Novel Smart Sensor Glove for Arthritis Rehabilitation

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Abstract— **Rheumatoid Arthritis (RA) is a disease which attacks the synovial tissue lubricating skeletal joints. This systemic condition affects the musculoskeletal system, including bones, joints, muscles and tendons that contribute to loss of function and Range of Motion (ROM). Traditional measurement of arthritis requires labour intensive personal examination by medical staff which through their objective measures may hinder the enactment and analysis of arthritis rehabilitation.**

This paper presents the development of a smart glove to facilitate this rehabilitative process through the integration of sensors, processors and wireless technology to empirically measure ROM. The Tyndall/University of Ulster glove uses a combination of 20 bend sensors, 16 tri-axial accelerometers and 11 force sensors to detect joint movement. All sensors are placed on a flexible PCB to provide high levels of flexibility and sensor stability. The system operation means that the glove does not require calibration for each glove wearer.

Keywords—Microsystem, Wireless Sensor Networks, flexible PCB design, Assisted Living, Rehabilitation

I. INTRODUCTION

Rheumatoid Arthritis (RA) is an autoimmune disease where white blood cells attack joint tissue, causing synovitis. This results in stiffness, swelling and deformity. Stiffness is a resistance of the mobility of a joint that may arise from physical damage around the joint or from a muscle spasm associated with pain [1]. The symptom of stiffness is quantified by a subject as their perception of difficulty in joint movement. This is not the same as loss of movement. Stiffness intensity varies between patients and occurs most commonly in the hands. In the UK, approximately 300,000 of the adult population have RA and approximately 20,000 patients are newly diagnosed with RA each year [2]. Up to 4 out of 10 of the working population with RA lose their jobs within five years of diagnosis, with three quarters of job losses attributed to RA [3]. If an RA patient can remain economically active for longer through better monitoring and early diagnosis, their drain on the stretched resources of the National Health Service (NHS) can be reduced. Recent figures released by the UK Work and Pensions Department report that Arthritis is the most common condition for which people receive Disability Living Allowance (DLA) [4].

Swelling, deformity and pain are common symptoms of hand arthritis. A patient who has suspected RA is examined by an Occupational Therapist (OT) to quantify joint Range of Motion (ROM) and determine hand function for the prescription of suitable treatment and education. The clinician visually inspects each finger joint for the presence of Heberden and Bouchard nodes, boutonniere and swan neck deformity. During assessment, a patient places their hand flat on the table top with the wrist and elbow in a resting position. A goniometer measures flexion, extension, adduction and abduction of the Metacarpophalangeal (MCP), Proximal Interphalangeal (PIP) and Distal Interphalangeal (DIP) joints of the fingers and thumb in degrees and records the maximum flexion and extension range of the wrist and supination and pronation of the forearm.

Joint stiffness is a symptom of RA that has long been used by clinicians as a parameter to measure the degree of damage caused to a joint, and as an assessment determinant to quantify how much improvement has occurred after therapy. Stiffness is a resistance to the mobility of a joint that may arise from physical damage around the joint or from muscle spasm associated with pain [5].

A. Current glove systems

Data gloves are capable of measuring finger joint kinematics and can provide objective ROM information useful for clinical hand assessment and rehabilitation. Gloves are designed to fit specific hand sizes, however human hands are not identical, resulting in the need for calibration of the gloves for each user. Limitation of patient ROM affects the glove calibration process and angular accuracy. Accuracy is also affected by the non-linear nature of glove sensors and ill-fitment of a glove to the wearer's hand. If a glove is too large, then each sensor does not move in tandem with its associated finger joint. If the glove is too small, extra pressure is placed on the underside of each sensor, particularly during midway to maximum flexion of each joint. Accurate dynamic characterization of ROM for a joint is also affected. This is important if total finger joint movement is analysed such as in rehabilitation where angular acceleration and velocity of ROM is examined.

Researchers have experimented with various sensor constructions to improve finger joint detection within their area of study. However few gloves have been commercially developed. This study examines commercial systems that are comparable to the Tyndall/UU glove. Glove systems are examined for the number and type of sensors used, sensor resolution, data rate, interfacing options, battery duration, extra features, intended market.

The CyberGlove III [6] is one of the most popular data gloves systems currently available. This glove provides maximum 22 bend sensors placed along each MCP, PIP and DIP finger joint, between each finger to detect abduction, and across the back of the hand. A default calibration is stored in the VirtualHand software used to control the data glove. Additional calibration is required to improve accuracy for each sensor. Calibration is achieved by completing a set of finger positions. Advanced calibration can be completed for each sensor by adjusting offset and gain values for each sensor. The 5DT glove [7] contains maximum 14 sensors placed above each MCP and PIP finger joint and between each finger to measure abduction. It uses fibre-optic sensors developed by 5DT to measure finger movement as a variance in light intensity produced by an LED transistor and detected by a phototransistor. The X-IST glove [8] contains either a combination of 5 bend sensors and 5 pressure sensors, or 15 off-the-shelf bend sensors and one optional two-axis accelerometer. Bend sensors are placed along each of the three finger joints and the thumb. Alternatively, pressure sensors are placed on each fingertip. Sensors are positioned on an inner cotton glove and protected by an outer silk glove.

The Tyndall/UU developed glove outlined in Fig. 1 uses a combination of 20 bend sensors, 16 tri-axial accelerometers and 11 force sensors to detect joint movement. All sensors are placed on a flexible PCB to provide high levels of flexibility and sensor stability. The Tyndall/UU glove is controlled by bespoke software and does not require calibration for each glove wearer.
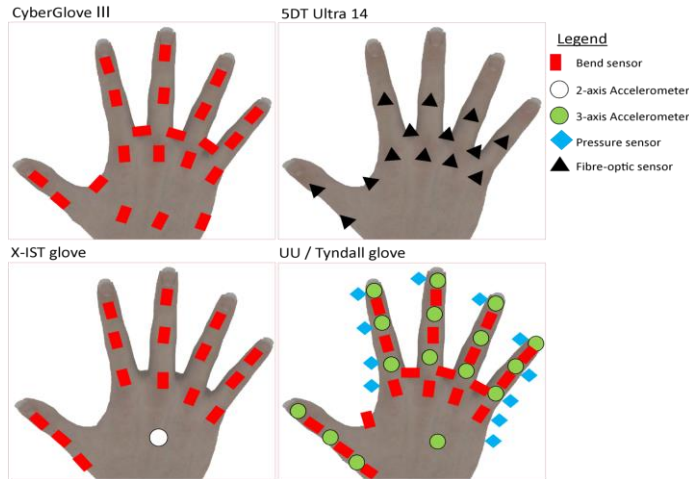

Fig. 1. Graphical comparison of current start-of-the-art data gloves with the Tyndall/UU glove. The glove contains bend sensors and accelerometers over each finger joint for dual movement determination. Additional force sensors demonstrate its suitability for rehabilitation.

II. REHABILITATIVE SYSTEM DESIGN

For the purpose of addressing some of the common short comings of data gloves currently available in the field [9], [10], we define a glove-based system that can be worn on both the right & left hand (by flipping PCB), focusing on the limitations of patients with hand disabilities. Fig. 2 shows a block diagram of the implemented design. From a signal interfacing point of view, a total of 47 sensors are divided into 3 groups wherein each one of the sensors pertaining to the group is multiplexed

and interfaced by the same analog/digital blocks, enabling sharing of signal conditioning circuitry. The control unit is a low power Atmel Atmega1281 8-bit microcontroller (MCU) that incorporates, amongst others, 10 bit analog to digital converter and SPI/I2C/UART interfaces. After the data is processed by the MCU, it is then transmitted via a wireless link to a remote base station where data is visualized and processed. The RF chip is the CC2420, a single-chip 2.4 GHz, IEEE 802.15.4 compliant RF transceiver designed for low-power and low-voltage wireless applications from Texas Instruments
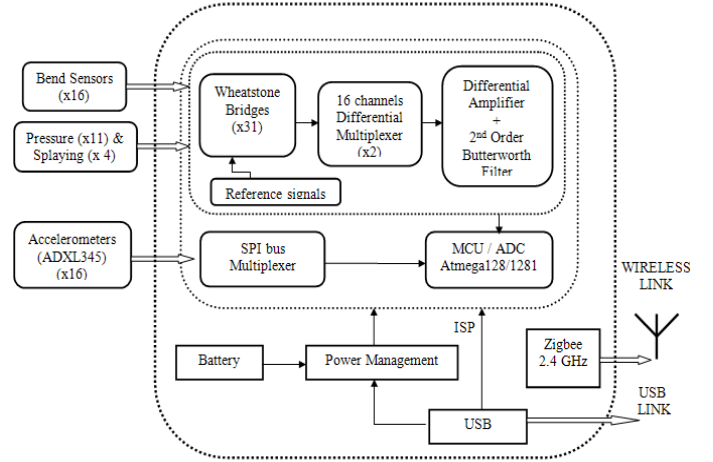

Fig. 2. Block diagram of the implemented design.

A. Biomechanical model

With the aim of capturing accurate hand motion with a manageable amount of data transfer, Fig. 3 shows the hand bones and joints, resulting in a design based on 15 segments (Phalanges bones or finger bones and thumb), 2 planes (Metacarpals Bones or palm of the hand and Carpal Bones or wrist bones) and 16 joints biomechanical model of the hand.
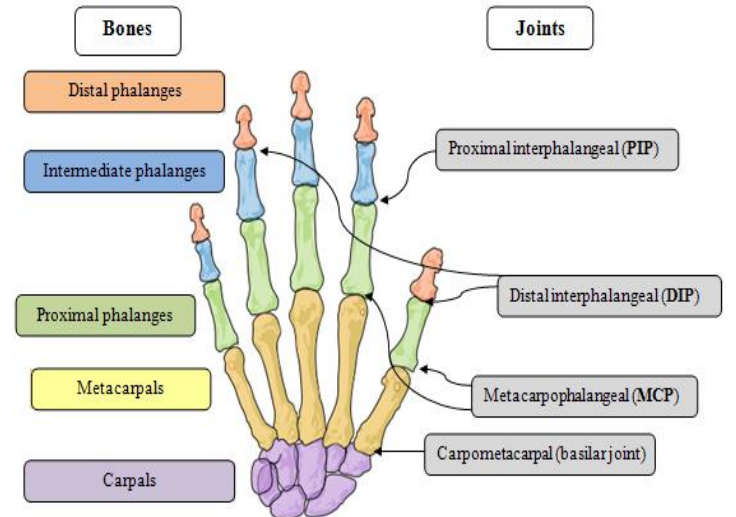

Fig. 3. Biomechanical model of the human hand illustrating bones & joints of interest.

The movement of each element of the model is constrained to a certain number of degrees of freedom given by the flexion and splaying of the fingers and up/down and left/right rotations

of the palm of the hand with respect to the wrist, which is the reference plane for all the angles. Motion of the wrist is not accounted for by the data glove sensors but incorporated as an additional wireless inertial measurement unit attached to the wrist [11].

B. Sensors choice and signal conditioning

The main objective of the glove is for the measurement of joint range of the hand, including: flexion, extension, adduction and abduction of the MCP, PIP and DIP joints of the fingers and thumb in degrees. The Glove integrates a total number of 47 sensors to capture hand and finger motion, provide a calibration procedure for wearers with varying degrees of movement in their finger joints, hand sizes and ability to move each joint to its limits and for Kapandji index measurement.

The flexion of the fingers is measured by bend sensors on each finger and thumb. The bend sensor used, shown in Fig. 4, is the flexible bend sensor from Flexpoint Sensors systems [12]. The position of the bend sensors crosses over the DIP, PIP and MCP joints. Each joint has its own sensor to record accurate angular joint movement. In addition to the angular joints angle, bend sensors are also used to account for the splaying of the fingers so that, the thumb-index, index-middle, middle-ring and ring- little abduction angles are also recorded. An additional bend sensor on the lateral side of the wrist/palm accounts for left/right wrist rotation. The Glove integrates a total number of 20 bend sensors on a flexible PCB substrate.
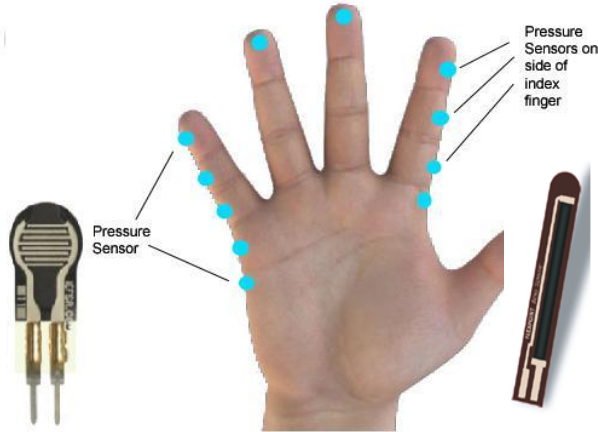

Fig. 4. Pressure sensor (Interlink) hand positions &bend sensor (Flexpoint Inc.) utilised

Additionally, 11 force sensors are also incorporated for the Kapandji index measurement (also known as opposition scale). The Kapandi index grades the range of movement of the patients thumb against various points down the side of the index finger, on each fingertip and along the pinkie finger as shown in Fig. 4. The force sensor shown is the FSR® 400 Short from Interlink Electronics [13]. Measurements from each of the 31 sensors is converted to a voltage signal by means of Wheatstone bridges.

Finally, the glove integrates 16 tri-axial accelerometers, one on each of the finger's phalanx and on the palm. The accelerometer is the ADXL345 [14] from Analog Devices. The ADXL345 is a small, thin, ultralow power, 3-axis

accelerometer with high resolution (13-bit) measurement at up to ±16 g. Although the precision of the accelerometers as inclinometers is constrained to static or slow motion, the combination of the bend sensors with accelerometer information, for instance, via Kalman filtering [15] can lead to a more precise finger's flexion estimation than that from each one of the sensors individually. Accelerometers can also provide additional useful information on the rotation motion of the hand such as shaking / vibration motion.

C. Flexible Circuit PCB design

The glove has been fabricated using flexible PCB technology. It is an 8 layer flexible PCB with an overall circuit size 202.5mm x 124.9mm, thickness = 0.45mm. Fig. 5 shows the location of the sensors and different ICs along the PCB. Circuitry on the finger side of the PCB has been limited to the sensors and a minimal number of 0402 surface mount passive components.

The finger side of the PCB is expected to be under flexion repeatedly under glove usage, and, with this in mind, it was decided to implement a meander-type shape of the PCB on the area that crosses over the finger joints, with small continuous islands separating the different meander joints and allowing for the accelerometers' placement, bend and force sensors attachment as illustrated.
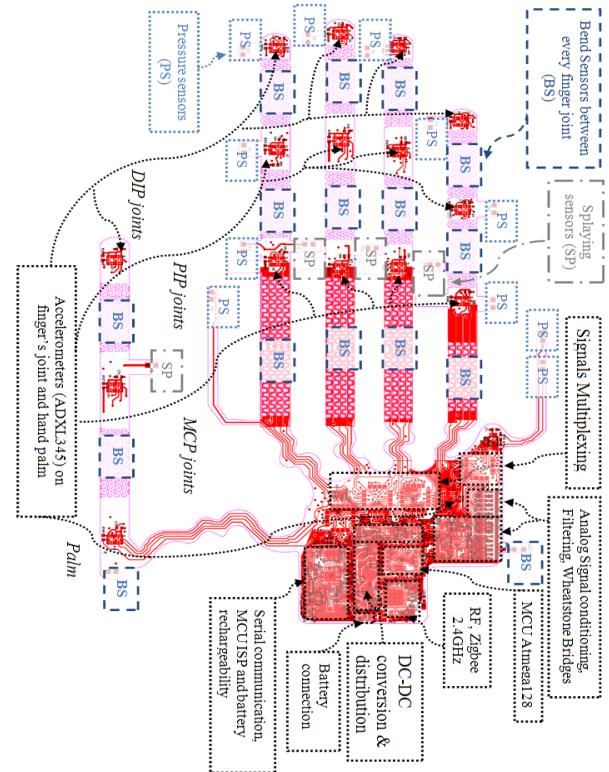

Fig. 5. Glove Flex-PCB sensor positioning overview

Minimizing the stress under finger flexion, the meander-type structure allows the PCB to undergo large deformations without fracture, providing high flexibility, robustness and some degree of stretchability. Fig. 6 & 7 show the final manufactured and assembled glove PCB top side and PCB under flexion.
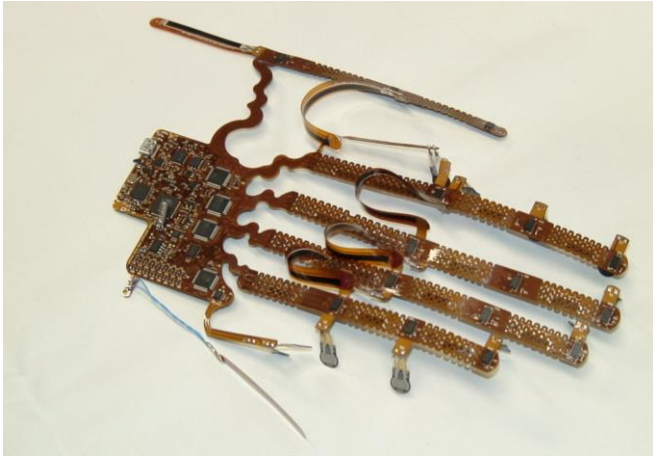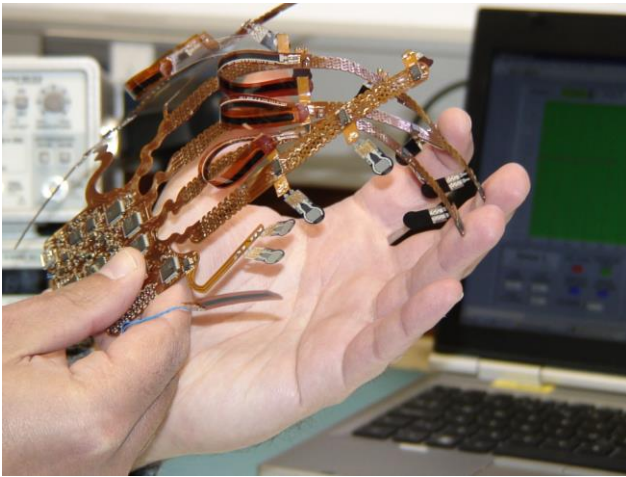
Fig. 6.   Final assembled glove

Fig. 7.   Glove PCB under flexion.

D. User Interface

The software system manages objective routines defined by a clinician and performed by the patient at home at set times throughout the day. Each patient initially attends a clinic session for some basic system training. A reference objective routine recorded during this visit is used as a comparison to future objectives completed at home. Objectives are typically completed first thing in the morning when the patient arises, at lunchtime and in the evening. Software system calculates angular and velocity data generated from the glove when the patient is performing an objective routine. Completed objectives are uploaded to a cloud system for immediate access by the clinician for analysis and patient feedback.

Fig. 8 demonstrates how live data received from the Tyndall / UU data glove is displayed by the glove controlling software. Accelerometer and bend sensor data is displayed to the left of the screen. 3-axis values from each accelerometer are converted to angle of bend. Bend sensor data is converted to degrees and verified against accelerometer calculations. Completed objective routines are shown in the objective summary window (a). An objective consists of many repetitions that are displayed in the objective detail window (b). One repetition is achieved once the joint under investigation is opened and closed. Repetitions consist of velocity (c) and angular movement (d). Charts show repetitions 1-4 in overlay mode allowing instant comparison of repetitions.
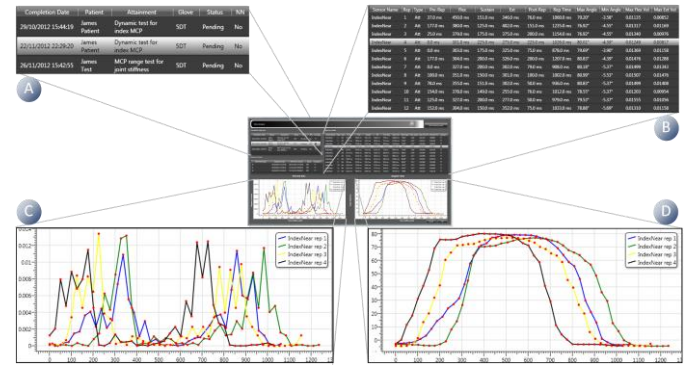

Fig. 8.   Screen shot of glove control interface.

III.   DYNAMIC MOVEMENT CHARACTERISATION USING A DATA GLOVE

Fig. 9 demonstrates a typical flexion and extension angular movement profile for a finger joint of the hand. Flexion and extension movement is sigmoidal shaped and an open-closed hand movement produces a Gaussian shaped curve. The non-linear properties of glove sensors become apparent within dynamic finger joint movement. As the glove wearer cycles their hand through flexion and extension movement, kinematic parameters such as angular velocity and angular acceleration become inaccurate as a consequence of angular inaccuracy calculated from the glove, particularly whilst measuring maximum velocity and acceleration.
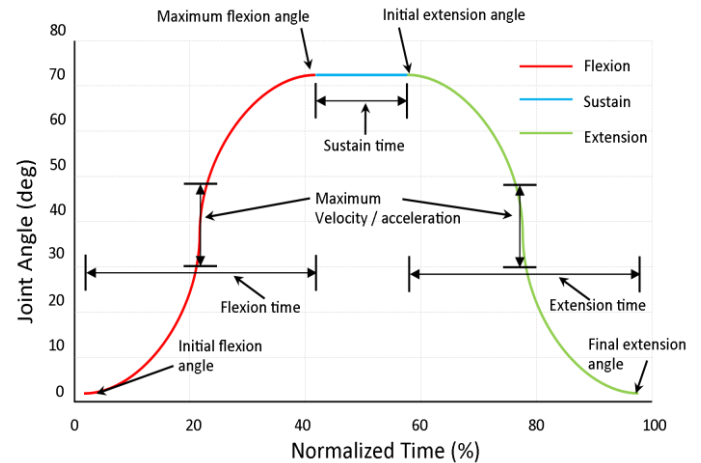

Fig. 9.   Flexion and extension profile for an open-closed finger movement. Flexion and extension movement is sigmoidal in shape. Overall movement profile is Gaussian shaped.

Capturing finger joint movement using a glove containing multiple accelerometers, bend sensors and force sensors eliminates the need for calibration and offers accessibility to users with limited ROM. Accelerometers improve accuracy of both static and dynamic finger joint movement. Bend sensors work in collaboration with accelerometers to accurately measure finger joint angle, velocity and acceleration. Force

sensors provide measurement for opposition testing of the thumb to the fingers and palm, such as Kapandji scoring.
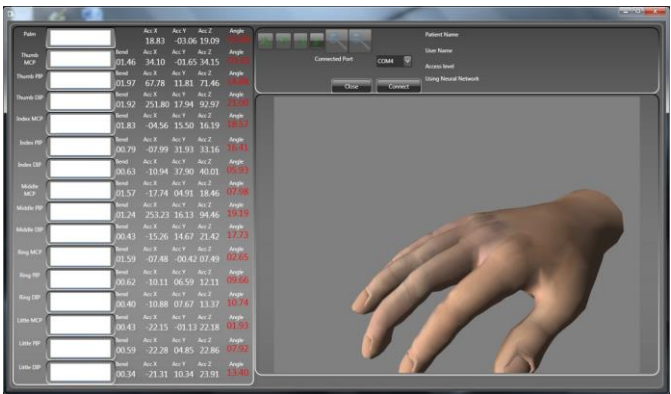

Fig. 10. . Control system for the Tyndall / UU glove. Real-time data from the glove is displayed both numerically and graphically.

Fig. 10 demonstrates a screen shot of the control system for the Tyndall / UU data glove. Live movement data captured from the data glove is displayed numerically and graphically. Numeric data is displayed to the left of the screen. This includes bend sensor, force sensor and three axes from each accelerometer. A 3D hand graphically represents numerical data captured from the glove. The hand moves synchronously with all glove sensors.

An objective typically consists of 12 repetitions. Each repetition is analysed for time taken during flexion and extension, minimum and maximum ROM and minimum and maximum velocity. Analysis of angular and velocity percentage change throughout each flexion and extension portion of a repetition provides dynamic analysis of joint movement and an indicator of change between repetitions. Information is used by the clinician as an assistive tool to detect change in movement over time for each patient.

Fig.11 demonstrates the patient interface. Hand movement performed by the patient is displayed as a 3D animated hand. The repetition progress panel provides real-time indicators on the status of each flexion and extension action for each sensor included in the objective routine.

Fig. 12 demonstrates the dynamic movement analysis window providing comparison of an initial reference point routine to objective routines completed at pre-agreed times with the clinician.
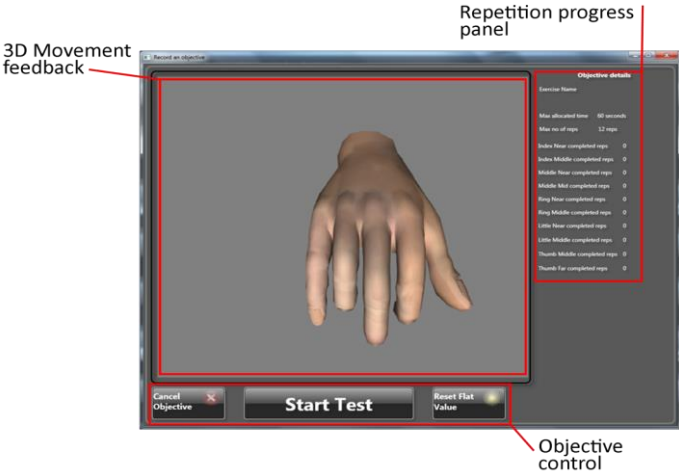

Fig. 11. Patient interface provides live feedback of glove sensor movement and progress of the objective routine performed by the patient.
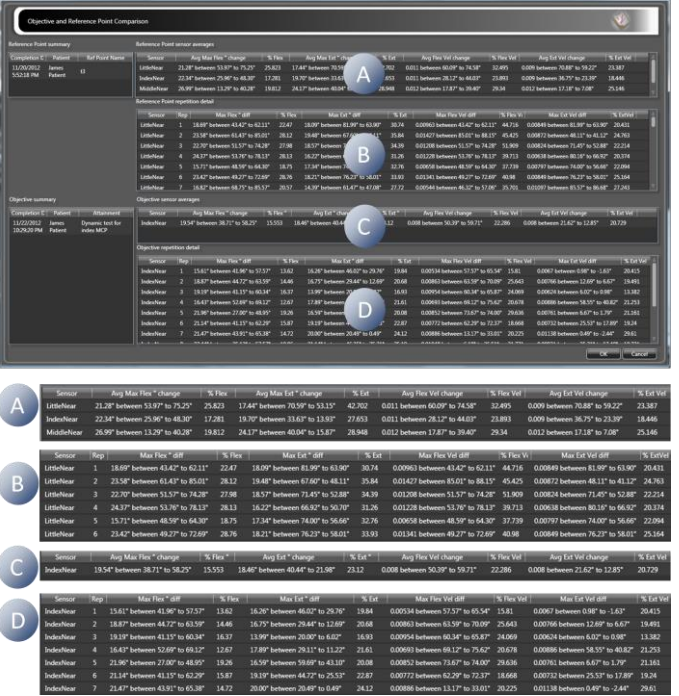

Fig. 12. Dynamic movement analysis provides detailed feedback on angular and velocity percentage change for each repetition recorded for the patient. Dynamic analysis provides an indicator of improvement or decline in movement over time. Clinicians use this information to assist their diagnosis of restriction in patient movement.

Fig. 12(A) is a summary panel for each group of repetitions within the reference point. Each summary displays the maximum degree change and overall percentage change for total flexion and extension movement. Fig. 12(B) provides a detailed breakdown of each repetition for each reference point sensor. It displays peak flexion and extension angular and percentage change, together with peak velocity change. Fig. 12(C) displays the comparison objective summary panel. It too displays maximum angular and velocity degree change for flexion and extension movement. Fig 11(D) displays a detailed breakdown for each glove sensor included in the selected objective summary.

IV.   System Test and validation

Clinical trials will commence within the Western Health and Social Care Trust [16] in the near future. Initially a small group of six patients will be studied to test performance of the glove and examine our processes and procedures used to determine joint stiffness. Selected patients will have significant stiffness in their hands due to RA. Clinical trials will establish the effect that mild to moderate degree of swelling of the joints has on glove accuracy and if the glove is tolerable to those patients. The study will also document the reproducibility of stiffness tests and determine if the patients' perceived variance in stiffness between morning and night will be demonstrative in collected measurements. Each patient will initially visit a clinic for basic training with the glove and its controlling software. The patient will then take the glove and controlling software home to continue their rehabilitation.

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