Personal sensing wear:

The role of textile sensors

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Abstract.
Wearable sensors for fitness tracking are becoming increasingly popular and are set to increase as smartwatches begin to dominate the wearable technology market. Wearable technology provides the capacity to track long-term trends in the wearer's health. In order for this to be adopted the technology must be easy to use and comfortable to wear. Textile based sensors are ideal as they conform to the body and can be integrated into the wearer's everyday wardrobe. This work discusses fabric stretch sensors that can measure body movements. An application using a sensor glove for home assessment of Rheumatoid Arthritis is presented. This work is the result of a multidisciplinary effort, involving expertise in material science and functional design, computer science, human health and performance and influenced by the end user needs.

Keywords. Wearable sensors, piezo-resistive textile, home monitoring, rheumatoid arthritis, personal health, smart garments, interactive textiles

1 Introduction

For healthcare delivery to become more personalised it is essential to find ways to track the long- term physiology of the person. Clinical visits are sporadic, and rely on patient's subjective reporting of their symptoms. Quantifiable measures of physiological output could provide a more definitive account of personal well-being. Smartphones are already equipped with motion and location sensing devices which, from a healthcare perspective, can be used to monitor activity levels and exercise. The use of a smartphone is a successful model as it does not encumber the user with additional technology, and many people have access to this hardware. The concept of a smart garment is similar; by integrating miniature or textile-based sensors into garments, the garment functionality can be extended to monitor the wearer's health without the need for additional technology, wires or supplementary devices. Wearable sensors and smart textiles therefore offer the possibility of monitoring the body in an unobtrusive manner (Castano and Flatau, 2014, Coyle et al., 2014, Stoppa and Chiolerio, 2014, O'Quigley et al., 2014). Smart garments may be used to assess chronic conditions at home and as a rehabilitation tool. As part of a user interface system, visual and audio feedback can be given to motivate users and encourage adherence to prescribed exercises. Home monitoring of exercise performance can also be used to indicate the effectiveness of treatment to therapists. This can allow a personalised approach to healthcare delivery and rehabilitation strategy. The wearer's own "smart" garments can log their physiology automatically as they go about daily tasks creating a personal physiological diary of their wellbeing.

Rheumatoid Arthritis (RA) is a chronic condition requiring on-going treatment and disease management. It is an auto-immune disease which attacks the synovial tissue lubricating skeletal joints and is characterized by pain, swelling, stiffness and deformity(National Collaborating Centre for Chronic Conditions (UK), 2009). This systemic condition affects the musculoskeletal system, including bones, joints, muscles and tendons that contribute to loss of function and Range of Motion (ROM). Early identification of RA is important to initiate correct drug treatment, reduce disease activity and ultimately lead to its remission.

This paper discusses the use of textile stretch sensors that can detect kinematics of the body to monitor joint movements. We present the design of a sensor system to assist the management of RA through home monitoring of hand exercises. The glove has been designed with the user's dexterity and comfort in mind. Fabric sensors are comfortable to wear, lightweight, stretchable and conform to the user. The glove was first designed using a single sensor on each finger and thumb, and its performance compared to a commercial data glove. While the commercial data glove is not a gold standard for measuring joint angles it gave an indication that the textile sensor system could be suitable for our application. Following on from this the glove design was improved by adding additional sensors to differentiate between different finger positions. Testing of this was carried out using Vicon motion capture to evaluate its performance in controlled laboratory conditions. A graphical user interface was developed to guide patients through prescribed exercises, providing motivation while also giving the option of logging daily performance. The aim is to be able to monitor the patient's level of stiffness and range of motion throughout the day, away from the clinical setting, in order to develop a personalised treatment for their condition.

2 Methods

2.1 Glove design

A sensor glove has been developed using fabric stretch sensors integrated into an oedema glove. It is important that the glove design does not restrict or influence movement. The stretch sensors are made of a knit fabric coated with conducting polymer, giving them piezoresistive properties. This means that when the fabric is stretched the resistance changes, which can be measured using straightforward circuitry and captured with a microprocessor platform. An Arduino Fio with integrated Xbee radio was used to collect and wirelessly transfer the data to a laptop.

Two glove designs are presented here. First a glove with five sensors was created and tested (Design 1). After testing its performance, an improved design (Design 2) was created which integrated more sensors to identify more specific finger movements. Design 1 was a straightforward design using just one stretch sensor on each finger. Each stretch sensor covered all three finger joints - the distal interphalangeal joint (DIP), proximal inter-phalangeal joint (PIP) and metacarpal-phalangeal joint (MCP), Fig. 1(b). Strips of sensor fabric of 5mm width were stitched in place using conductive stainless steel thread, shown in Fig. 1(a). A circular sew-in prototype board (Lilypad protoboard) was used to connect to the electronic circuitry. The sensor fabric and conductive thread were covered using a lycra® fabric for protection and this layer also held the sensor in place over the joints. The protoboard was encased with moulded silicone (Sugru®) to secure the connections. The Arduino Fio and its Lithium Polymer battery were housed in a 3D-printed custom fit enclosure designed to fit the curvature of the wrist. A battery of 400mAh was chosen for its small size, providing an operation time of approximately one hour continuous use. This was sufficient for initial tests based in a laboratory setting with constant wireless data transmission. Longer term battery use could be achieved using power optimization strategies e.g. integrating an SD card and transmitting data when necessary.

(a) (b)

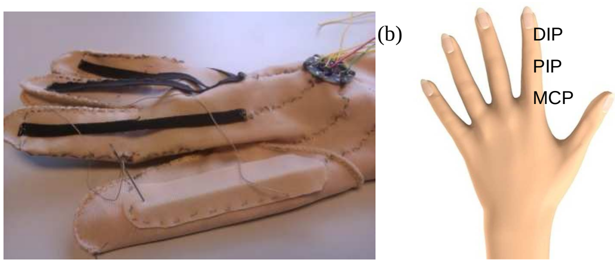


Fig. 1. (a)Glove design 1 with stretch sensor on each finger and thumb, each sensor strip covered three joints on the finger (b) location of the finger joints, Distal interphalangeal joint (DIP), Proximal inter-phalangeal joint(PIP) an Metacarpal-phalangeal joint(MCP).

Design 1 may be sufficient for some applications, and is easier to manufacture, but due to the nature of the sensors it cannot identify the location of the bend. Therefore the second glove was designed to have more specific measurement of the position of each joint. Two sensors were positioned on each finger – one covering DIP and PIP (these joints tend to move together) and the other one covering MCP. A digital 3-axis MPU-6050 containing an accelerometer/gyroscope (Sparkfun Electronics, 2012) was included on the back of the hand (see Fig. 2(a)). The MPU-6050 contains a MEMS accelerometer and a MEMS gyro in a single chip. It has a digital output and uses the I2C interface for communication. A multiplexer (74HC4052) was used to expand the inputs on the Arduino Fio board from six to twelve, allowing ten fabric sensor inputs and two inputs for the MPU-6050. As with the first glove prototype the sensors were covered using fabric and the wired connections reinforced using moulded silicone (Sugru®). Fig. 2(b) shows the 3D printed enclosure for the Arduino Fio, multiplexer circuit and battery. The enclosure also allowed a Velcro strap to be fastened around the wrist.

(a) (b)

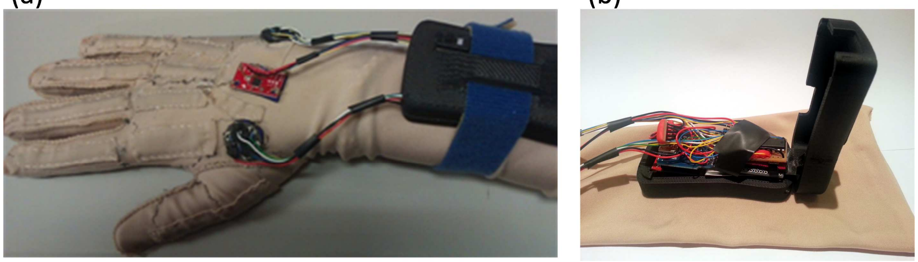


Fig. 2. (a) Glove design 2 with two sensors on each finger and a 3-axis accelerometer, gyroscope on the back of the hand. (b) 3D printer enclosure showing control circuitry

To connect to the user interface this glove was given Wi-Fi capability using a RN-XV WiFly module (Roving Networks, 2011). This component provides wireless communication with any device capable of receiving 802.11 b/g data. It contains built-in applications for DHCP, DNS, Telnet, FTP and HTML. This interface can be attached directly to any suitable device through an ad-hoc network, or can be configured to attach to a network infrastructure by TKIP authentication and communicate using its integrated TCP/IP communication stack. The Wi-Fi module is configured with an SSID, TCP socket number, and static IP address. The SSID is broadcast from the Wi-Fi module once the data glove is powered on. A local device capable of detecting the SSID broadcast may connect to the Wi-Fi interface to create an ad-hoc network with the data glove. The Wi-Fi module is configured using a static link-local (Cheshire et al., 2005) IP address 169.254.1.1. A link-local address is suited to the typical operating environment of the ad-hoc connection between data glove and connected device.

2.2 User interface

The graphical user interface developed by the School of Computing and Intelligent Systems at Ulster University provides the motion capture software to regulate glove functionality. This includes sensor calibration, sensor recording and playback, alongside detailed statistical analysis of recorded movement to measure and evaluate variance within exercise routines. The interface has been designed in collaboration with target patient and clinician end-users in Altnagelvin Hospital in Co. Derry.

The custom software captures real-time data streamed from the data glove and post-processes it using software algorithms. The software also provides real-time user feedback and analysis of exercise recordings for clinicians to assess. The bespoke software records objective routines that are defined by the clinician and performed by the patient at home at prescribed times throughout the day.

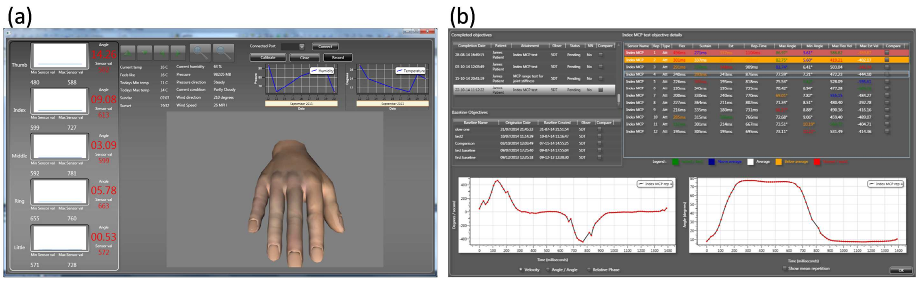


Fig. 3. (a) Screenshots of the graphical user interface providing visual feedback during hand exercise routine. (b) Data analysis window showing measurement information for completed hand exercises

Fig. 3(a) shows a screen capture of the visual feedback window with a real-time hand animation and detailed information on calculated joint angles. The 3D hand mimics patient finger joint movement as detected by data glove sensors; therefore the hand exercise routines completed remotely by the patient at home can be played back and viewed by the clinician. Each routine is analysed by controlling software and automatically partitioned into constituent repetitions. Each repetition is further subdivided and provides timing information on flexion and extension movement as well as minimum and maximum angular and velocity information calculated for each repetition. Fig. 4 shows one typical flexion and extension angular movement profile for a finger joint. Individual flexion and extension movement is sigmoidal shaped as demonstrated by the flexion and extension lines, and one complete open-closed hand movement produces a Gaussian shaped curve. This information is used to provide indicators of changes in movement kinetics between exercise routines. Information is presented to the clinician as an assistive tool to aid with finger joint ROM assessment (see Fig. 3(b)). Colour coding of each exercise routine visually identifies variation in patient movement. Such information can help support the clinician during initial patient diagnosis and to measure progression or decline throughout patient treatment.

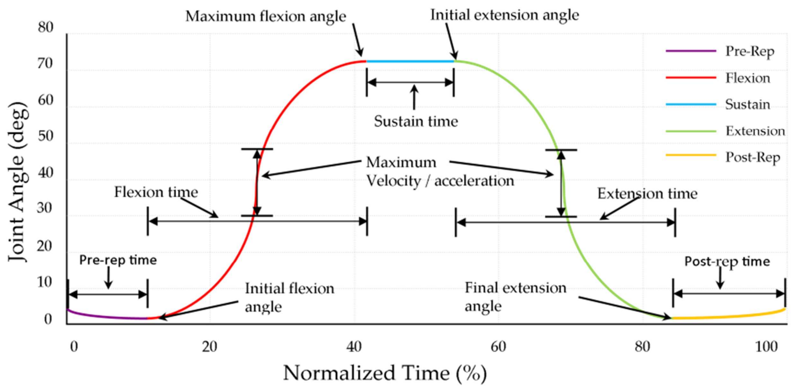


Fig. 4. Chart demonstrating segments that characterise a typical repetition within an exercise routine

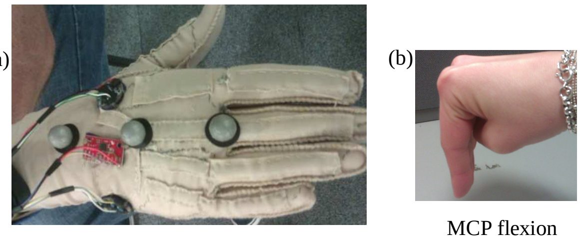
2.3 Testing procedures

Glove design 1 - Comparison with 5DT data glove.
The oedema fabric sensor glove has been compared to the 5DT Ultra 14 off-the-shelf virtual reality glove to determine accuracy of ROM measurement. The 5DT glove is a popular high-end commercial product that is representative of current state-of-the-art data gloves (5DT Data Glove, 2011). Both gloves were calibrated using software algorithms within the controlling software. Both gloves were then simultaneously worn on the dominant right hand of a subject with 19.7cm hand size and were connected to individual computers hosting identical copies of the controlling software system. An exercise routine was configured on the controlling software that consisted of 12 flexion and extension repetitions that measured movement of the middle MCP finger joint. The first repetition was used to synchronise recordings between computers and to remove unintentional delays in initial finger movement. Data was sampled every 25 ms from both data gloves. The controlling software segmented data into constituent flexion and extension movement.

Fig. 5. Hand position during exercise routines

Glove design 2 - Comparison with Vicon Nexus Motion system.
A 12 camera Vicon Nexus system (Vicon Motion Systems, 2013) was used as a gold standard reference for testing the performance of the second glove prototype. This procedure was carried out in collaboration with the School of Health & Human Performance at DCU. The Vicon system is generally used for larger range movements of the body. The markers used were 12 mm diameter and the cameras covered a space of 5m x 5m. The subject sat on a chair and raised their hand above their head and away from the body to reduce the risks of occlusion and inaccuracy of the Vicon system. Testing focused on a single finger at a time as placement of markers on every finger joint caused reading inaccuracies by marker-ghosting. Markers were placed on the flat part of the joint as placing them directly on top of the joint caused too much movement of each marker and affected angular accuracy. Three markers were used to study an individual joint in each trial. Fig. 6 shows the placement of markers for studying the middle finger MCP joint and Fig. 7 shows the placement of markers for studying the middle finger PIP joint.

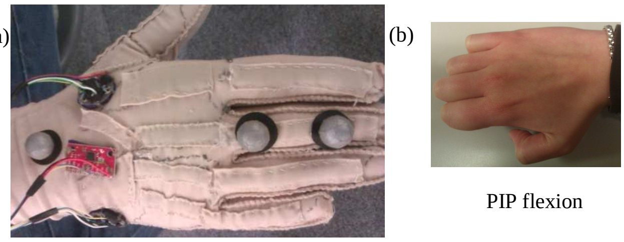
(a) (b)



MCP flexion

Fig. 6. (a) Placement of Vicon markers for MCP joint measurements (b) position of hand during MCP full flexion

(a) (b)



PIP flexion

Fig. 7. (a) Placement of Vicon markers for PIP joint measurements (b) Hand position during PIP flexion:

3 Results

Study 1 – Textile sensor glove 1 compared with 5DT data glove.

Initial results demonstrate a high correlation (r = 0.96) of recorded angular movement between the oedema fabric sensor glove and 5DT virtual reality glove. Fig. 8 shows a comparison of the recorded angular and velocity movements from the two gloves during a single flexion/extension movement. These are results captured from the middle finger MCP joint.

The minimum and maximum angular measurements for the middle finger MCP joint were averaged across the twelve repetitions, for each glove. Fig. 9 illustrates these results. The average minimum angle during hand flexion for the textile glove was 7.9º (standard deviation of 0.5º) and for the 5DT glove was 3.9º (standard deviation of 1.1º). The maximum angle during hand extension for the textile glove was 72.97º (standard deviation of 1.17º) and for the 5DT glove was 87.94º (standard deviation of 1.68º). The minimum angle would ideally be 0 º and the maximum 90 º. A gold standard system such as Vicon is needed to verify the actual value of the angle as the 5DT glove is not a gold standard system. Fig. 10 shows the average timings of the hand movements, the sustain time is the time between hand flexion and extension, as illustrated in Fig 4.

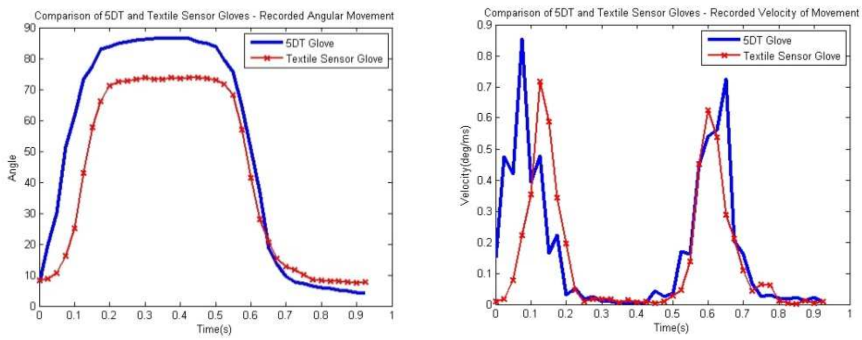


Fig. 8. Comparison of recorded angular and velocity movements from 5DT and Textile Sensor Glove for a single extension/flexion movement

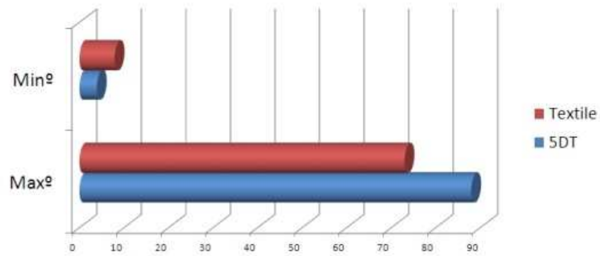


Fig. 9. Average minimum and maximum angular measurements from 5DT and Textile Sensor Glove

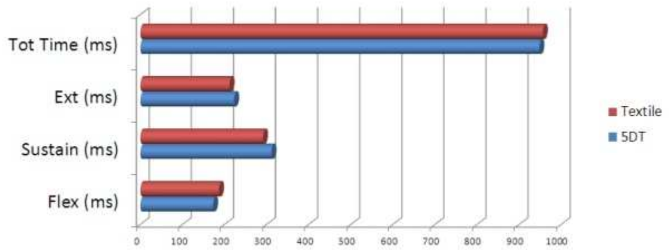


Fig. 10. Average timing measurements from 5DT and Textile Sensor Glove

Study 2 – Textile sensor glove 2 compared with Vicon Nexus Motion system.

To analyse the Vicon data the distance between each marker was calculated to give 3 sides of a triangle. Then the cosine rule was used to determine the internal angle which corresponds to the joint under analysis. The measurements for movements of the hand from full extension to full flexion are shown in Fig. 11 and Fig. 12. At the start of data collection the hand was held closed for 5 seconds to synchronise the data. Fig. 11 shows movement of the PIP joint for three flexion/extension actions. The glove sensor shows repeatable measurements for this, correlating to the Vicon measurements. There is a lag in the time response of the fabric sensors, before reaching the maximum value there is approximately a 2 second delay with the glove fabric sensor. Fig. 12 shows the measurements taken during the middle finger MCP trial. Six hand flexion/extension actions were performed, the first held for 5 seconds at the start. Measurements from this first exercise were used to calibrate the glove data for the following five exercises. The average error based on the maximum and minimum measurements was ±10.7º.

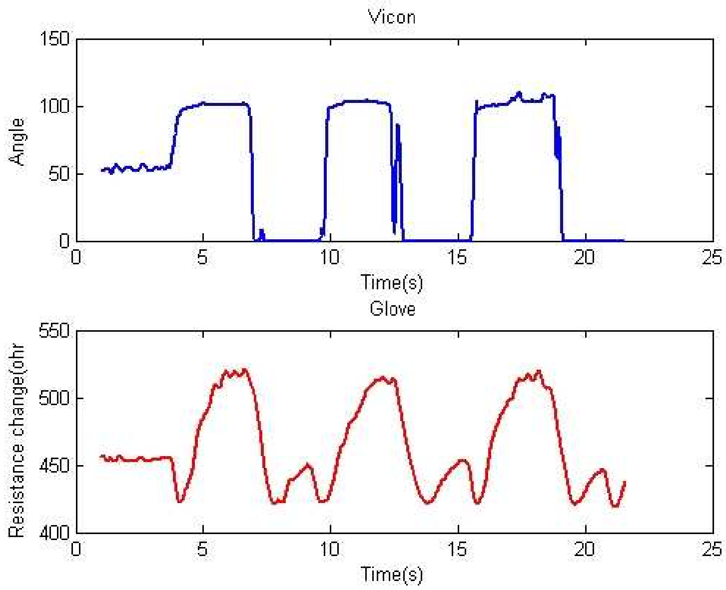


Fig. 11. Middle finger PIP measurements using Vicon and the sensor glove

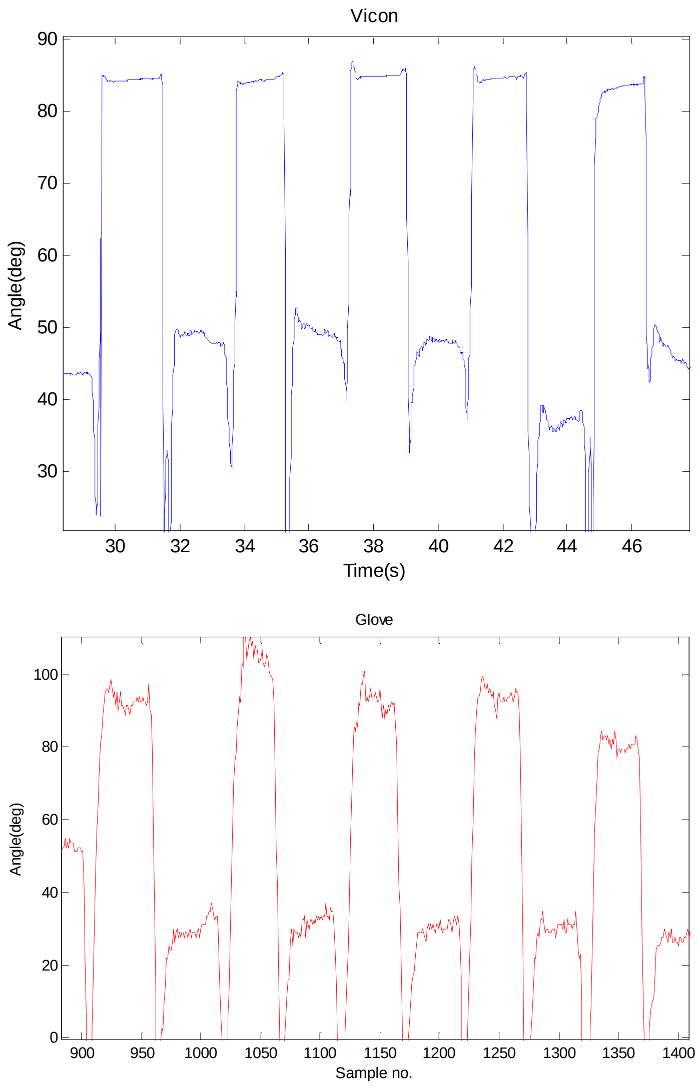


Fig. 12. Middle finger MCP measurements using Vicon and the sensor glove

4 Discussion

In the first part of the study the textile sensor glove shows similar performance to the 5DT commercial data glove and therefore shows potential for a home monitoring wearable system. The textile glove has the advantage of being comfortable to wear and suitable for wearing in cases of impaired dexterity. To evaluate the accuracy of the textile sensor glove testing with Vicon was carried out in the lab setting. While

there is error of up to 10º and a small latency in the textile sensor signals the glove may be useful in monitoring day to day flexibility and range of movement. Gold standard systems such as the Vicon Nexus Motion system used in this study are very expensive and not practical for everyday use by patients.
The sensors may also be integrated into other smart garments to monitor other joints to provide long-term measures and trend analysis of the patient's condition in the home setting. Such objective measurements would reduce dependence on patient memory and provide the clinician with accurate information for better and targeted care proposals. This information may help the patient and the clinician to understanding the individual condition and assist in disease management. Combined with a user interface to motivate users a personalised care and treatment plan may be formulated. Shorter patient analysis times also would enhance patient care through increased possibilities for clinician-patient interaction. A glove that fits the user may help analyse trends and daily variance in flexibility and mobility. Improving sensor accuracy could address problems of traditional inter-tester and intra-tester reliability of finger joint measurement (Lewis et al., 2010) using current measurement systems.

A smart glove was designed with a focus on fit and comfort for the wearer. In this work the sensors and the glove itself are made from a Lycra® material. Conventional bend sensors and fibre optics typically used in computer gaming and motion capture gloves tend to be more rigid. These are not ideal for use in people with impaired dexterity and mobility as to enhance uptake and use the glove must be straightforward to put on and must also not restrict movement. Textile sensors may be integrated into support garments such as knee support sleeves, which may already be worn to help alleviate an injury. The ideal strategy therefore is to provide additional functionality to such medical textiles. An oedema glove was used in this work as an initial motivation for the glove development was for another application in stroke rehabilitation, where patients would often wear oedema gloves to reduce swelling, and compression gloves are often use in arthritis also. A key to the success of wearable technology is to build on garments that are already being worn and to seamlessly integrate the sensing technology technology into the garment. Recent developments in flexible circuitry and stretchable conductive inks will help the integration of fabric sensors in this way.

5 Conclusions

Initial comparative testing between the oedema fabric sensor glove and 5DT virtual reality glove demonstrate high levels of correlation. This achievement exhibits the gloves capabilities when compared to a commercial state-of-the-art glove product. Further testing is needed with a Vicon system that is set up with smaller markers and using cameras in a closer range. Initial results show repeatable measurements using the glove compared to Vicon. Long-term testing to ensure reproducibility and robustness of design is also required.

This project is a multidisciplinary effort, involving expertise in material science and functional design, computer science, human health and performance, and influenced by the end user needs. The aim is to have a better understanding of joint stiffness by monitoring dynamic movements of the hand at different times of the day. This quantifiable information can be measured offline from the clinic. The controlling software manages user access throughout each exercise recording. It controls data glove functionality for accurate, reliable and repeatable measurement of joint movement to determine limitation and variance throughout each day of measurement. Having such information can help to develop a personalised approach to management and treatment of various chronic conditions.

Acknowledments

End-user advice and input provided by Dr. Philip Gardiner Altnagelvin Hospital, Western Health and Social Care Trust, Derry

This work was funded by Science Foundation Ireland under the INSIGHT initiative, grant SFI/12/RC/2289 (INSIGHT)

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