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Active Range of Motion Measurement System Using an Optical Sensor to Evaluate Hand Functions

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Abstract— **Impairment of hand function greatly affects the independence of a human being. Proper assessment of hand function before and after any treatment for functional restoration is important to decide better treatment strategies. Despite traditional techniques of hand function evaluation, individual joint based assessment is vital to better track the details of the hand function. Current clinical assessments with goniometers are labour intensive, cumbersome and highly depend on the skill level of the practitioner. This study introduces an active range of motion (AROM) measurement system to measure individual range of motion of finger joints using an optical sensor. The proposed method is highly efficient, and the results demonstrated that the measurements are instant, repeatable and can successfully be employed in a clinical setup for patient evaluations.**

Clinical Relevance—**Closely working with clinician to develop rehabilitation systems, we have identified that the assessment of patient hand functions is time consuming, and accuracy can be depended on the skill level of the practitioner in measuring joint range of motions (ROM). System introduced in this study can measure the joint AROMs instantly and independent of the practitioner's skill level and hence can provide a reliable, repeatable assessment of patient's hand function.**

I. INTRODUCTION

Impairment of a hand or both hands greatly affects the independence or quality of life of the patient [1]. Stroke or other medical conditions such as spinal code injury, other neural disorders, wound or injuries contribute to the functional loss of human hands [1], [2]. Rehabilitation techniques such as robotic rehabilitation with hand exoskeleton robots [3], [4] or other traditional rehabilitation techniques [5] can successfully be employed to functional restoration of the hand functions.

For proper healthcare, it is important to correctly assess the impaired body function and followup to evaluate the effectiveness of the rehabilitation therapy before and after the treatments [2]. To this end, traditional upper limb function assessment tests such as Action Research Arm Test (ARAT) [6], or Wolf Motor Functions Tests (WMFT) [7] focuses more on evaluating the functional improvements towards performing activities of daily living tasks [1]. However, assessment methods that can measure range of motion (ROM) of individual joints can provide more details of the impairment of the hand function as well as the recovery with the rehabilitation techniques. Thus, techniques based on goniometers [8], data glove [1], [9], smartphone photography [10] or optical sensors [2] are available to measure ROM.

Measuring methods using goniometers [8] were conventionally in use to evaluate the ROM of finger joints. However, such techniques take a long time to complete a measurement as each joint has to be measured individually, hence labour intensive and cumbersome. Further, the repeatability and the accuracy of the measurements can be depended on the skill level of the practitioner. In addition, as reported in [1], resistive bend sensor based wearable glove was used to measure the metacarpophalangeal (MCP), proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints of the index finger and interphalangeal (IP) joint of the thumb. The glove was pre-calibrated to match the joint angles to the voltage output values of the bend sensors in the range of $0^o - 120^o$. The glove measured joint angle with a repeatability of $\pm 5^o$, at a 0.5^o resolution. Despite commercially available data gloves can provide a better support for augment reality and animation based applications, they lack the support necessary for hand evaluation with individual joint angle measurement capabilities and hygiene.

Alternatively, [10] proposed a joint angle measurement method based on smartphone photography. In this method, photographs of the fingers were taken with a smartphone and were used to measure the joint angles using a computer software. Although the measured values were within an acceptable error range and comparable to goniometer readings, this method also required analysis of individual joint measurements together with the disadvantage of not being able to provide a reading in a dynamic environment, while fingers move. However, the method proposed in [2] can be used to measure joint angles in a dynamic environment while fingers are in motion. It used, Ultraleap controller that uses infrared images to locate the coordinates of finger joints in a detected space that were used to compute the finger joint angles in real-time. However, as also reported in [11], occlusion and aliasing can affect the successful detection of hand under different conditions. Further, the measurement setup proposed in [2], [11] cannot be used with some patients as their upper extremity has a limited mobility. In addition to this, inertial measurement units (IMU) based post stroke Brunnstorm stage classification scheme [12] and Fuger Meyer Assessment [13] schemes also have been proposed. Despite successful integration for limb function assessment, IMUs are relative large to be employed for finger joint assessment [2].

Thus a new method that can be implemented to measure the active ROM (AROM) of joint angles of finger joints

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in a dynamic environment (i.e. while fingers move) is in demand. AROM provides better reading of the patient's muscle activity as it provides a reading corresponding to contract and relax of the opposing muscles of the joint in motion. Further, it should have the ability to cater for the individual patient differences with limited mobility and ability to perform repeatable measurements in a short period of time. This study proposes a fast human finger AROM measurement system to address above requirements, using a vision based sensor and measurement platform to support patients with different mobility limitations. Next section of the paper explains the methodology followed in this study including the main requirements of the system, system architecture and the details of the experiments for evaluation. It will be followed by the results of the study. At the end of the paper, discussion and conclusions are presented.

II. METHODOLOGY

This section explains the main requirements of the AROM measurement system, proposed AROM measurement system and the details of the experiments for evaluations.

A. Requirements

Figure 1 shows the main joints of the hand and their main Degrees of Freedom (DOF). Hand has five fingers out of which thumb has a distinct functionality and the rest of the four fingers, index, middle, ring and little fingers have a similar construction and a similar functionality. Thumb has three main joints, carpometacarpal (CMC) joint, metacarpophalangeal (MP) joint and the interphalangeal (IP) joint. CMC has two DOFs extension, flexion, adduction and abduction. MP and IP joints have 1 DOF each, extension and flexion. Other four fingers have three main joints; MCP, proximal interphalangeal (PIP) and distal interphalangeal (DIP). MCP joints have two DOFs, extension, flexion, adduction and abduction, while other two joints have one DOF each, extension and flexion. In this study all the four DOFs of the thumb and three DOFs of the other fingers were measured using the optical sensor.

In addition, when designing a system to measure the AROM of finger joints of hand impaired patients, few key design requirements were identified based on opinion from expert clinicians. They can be listed as follows.

- As a result of the impairment, some patients have an extremely stiff upper extremity resulting a limited mobility. There should be some supportive structure to hold the hand in position during the measurements.
- Some patients have an extremely arranged finger positions mostly in a closed fist arrangement. Hand detection during the real-time measurement should be capable of identifying these extreme finger arrangements.
- AROM of the finger joints need to be measured and recorded in both flexion and extension directions of the hand motion.

Considering the above requirements after numerous iterations of testing, this study introduced the system shown in Fig. 2 to measure finger AROM of patients with hand impairment for hand function assessment.

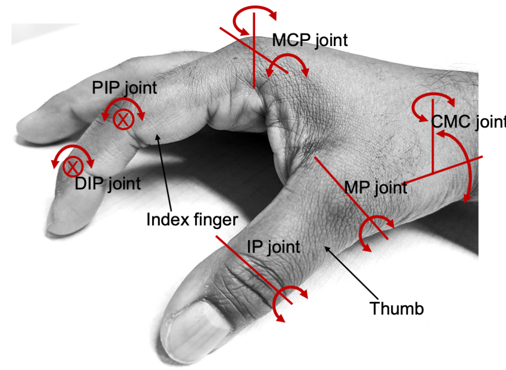

Fig. 1. Main joints of thumb and index finger and their main DOFs

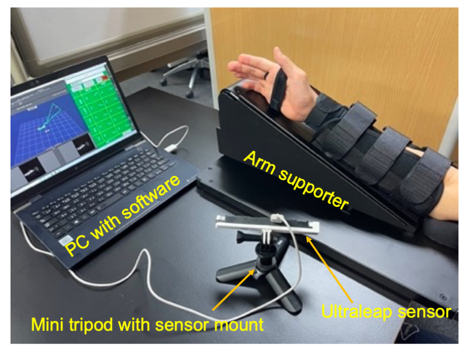

Fig. 2. Measurement environment

B. Finger joint measurement system

Figure 2 illustrates the AROM measurement system that comprises of three main components, PC with developed software, arm supporter and the Ultraleap sensor with the mini tripod. Ultraleap IR 170 [14] is the next generation of the Leapmotion sensor used in [2] by ULTRALEAP Inc., USA. It was connected to the PC via USB cable. Then the visualization software Brekel [15] communicated with the Ultraleap sensor and displayed the model view on the screen. Joint data information of the hand motion were transferred from Brekel to a customly developed software interface through open sound control (OSC) protocol. Customly developed software read the OSC messages and translated them into a meaningful AROM data and allowed the user to visualize the AROM, record patients data and store AROM data of multiple sessions into a patient specified file stored in the PC storage. Figure 3 illustrates the software environment for AROM measurement. Figure 3 (a) shows the desktop view of the PC. It shows the model view from the brekel software, camera view from the Brekel software and the customely developed measurement software for AROM recording. The main functions of the AROM recording software are illustrated in fig 3 (b).

Next most important part of the proposed system was the arm supporter. The general way of using the Ultraleap sensor was to mount it from the top of the head or to place

(a) (b)

Fig. 3. Software environment (a) Desktop view on PC (b) Software to record the AROM

it in the desktop facing upwards. However, after enormous times of testing in different configuration environments, we proposed a setup with the sensor placed to the side of the arm supporter, allowing the sensor to view the palm of hand facing towards it. It was important for the arm supporter to be in the given setup, which supported the patients with upper extremity mobility limitation to perform the AROM assessment in a much user friendly manner at a clinical setup and allowed better detection of the deformed hand profiles (such as with clinched fists). For left and right hands the sensor and the tripod were needed to be moved to either sides allowing the sensor to view the hand facing to its palm.

C. Experiments

Experiments were carried out to evaluate the effectiveness of the proposed system for the AROM measurement of the finger joints. Thus the detection capability of the hand and the repeatability of the measurement were investigated. The experimental procedures followed the principles outlined in the Helsinki Declaration of 1975, as revised in 2000.

Experimental setup was similar to the measurement environment as shown in the Fig. 2. 5 healthy male subjects of age 25-36 joined the experiments. During the experiments, subjects were asked to be seated in front of the arm supporter and alternative measurements were carried out for the right and left hand one after the other. Two types of experiments to investigate the detection capability and repeatability were performed with each subject.

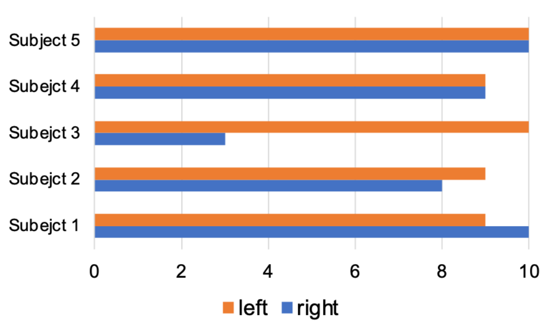

Fig. 4. Successful hand recognition times over 10 trials for each subject

At first, the detection capability was investigated. During the experiments the hand was placed on the arm supporter ten times repeatedly and the successful detection of the hand was confirmed in the model view. The subject was instructed to simulate a hand posture of a patient with fingers arranged closely together deviating from the healthy arrangement. Detection frequency was counted for both left and right hand.

In the next experiment, repeatability of the AROM measurement system was evaluated. During the experiment the hand of the subject was placed on the arm supporter and was fixed with velcro straps. After observing the successful detection of hand on the model view, the subject was asked to perform full range of motion of hand open and close for ten cycles of motion. Five sets of recordings were taken for each side, left and right hands for each subject.

III. Results

This section explains the results of the evaluation experiments.

Figure 4 shows the success hand recognition times over 10 trials for each subject. For all the 5 subjects, the hand could successfully be detected more than 8 times or more except for the right hand of the subject 3. In case of the right hand of the subject 3 it could only be detected 3 times. Though not reported as an evaluation, the healthy posture of the hand could be recognized at rate of 100% accuracy with each subject. However, as the subjects were simulating a patient's posture with their hand, the detection rate was low in some cases. Further, the successful detection was counted only if the hand was identified instantly. With hindsight, when the sensor position was changed towards or away from the arm supporter or rotate around the vertical axis, the hand can be made to recognize. This strategy will be followed in a clinical setup during the implementation of the AROM measurement system with patients.

Table 1 shows the results of the repeatability evaluation for right and left hands. Results show the average of the recorded ROM value for the 5 sets of recordings and standard deviation of the data. All the recorded data were within the normal range of ROM of finger joints as reported in [2]. Accordingly, for the thumb MP and IP joints the ROMs were within the range of $0^o - 60^o(+40^o)$ and $0^o - 80^o(+30^o)$,

TABLE I

AROM OF THE RIGHT HAND AND LEFT HAND

Finger	Thumb			Index Finger			Middle Finger			Ring Finger			Little Finger		
Joint	CMC	MCP	IP	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP	MCP	PIP	DIP
right hand															
Sub1	31±5	27±1	18±1	87±1	76±1	25±1	101±1	84±1	34±1	101±1	84±1	30±1	91±1	79±1	38±1
Sub2	35±1	21±1	29±1	78±3	78±3	23±2	85±1	82±2	33±1	84±2	82±1	31±1	78±1	77±2	38±1
Sub3	59±3	31±1	21±2	77±4	83±8	25±1	87±3	86±5	41±2	99±1	86±5	34±1	94±2	84±6	43±1
Sub4	41±1	26±2	26±2	89±5	80±2	29±1	97±2	84±1	35±1	95±1	86±1	32±4	78±2	80±1	35±1
Sub5	25±3	17±1	9±1	80±1	72±1	30±1	84±1	83±1	38±1	88±1	84±1	34±1	71±1	79±1	40±7
left hand															
Sub1	30±1	25±3	24±2	84±4	76±1	26±1	96±2	87±1	34±1	95±2	87±1	32±1	89±2	81±1	36±1
Sub2	36±2	19±1	23±3	67±3	79±1	20±2	85±4	82±1	30±2	74±3	79±1	28±2	66±2	74±1	40±2
Sub3	56±8	33±2	27±3	93±5	98±5	30±3	98±4	105±4	39±5	97±2	103±4	33±2	84±3	109±7	44±5
Sub4	41±2	39±1	18±2	92±2	84±4	33±6	95±1	88±6	38±2	96±1	87±6	33±1	77±1	82±9	34±1
Sub5	31±3	22±1	12±3	75±2	78±1	25±3	81±1	84±1	36±2	87±1	84±1	32±1	71±1	82±1	37±1

respectively. For the other four fingers, MCP, PIP and DIP ROMs were in the range of $0^o - 90^o(+20^o)$, $0^o - 100^o(+30^o)$ and $0^o - 70^o(+30^o)$, respectively [2]. [8] reports repeatability coefficients of $7^o - 9^o$, and $4^o - 5^o$, between inter-rater and infra-rater respectively with goniometric readings. In comparison most of the readings from the proposed AROM measurement system were below the repeatability coefficients reported with goniometer. Only a few of the joint readings show a standard deviation in the range of $7^o - 9^o$.

IV. DISCUSSION AND CONCLUSIONS

This study proposed a hand joint AROM measurement system with an optical sensor and a measurement environment suitable for patients with extreme mobility limitations of the upper extremity. Measurement environment comprised of an arm supporter to support the upper extremity during the AROM measurement and the sensor placement was strategically decided to maximize the detection capability for hands with different sparsity levels. The proposed system can measure and record the AROM values instantly and repeatably with a single cycle of motion of the hand which will reduce the burden on the patients and practitioner. The results demonstrated the successfully implementation of the AROM measurement system with healthy subjects, including patient simulated evaluation. Further owing to non-contact measurements, it also serves hygienic requirements that is important in infection disease controlling. Although, no information can be found about the time taken to complete a ROM measurement of finger joints with goniometer, the proposed AROM measurement system can complete a measurement within 5 - 10 mins, including the setup time of the system.

In the scope of the current study, we have not performed a comparison of AROM values to ROM values measured with a goniometer. As the next step of the study, currently clinicians are working on evaluating the proposed system in a clinical setup with patient data recording and comparing them to the goniometric readings.

V. ACKNOWLEDGEMENT

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