A new method to determine joint range of movement and stiffness in Rheumatoid Arthritic Patients

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Abstract— **Rheumatoid arthritis affects 0.5 – 1% of the general population. The prediction and prognosis of the disease varies for each individual and its course can detrimentally affect the psychosocial condition of the patient. Clinicians and Therapists aim to quickly diagnose and treat those with this debilitating disease. Detection relies heavily on manual evaluation methods that are dependent on training and can vary between observers. Angle measuring instrument, tape measure and grip strength dynamometer are used to assess the joint range and strength of a patient to determine their hand function. Joint stiffness can be a determining factor when diagnosing the advancement and improvement of Rheumatoid Arthritis (RA). This paper outlines the development of a hand movement measurement tool to accurately quantify patients' flexion, extension, abduction and adduction movement of each finger joint and quantifies the symptom of "early morning stiffness". It also describes the problems that arise when using a data glove to accurately measure Range Of Movement and discusses alternative methods to overcome these issues.**

I. Introduction

Rheumatoid Arthritis (RA) is a disease which attacks the synovial tissue that lubricates the joints of the human skeleton. This systemic condition affects the musculoskeletal system, including bones, joints, muscles and tendons that contribute to loss of function and range of movement and difficulties in performing activities of daily living (ADL). Approximately 20,000 new cases are diagnosed with RA each year [1]. Up to 4 out of 10 of the working population with RA lose their jobs within five years of diagnosis [2]. Current evaluation techniques used to quantify RA are time consuming. A patient who has suspected RA is examined by an Occupational Therapist (OT) to quantify joint range using a goniometer, a tape measure, a Health Assessment Questionnaire (HAQ) disability index and a grip strength dynamometer. 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. The degree of stiffness suffered by an RA patient is assessed via responses to a HAQ alongside patient feedback. Joint stiffness is used by clinicians as a parameter to measure the degree of damage caused to a joint and as an assessment determinant to quantify improvement after surgery. To date, stiffness has not been sufficiently identified to provide a standard for identification and diagnosis to be of any benefit. This study focuses on the development of a hand Range of Movement (ROM) measuring tool to quantify joint stiffness continually using a data glove and controlling software.

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II. Methods

The proposed ROM tool consists of a data glove and controlling software. The software system provides administration for user management, calibration control, objective and reference management and detailed data analysis. The system has initially been developed using the 5DT Data Glove 14 Ultra [3], [4] which uses stretchable lycra to support the manufacturers' proprietary fibre-optic sensors. The glove contains 14 sensors placed over the metacarpophalangeal (MCP) and Proximal Interphalangeal (PIP) joints and abduction sensors between all MCP finger joints and the thumb and index finger.

Figure 1. Controlling software with 5DT glove

User creation and glove calibration is initially performed within the clinical setting. Varying differences in hand height, width and finger thickness necessitates glove calibration for each user of the system. Finger length affects the coverage of each sensor in relation to the corresponding finger and thickness varies the underlying sensor support provided by the wearer's hand. Calibration is achieved by completing a preselected set of finger positions and movements that place each finger joint and matching sensor to minimum and maximum positions. The maximum value for each finger sensor represents the maximum achievable flexure for the glove wearer. Minimum and maximum readings are used to calculate angular and velocity values. An objective routine contains a set of instructions to the patient and parameters used during a recording including minimum and maximum angular range for each joint, the number of desired repetitions and the maximum permissible time for an objective completion. An objective is assigned to a patient and is performed at home during bouts of joint stiffness and at specific times defined by the clinician. Angular movement and velocity data are captured during an objective routine. Joint stiffness is detected by measuring the maximum levels of velocity captured during flexion and extension hand movement. Joint stiffness change is measured as a variation in maximum velocity readings when compared to previous velocity calculations obtained during an objective. Objectives recorded by a patient with reported joint stiffness are also compared to velocity measurements of normal patients. Stiffness is identified as a comparable decrease in maximum velocity to that from normal patient velocity levels.

III. RESULTS

The movement and velocity data shown in the figures opposite have been collected during an objective routine completed by an adult male with normal ROM. The objective routine tested ROM for the Index MCP joint with an angular range set between 10º to 80º. The subject was asked to perform 5 repetitions within 20 seconds. The subject began the objective by holding their hand in a level position, followed by a clenched-fist position. A repetition was completed once angular movement surpassed the angular range defined in the objective routine. A detailed breakdown of results is shown in Table 1 and both Fig. 2, Fig. 3 graphically represent movement and velocity data generated by the subject whilst they completed the objective routine. Table 1 shows a detailed breakdown of flexion and extension time and the minimum and maximum angles achieved during each objective repetition. The subject needed 0.43 seconds to flex their index MCP joint to 80º during repetition 1 and a further 0.36 seconds to extend this joint back to 10º. The complete repetition was completed in 0.79 seconds. The maximum angle reached during repetition 1 was 86º, and the minimum angle reached was 4.7º.

Fig. 2 is a graphical representation of angular data collected during this same objective routine. The overall shape of each repetition is square in appearance, representing smooth finger joint movement from minimum to maximum objective boundaries. Fig. 3 shows the velocity collected during the objective routine. Each column represents velocity detected during flexion and extension of the index MCP joint. Velocity values peak when the direction of the subjects MCP joint changes. Velocity values are displayed in degrees / second. A subject who suffers from joint stiffness has a perception of difficulty moving a joint, although ROM should not be affected. To demonstrate how angular and velocity values should appear for an RA patient with stiffness, the same objective routine was performed by a subject with normal hand movement at a slower rate. Slower joint movement demonstrates how the angular and velocity data from an RA hand should look. The subject was asked to perform 5 repetitions within 40 seconds. Fig. 4 shows angular data for the simulated damaged hand. Joint movement is slower as demonstrated by the gently sloping curve of each repetition in comparison to the square-shaped one of a normal hand (Fig. 1). An RA patient may move their hand more rigidly, providing further distinction between normal and RA joint movement in the shape of a stepped movement curve.

Table 1. Summary of flexion and extension timing for each objective repetition during an objective routine

Value	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Mean	Max	Min	Range
Index MCP									
Flex(secs)	0.43	0.68	0.56	0.64	0.55	0.5708	0.427	0.683	0.256
Ext(secs)	0.36	0.4	0.52	0.35	0.45	0.4164	0.353	0.518	0.165
Total (secs)	0.79	1.08	1.07	0.99	1.0	0.9872	0.79	1.081	0.291
Max Angle º	86	90.8	91.4	90.4	95.2	90.8	95.2	86	9.2
Min Angle º	4.7	3.5	1.5	4.6	3.5	3.6	4.7	1.5	3.2

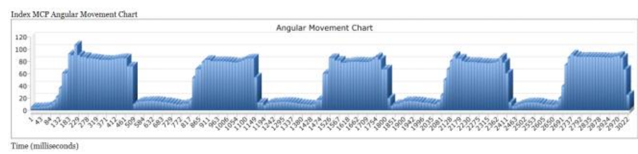

Figure 2. Angular values calculated during the exercise routine

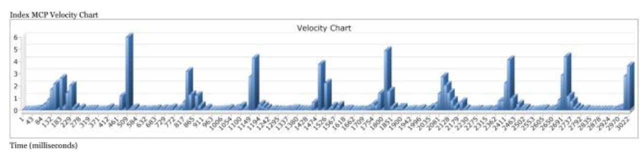

Figure 3. Velocity values calculated for the exercise routine

Table 2. Summary table showing flexion and extension time for a damaged index MCP joint.

Value	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Mean	Max	Min	Range
Index MCP									
Flex(secs)	2.55	2.52	2.03	1.59	1.56	2.0484	1.559	2.545	0.986
Ext(secs)	3.6	3.26	3.03	3.1	6.83	3.9666	3.033	6.834	3.801
Total (secs)	6.15	5.78	5.06	4.69	8.39	6.015	4.688	8.393	3.705
Max Angle º	89.9	97.8	96.7	97.5	96.2	95.6	97.8	89.9	7.9
Min Angle º	8.5	5.2	6.6	5.2	7.4	6.6	8.5	5.2	3.3

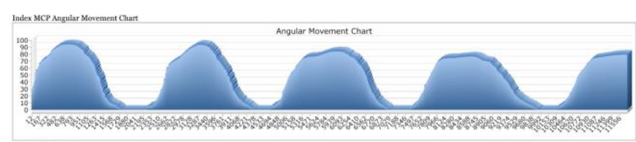

Figure 4. Angular values recorded during an objective routine to simulate joint stiffness

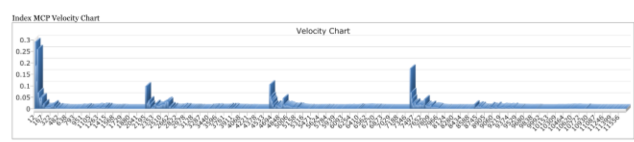

Figure 5. Lower recorded velocity values may be a characteristic of joint stiffness

The velocity chart in Fig. 5 demonstrates the velocity recorded during the same simulated RA hand movement. Velocity remains quite close to zero, with a maximum peak of 0.3 degrees/second. This figure is very small when compared to the normal hand when velocity data peaked at over 6 degrees / second (Fig. 3).

IV. Validation of Results

Data presented in the Section III is currently verified using a set of rectangular blocks of wood accurately cut to 20°, 45°, 60º and 80° angles. Goniometric measurement of the angles cut into each block verifies that all angles are correct. When a subject places their hand onto each block of wood whilst wearing the 5DT glove, angular readings are within 5° of values as shown by the goniometer, although readings may vary if maximum flexion is applied to the glove sensors by clenching the hand in a fist gesture. This may be caused by the stretchable property of the lycra-based material used by the glove to support each glove sensor. Results return to within 5° of accuracy after a short time period (approximately 40 – 50 seconds). Hand size also has an effect on accuracy, with smaller hands producing the highest level of imprecision compared to larger hand sizes.

V. Accuracy Improvement

Calibration can be quite problematic for RA patients with limited ROM. If full patient movement range was achievable without performing minimum and maximum flexion and extension then the data glove should be a more attractive proposition. Each sensor on the 5DT determines joint movement as a variance in light intensity passed along its fibre-optic cable. When the glove is placed on an ill-fitting hand, limitation in the support provided to each sensor by the ill-fitment can distort the accuracy of calculated angular readings. As an oversized finger joint bends, increased pressure applied to the underside of the sensor distorts the shape of the fiber-optic cable, causing inaccurate raw calculations. The same occurs with an under-sized finger: decreased support allows excessive glove material to accumulate below the sensor, resulting in erroneous readings. Furthermore, if the glove is loosely-fitting, sensors are not placed sufficiently close enough to the corresponding joint to move synchronously with it as it bends, so allowing the finger joint to move before the glove sensor detects its movement. This produces inaccuracies in angular calculations and imprecision of start/stop timing during the flexion and extension movement in an exercise repetition.

A. *Calculating ROM linearly*

The current measurement technique determines minimum and maximum range for each joint during the calibration process. This range represents the start and end raw values used to calculate an angle for the specific joint between the minimum to maximum average joint range. In Fig. 6, an angle may be calculated at any point along the line using a raw value along the x-axis. Using this principle, the minimum and maximum values should be derivable using two raw-angular sets of data and a simple equation to determine the full ROM for that joint. An accurate instance of a range relies on two precise angles and their associated raw values.

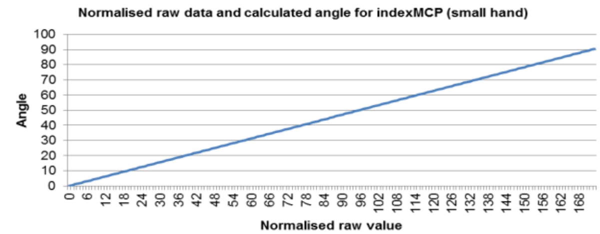

Figure 6. Raw glove data and associated angles for the index MCP joint of a small hand

Two wooden blocks cut at 45º and 90º and a flat surface that represented 0º were used on two subjects with small and medium hand sizes. Initial findings focused on the index MCP joint. Each subject placed their hand on a flat surface and a raw value was captured from the glove to represent 0º. Each subject then placed their hand on either the 45º or 90 º wooden blocks. Both raw values and their corresponding angular representations were used to calculate the full raw range and associated angles. This range was stored in a lookup table within the controlling software. When a raw value was captured from the glove, its associated angular value was determined from the lookup table and presented on-screen.

When the medium sized hand was calibrated using 0º and 45º, both angles were accurately reproducible. However the 90º value was greatly exaggerated and extended beyond 100º. The same findings were discovered when using 0º and 90º to calculate an angular range. Again both determining angular values were repeatable. The 45º value was less accurate, with an average representation of 20º. Closing the hand into a fist affected the accuracy of readings. However results returned to their original calibrated range within 40-60 seconds after the hand was flexed a fist position. The order in which the calibrating angles were used affected the accuracy of readings. Angular values were more accurate when the maximum value was determined first, followed by the lesser angles. Also, the 0º value varied by 3º if the hand was placed flat on a surface, compared to the value when the hand was held flat but raised slightly above the flat surface. This may have an effect on angular accuracy as the hand will not be placed on a flat surface during an exercise, especially when determining values close to 0º.

When the small handed subject calibrated their hand using 0º and 45º wooden angles, both readings were reproducible but the 90º reading was extended beyond a 100º angle. When 0º and 90º wooden blocks were used for calibration, again both angles were reproducible when placed on the wooden blocks, but the 45º value was not represented accurately, with an average value of 20º. Closing and opening the fist had a greater effect on 0º accuracy than that of the medium sized hand. This may be due to more movement of the smaller hand inside the glove as the finger joint is extended to the 0º position.

Results suggest that readings taken from the glove sensors do not follow a linear pattern and are affected by variances in hand size and shape.

B. *Calculating ROM using a neural network*

An Artificial Neural Network (NN) may provide more accurate ROM for each sensor than the current linear approach. After careful consideration, a supervised back propagation NN was chosen for its appropriate characteristics. The back propagation NN algorithm is provided with examples of inputs and required outputs and the error rate is then calculated (the difference between actual and expected results). The key aim of a back propagation NN is to minimize its error rate until the NN learns the training data. Training begins with random weights, which are adjusted to reduce the error rate as much as possible. The inputs used for the back propagation NN is raw glove data and example outputs are the associated angular value for the given raw value. Initially, the NN was provided with four values (0º, 45º, 60 º and 90º) and the NN provided estimations for a small and medium hand. The wooden blocks used previously to validate results using predefined angles were also used as input angles for raw glove data. Initial findings for the medium sized hand found an improvement for the full range of movement, especially at the recorded angles (0º, 45º, 60º and 90º). Optimally, the range generated by the NN should contain one raw value for each estimated angle. Fig. 7 shows the optimum ratio of raw values to angular pairs (green) and excessive or sub-optimal range (grey). An excessive amount of raw values exist for each angle range between 0.5º - 24.5º, and between 93.5º - 102.5º. A sub-optimal range exists for values between 36.5 º and 84.5 º where there is a gap of at least two raw values between each calculated degree. At its peak, there are five missing raw values between each estimated degree. The optimum pairing of one raw value for an associated angle occurs for angles between 34.5º - 36.5º and between 84.5º - 93.5º.

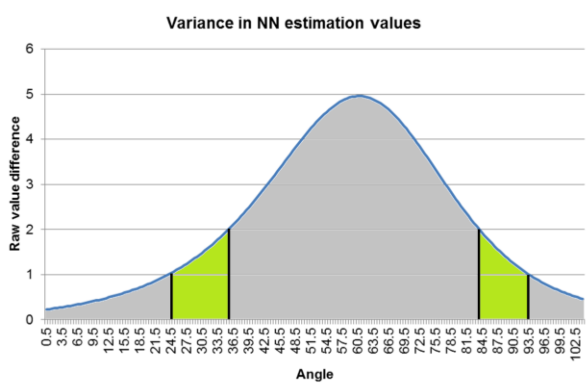

Figure 7. Relation between NN generated raw values and estimated angles. Optimum estimation occurs for raw values with only one associated angle.

Two main issues occur from the imbalance of raw/angular values across the NN estimation range. An excessive amount of values for a small angular range creates a problem when deciding which angular output is best suited to the currently inputted raw value. If the first match is chosen from the lookup table, the angular accuracy will vary depending on the current flexure of the sensor. Sensor readings will be more accurate in the 0.5º - 24.5º and 93.5º - 102.5 º ranges if the hand is in flexion and accuracy is greatly affected in this range during extension. For example, if the sensor has reached maximum flexure and is returning to 0 º, the last raw input will have an angular value of up to 24.5º, even though the hand may be in the 0º position. Secondly, accuracy is greatly diminished as the gap in raw values increases for each associated angle. Issues could be resolved by smoothing the NN estimation to remove raw data and angular pairing where duplicates exist and increase the number of pairs where none exist.

C. *Smoothing of NN data*

NN smoothing occurs in several stages. Firstly the table of raw values is examined. If the results of the second raw value subtracted from the first is less than one, then it is added to a temporary lookup table. As the result increases, so does the missing number of raw values and angle pairs in the lookup table. To resolve this, additional pairs are added in response to the size of the gap for each subtraction. When missing data has been added to the table, duplicate values are then removed. If the first raw value is less than the second value, then it is added to a new lookup table. If both values are the same or the second value is greater than the first, it is skipped during the search process. Finally, angular values are processed for duplicates.

Fig. 8 shows the full range of NN estimated data and the differences in each raw value and angular pair. Essentially, the variance across the total range is less than two raw values.

Fig. 9 shows the NN estimated lookup table values once smoothing has been applied. This range is for estimation of a normal sized hand. The non-linear appearance of the NN derived data in Fig. 7 more closely mimics the real world movement of its associated glove sensor than the standard linear approach used by the glove manufacturer [4]. Four wooden blocks were used as inputs to the NN. These ranges were 0º, 45º, 60º and 80º. The resultant lookup table provides accurate repeatable results for the four angles.

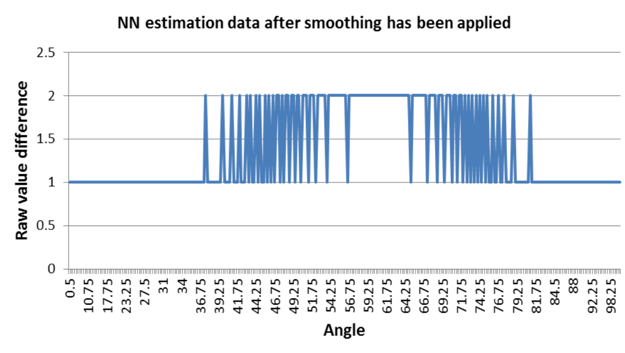

Figure 8. NN estimated lookup range after applying the smoothing algorithm.

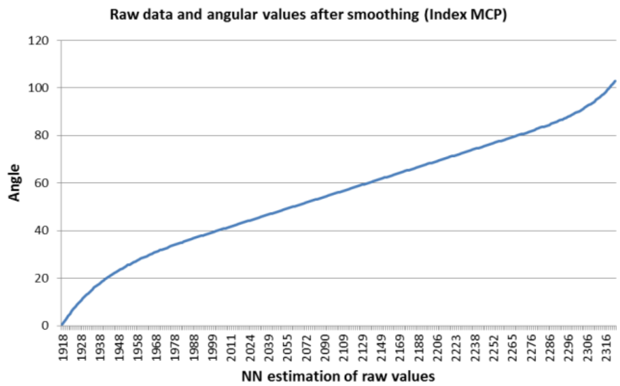

Figure 9. Full range of raw data and associated angular values that has been derived from the NN. Values have been smoothed.

VI. Conclusion

RA is a debilitating disease. The diagnosis and treatment of joint stiffness remains a challenging problem. To date, the quantification of joint stiffness has not been sufficient to specify a standard whereby patient stiffness can be calculated and categorized. Having an objective measurement of stiffness for all finger joints will provide valuable information on recovery progression and comparison data for different treatment strategies. This research examined the potential of using a data glove and a bespoke application to determine movement and stiffness of each finger joint using a user-defined set of exercises.

Initial results show how movement and stiffness may vary quite dramatically between normal and stiff joints and demonstrate how stiffness may be determinable using velocity and angular readings plotted in graphical charts. Stiffness and movement is currently detected throughout the full ROM for all finger joints, although this range may be restricted as further investigation into angular and velocity accuracy may reveal a ROM to provide optimum results.

Further improvements to raw data extracted from the data glove were achieved using a back propagation NN combined with a smoothing algorithm. This resolved inaccuracies within the full ROM of each glove sensor caused by the linear approach to angular resolution used typically by data glove manufacturers. Further validation of angular readings detected by the system software will use the Shadow Hand robotic hand [5]. The Shadow Hand could also be used for comparison analysis of angular readings from each joint. Although the finger size of each finger on Shadow Hand is 102mm from the fingertip to the middle of each knuckle, each of the four digits on the 5DT glove should fit onto the robotic hand since there are no fingertips on each glove finger. There may be issues with the glove thumb so separate measurements will be made for this digit. The ROM of Shadow Hand does not fully extend to the normal maximum range of a typical hand. Each MCP and PIP robotic joint has a maximum range of 90º.

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