621–640, 1997.