Monitoring the use of impaired hand by a new low cost device during daily life activities with a real-time visual feedback

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Abstract— **Hand movement tracking devices are important for monitoring impaired hand function during daily life activities. The study presented the design of a finger movement evaluation device to record hand movement in daily life activities. It also investigates the feasibility of using such a device for rehabilitative purposes. Finger Movement Evaluation Device (FMED) was developed for these purposes and was tested on six stroke subjects who used it at home for two days. Based on the results of the feasibility study and subjects' request to use the device for a longer period of time, a home-based therapy pilot study on one stroke survivor was done. Results show a high patient acceptance of using FMED, with an ability to use acquired data to extract quantitative information about finger movement. However, the clinical training trial shows that the first version of the device is not practical for intensive use and its performance is not stable. These preliminary findings lead to designing a new version of the device using different hardware and setup.**

Keywords- data glove; finger movement impairment; stroke; home-based therapy

I. INTRODUCTION

This paper extends the paper [1] that was presented at the 4th International Conference on Global Health Challenges. In the field of stroke rehabilitation, evaluating the use of impaired hand during daily life requires the use of motion-tracking devices like the Finger Movement Evaluation Device [1]. Stroke is the major cause of neurological disability all over the world [2]. However, upper extremity (UE) motor impairment, specifically hand paresis, is the most disabling and persisting residual impairment after this event [3] and it is evident that it limits basic activities of daily living [4]. For this reason, the role of stroke rehabilitation is to promote independence in daily life activities [5]. Moreover, the use of outcome measures (OMs) in neurological physical therapy is essential to evaluate the improvement of function during rehabilitation [6]. Therefore, an essential issue in the assessment after stroke is to determine how much of the impairment of upper extremity is the source of loss of function, and if the selected rehabilitation intervention improves the daily activities of stroke survivors.

Numerous standardized clinical measures are available for clinicians to evaluate UE function after stroke. However, these measures are rarely used in clinical practice because of time constraints, high level of difficulty, lack of equipment, and lack of knowledge regarding OMs [7]. Besides, most of these measures do not collect information about the use of UE in the Activities of Daily Living (ADLs) and do not provide clinicians with quantitative and objective information about patients' use of impaired limb during the day [8]; thus, they do not reflect how patients function in their daily life and real world [9]. The use of assessment tools at home and community is essential for evaluating UE function during daily activities in order to improve therapeutic intervention and avoid having patients stop using the impaired limb due to pain or absence of confidence and eventually lose the ability to use it due to the learned non-use phenomena [10].

Wearable measurement devices and home monitoring devices provide clinicians with additional assessment opportunities such as collecting hand posture and movement data when individuals perform daily activities outside the clinic [11]. Despite their importance in measuring the fingers' range of motion during dynamic tasks [12], different limitations exist; they are expensive, heavy and uncomfortable to be worn in daily life outside the clinic [13, 14] and do not provide long-term monitoring [13].

Preliminary research in the area of hand glove devices has focused primarily on testing protocols that evaluated the characteristics of glove devices [11-13, 15-18]. None of them has explored the use of these devices to monitor the impaired UE function during daily life.

This article describes the design, development, and testing of a low-cost device for the assessment of finger movement during daily activities. Section II provides a review of evaluation measures of hand function after stroke. Section III describes the device design and implementation. Section IV describes the methodology of feasibility studies. Sections V elaborates on the results and discussion, followed by conclusions provided in Section VI.

II. Evaluation Measures of Hand Function After stroke

A. Clinical Measures

Numerous clinical measures are disposable to clinicians to use in clinic for the evaluation of upper extremity functions after stroke, that either measures self-report or performance. Performance measures include different clinical tests, frequently the Action Research Arm Test (ARAT) [20], Box and Blocks Test (BB) [21], Chedokee Arm and Hand Activity Inventory (CAHAI), Jebsen-Taylor Hand Function Test (JTT), [22] Nine- Hole Peg Test [23], and the Wolf Motor Function Test (WMFT) [24]. The most cited self-report measures include the Stroke Impact Scale (SIS) and the Motor Activity Log (MAL) [25]. However, all of these clinical measures of motor function do not provide data about how the person functions in their daily life [19].

B. Quantitative Tools

Probably the most commonly used evaluation procedure is the measurement of joint range of motion (ROM) [26] using mechanical or electronic goniometers [12]. The range of motion (ROM) is defined by the ability to move the joint(s), and can be evaluated as active and passive ROM [27].

The complex structure of the hand negatively affects the accuracy of any hand ROM measurement [12]. Moreover, goniometry is related to static ROM measurement, but the hands are used principally in complex and dynamic tasks. Hence, ROM measurements using goniometry cannot predict the effective ability of the hand to perform functional tasks [28].

C. Hand Movement Data Gloves

In order to overcome the limitations of clinical measures and traditional goniometry and understand how individuals interact in the real world, there is a need for quantitative measures of finger joint motion over longer periods of time at home [15]. In principle, the use of glove devices establishes an objective procedure to measure hand function independent of examiner subjective interpretation [29]. Examples of data gloves in the market include the Cyber glove (Immersion Corporation, San Jose, CA), the Data-Glove Family (Fifth Dimension Technologies (5DT), Irvine, CA), the SIGMA Glove [16], the Human Glove [12], the shadow monitor [28, 30, and 15], the Wü glove [31], the Smart Glove [17], and the Neuro-Assess Glove [18].

Some of these systems are commercially available but are not feasible for use on individuals with severe hand and finger impairments and/or neurological disorders. This is due to the fact that these devices are too complex (some require specific software and extra accessories) and unaffordable to be owned by individuals for personal use [15].

D. Home-Based Therapy and Visual Feedback

Home-based upper limb therapy can be more beneficial than conventional therapy used in rehabilitation centers. Theoretically, home-based rehabilitation permits a repeated practice of occupationally embedded tasks in the individual's own environment [35]. This is perhaps more advantageous than hospital-based or outpatient treatment in accordance with the "specificity of learning" principle [36], which predicts that the learning of a new skill is improved when conditions of practice match those of the task in real life [35]. The FMED can be used in home-based upper extremity rehabilitation therapy as it is low-cost, lightweight, and easy to use. Furthermore, it is equipped with LEDs, which provide visual feedback, and can track the use of the subjects' upper extremities during daily life and supervise the exercises of home-based therapy to ensure that patients are following the instructions of their clinicians at home. The FMED's entity with visual feedback makes it suitable for home rehabilitation in that it engages and motivates patients during their exercises at home. Thus, an evaluation of the efficacy of the use of this device in the home-based stroke rehabilitation is essential. In addition, there are indications that integration of augmented feedback and exercises can stimulate the learning process in rehabilitation therapy by making patients more conscious of their performance [37]; hence, the use of FMED in therapy programs can add an important value to the rehabilitation efficacy.

III. The FMED : An overview

A. Finger Movement Evaluation Device (FMED)

Figure 1 represents the first prototype of the Finger Movement Evaluation Device worn by a volunteer. FMED was designed to act as an offline electronic goniometer that measures the angle of finger flexion of two joints simultaneously. The device includes two bending sensors (SpectraSymbol®, UT, USA) that can be placed on two fingers' MCP joints (for example, index and middle fingers) at a time using Velcro™. Only two joints can be tracked with this prototype in order to reduce the cost of the device and allow the user to focus on two fingers at a time with the freedom of choosing which joints to track. Figure 2 illustrates the main parts of the device. A voltage regulator circuit was implemented to downregulate the power from a 12V (6500 mAh) rechargeable battery to 5V. A dc-dc converter was implemented before the voltage regulator to convert 12V to 7V in order to avoid too much heat dissipation in case the voltage regulator downregulates from 12V to 5V. A charged battery (12V, 6500 mAh) was used to power the device for more than 48 hours.

The microcontroller (ATmega2560) reads input from the bending sensors through a voltage divider signal conditioning circuit. This is a low-power complementary metal–oxide–semiconductor (CMOS) 8-bit microcontroller that supports a real Read-While-Write Programming mechanism. The microcontroller processes the data and saves the values of each joint on an SD card in real time. The raw data is saved on the SD (Secured Digital) card in addition to the fractionation angle (difference in angle between the two joints). This device also gives patients a real-time feedback of their movement using a set of light-emitting diodes (LEDs) indicating the level of finger flexion in increments of 10º (10º, 20º, 30º, 40º, 50º, 60º, 70º, 80º, 90º) and fractionation in increments of 5º (5º, 10º, 15º, 20º,

25º). The main electronics of the device were chosen to be surface-mounted in order to reduce the size and weight of the device.

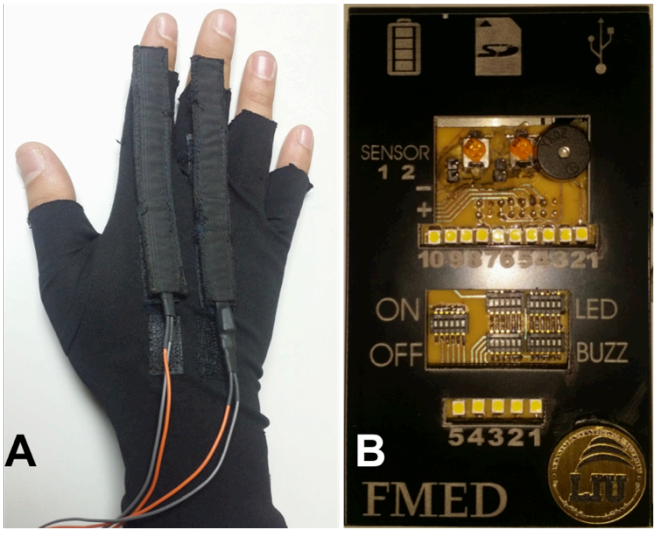


Figure 1. Prototype 1 of FMED. A. Glove worn by a volunteer. B. Device Hardware showing the set of LEDs for real-time visual feedback

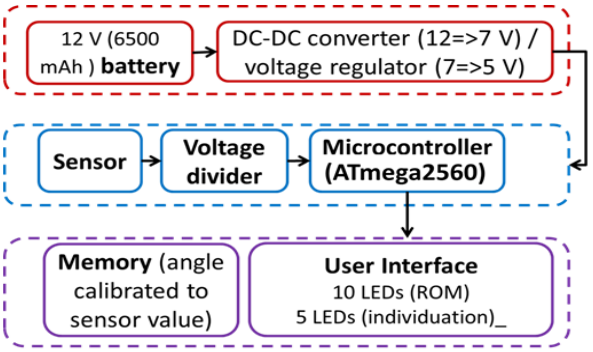


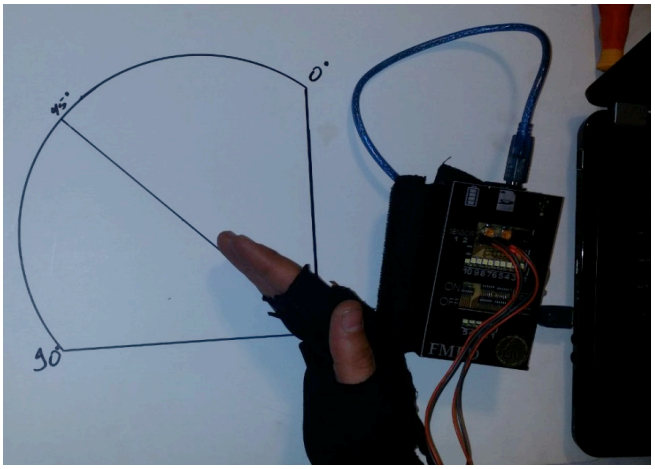
Figure 2. Main components of FMED

B. *Characterization of the Sensor*

Two procedures were used to characterize the linear relationship between sensor resistance and bending angle.

Test 1: A healthy volunteer who bends his index finger 0 degrees, 45 degrees, and 90 degrees wore the glove. Data was collected 4 times at each angle to check the repeatability of resistance at these fixed positions. The results show instability in the performance of the sensor on the mid-angle, which is around 45^0 (See Figure 3).

Test 2: A customized hardware was developed to read the accuracy and repeatability of the bending sensors. The device specifically mimics the actions of a finger joint. A stepper motor, a protractor, and flex sensor holder were assembled to work as a hinge. Materials needed for this testing device (Flex Sensor Testing Device, FSTD) are stepper motor, stepper motor driver, sensor and motor holder, and a protractor. The stepper motor uses a 12V input and allows rotation with increments of 2 degrees. The stepper motor driver is a driver board that includes three main electronic chips: the NE555 precision timer, L297 stepper motor controller, and L298 dual full-bridge driver.



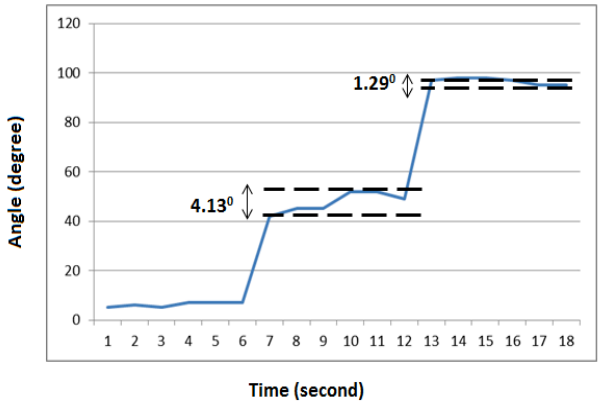


Figure 3. Top. Testing the sensor values at three angles, 0, 45, and 90 degrees. Bottom. Results of one trial, the sensor's values are not stable at 45 degrees.

The device was used to test the relationship between collected data (based on sensor impedance) and bending angles from 0 to 90 degrees (by increments of 2 degrees). Five trials were collected for the two used sensors. The results with the best and worst linear relationship between recorded value and protractor angle are shown in Figure 4.

C. *Collected Data*

As mentioned in the last section, the device saves the values of the variation of angles for sensors 1 and 2 (for example, index and middle finger flexion angles) and the individuation (difference between angles recorded by sensor 1 and sensor 2) versus time. A customized Matlab® algorithm was written to process this data. The first processing step was to calculate differences between adjacent elements of the dataset in order to detect movement

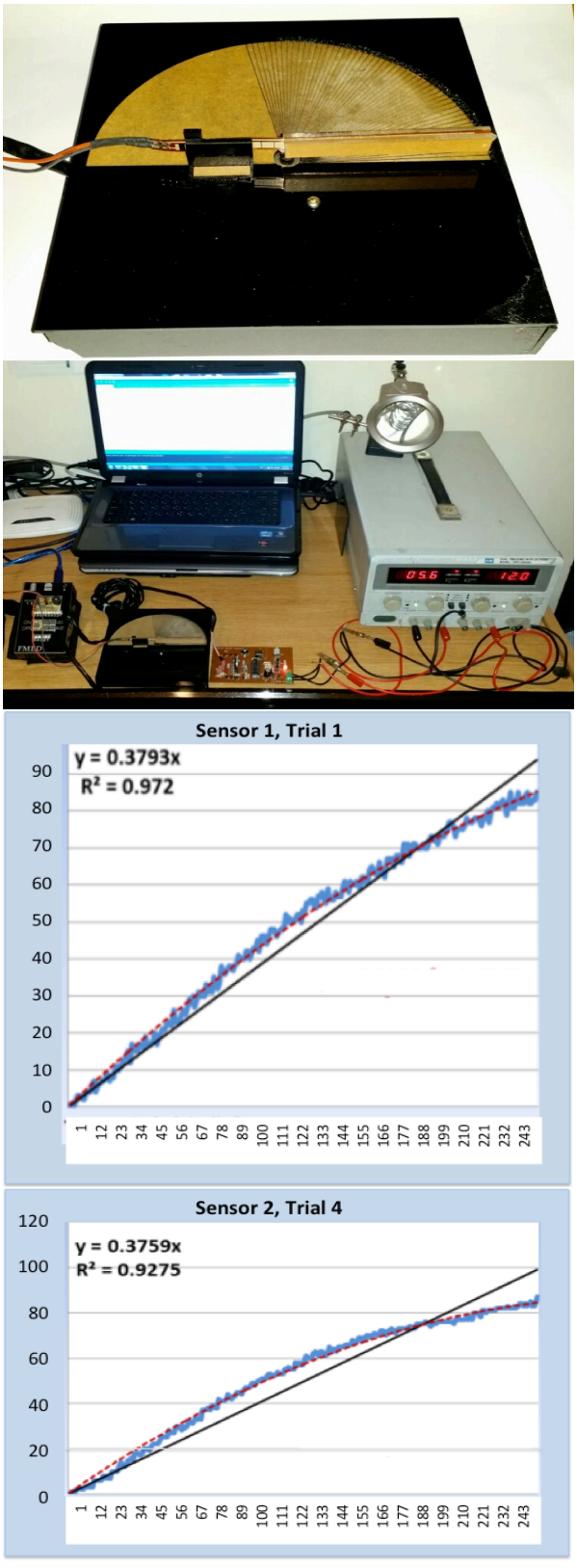


Figure 4. Upper two panels show the customized device and the setup to record sensor value at a range of 0 to 90 degrees. Lower two panels show the results of two trials.

episodes (change in flexion and individual angles). A threshold of 2º was used to count the episodes of movement (flexion angle exceeding a 2º predefined threshold). The ratio of counted samples over the whole dataset provided the Ratio of Movement (RaOM) values of each finger.

The other parameter that was calculated is related to the mean of difference in the angle between the two fingers (individual finger movement). Episodes or consecutive samples where there was a difference in flexion between index and middle fingers were reported. These episodes were counted to derive the Integral of Individuated Movement (IIM) episodes value. This value indicates how much the subject was moving the index finger independent of the middle finger and vice versa. IIM reflects how much the patient is capable of controlling one finger independent of the other during executing a functional task. The parameters (RaOM and IIM) calculated based on the recorded data were used as the main outcomes of FMED to effectively quantify the amount of movement during the day.

IV. USING FMED IN HOME-BASED THERAPY

A. *Feasibility Study*

1) *Subjects*

Subjects with stroke were recruited from multiple rehabilitation centers in Beirut, Lebanon. Six individuals with a clinical diagnosis of stroke in the chronic phase (three males and three females, mean age 49.33±8.1 > 6 months post-stroke) participated in the study.

Subjects were included because they had residual upper extremity impairments (Upper extremity Fugl-Meyer [FM] scores, with a range of (45-56)/66; and with mean flexion fingers ROM ± 1 standard deviation: 73.3 ±7.4 degrees). Table I presents the patient's demographic and clinical characteristics.

Inclusion criteria were chosen to give a nearly homogenous group of subjects between 40-60 years, with a similar representation of both sexes, and approximately same degree of hand function deficit. The participants signed informed consents approved by the Lebanese University, school of health ethical review board.

2) *Protocol of the Feasibility Study*

Subjects were trained for a few minutes on how to wear the device at home and turn it on or off. Subjects wore the glove at home for two days. In the first day, they were instructed to wear the glove in the impaired hand and use it like they usually do during daily activities and remove it before sleeping. In the second day, they received a call in the morning from the study personnel and were instructed to do specific activities using their impaired hand during the day in addition to their daily routine.

TABLE I. SUBJECTS' DEMOGRAPHICS AND CLINICAL INFORMATION

Subject	Age	Gender	Months since CVA	Fingers' Average ROM	CVA side	FM UL section (0-66)
S1	40	M	8	70	L	49
S2	60	F	8	60	L	50
S3	45	F	12	80	L	56
S4	53	M	48	70	L	50
S5	58	F	6	80	L	45
S6	40	M	24	80	R	52
Average	49.33			73.3		50.33
SD	8.12			7.45		3.61

SD: standard deviation. CVA: cerebrovascular accident. ROM: Range of Motion. FM: Fugl Meyer.

The list of activities is as follows:

- Stacking cups and dishes on shelves, organizing the laundry, and other different household tasks with the impaired hand (especially if subject usually does such tasks normally)
- Trying to write using the impaired hand
- Using a remote control with the impaired hand when watching TV
- Getting dressed with the use of the impaired hand like zipping and buttoning
- Combing his/her hair using the impaired hand
- Working on the PC using the impaired hand
- Tying shoes using the impaired hand
- Using the impaired hand while using the phone
- At night, removing the glove before sleeping.

The research team did not supervise the patient at home; however, the device recorded the data from the subject's movement on the SD card. After collecting the FMED device from the subjects on the following day, they completed a user feedback questionnaire, and the data was saved on the SD card were collected for offline analysis.

User acceptance of the device and patient feedback were evaluated based on a user feedback questionnaire [13] presented in Table III and an open-ended discussion, performed after using the device for two days. The participants were supposed to answer a list of 11 questions on a scale of 1 to 7; 1 meaning strongly disagree, 7 meaning strongly agree, and 4 meaning neutral. The study personnel was mainly interested in knowing whether the device was comfortable or not and if it was effective in engaging the subjects and motivating them to do more home daily activities. The recorded data was inspected for quality and movement quality parameters. The RaOM and IIM parameters were calculated in order to inspect if these parameters changed in the second day after the study personnel had asked the participants to do extra exercises.

B. Two Weeks Home-Based Therapy

The feasibility study shows the subjects' interest to use FMED for an extended period of time. Hence, the device was used in a two-week therapeutic intervention for a stroke survivor suffering from hand movement impairment and limited range of motion.

The training protocol is summarized in Table II. The participant was instructed to practice a set of exercises at home and use the device during exercise to receive real-time visual feedback of index and middle finger range of motion and individuation angle between the two joints. Wolf Motor Function Test (WMFT) [24] was used to evaluate functional movement before and after the training.

TABLE II. LIST OF EXERCISES TO DO AT HOME

Day	Training Type
Monday	Finger movement flexion/ extension exercising
Tuesday	Drawing, connecting dots
Thursday	Mirror training
Friday	Weight lifting
Saturday	Functional exercises (door unlocking brushing teeth, tying shoes, etc)

V. RESULTS

A. Feasibility Study

This section presents the results of the user feedback questionnaire and the recorded data. Table III lists the questionnaire questions and mean responses to each question, the results of the t-test performed between the mean responses to each question, and a hypothesized mean of 4 [neutral score]. Results show a significant difference from the neutral score ($p<0.001$). In the open-ended discussion, subjects expressed high satisfaction and reported that the visual feedback by the LEDs was engaging and motivating in moving the impaired hand more than usual. They also expressed their willingness to use FMED at home

TABLE III. USER FEEDBACK QUESTIONNAIRE RESULTS

Question	Average	SD	t-value	p-value
I felt comfortable as the glove was put on	6.33	0.82	7.0	
I did not feel like my fingers were put into any uncomfortable position as the glove was put on	6.33	1.21	4.7	
I felt any restriction to movement with this glove is similar to other gloves I have worn	6.67	0.52	12.6	
I would feel comfortable wearing this glove in public	6.67	0.52	12.6	
I felt comfortable performing the activities in this study	6.50	0.84	7.3	
I feel I can do most of my daily activities (except those involving water) while wearing this glove	6.67	0.52	12.6	
The glove did not feel too tight (it did not make my hands or fingers tingle)	6.83	0.41	17.0	< 0.001
I feel like I can bend my fingers just like I can without wearing the glove	6.83	0.41	17.0	
The glove did not feel too hot or too cold	6.50	1.22	5.0	
I did not feel like my fingers were put into any uncomfortable position as the glove was removed	6.33	1.03	5.5	
I felt comfortable as the glove was removed	6.33	0.82	7.0	
Average	6.55	0.20		

for a therapeutic intervention because of their desire to intensify their hand use during daily activities.

Figure 3 shows the results of data collected from the device during the two days. The subjects were doing a minimal impaired hand finger flexion activity around 60% of the time while using the device (RaOM range 0.55 – 0.61 over the two days). It should be noted that the activity initially reported on day 1 might not accurately reflect the regular activity of the participants without using the device; while wearing FMED, subjects might be moving more than they usually do, knowing that they are being watched. This is known as the Hawthorne effect [32]. However, the participants are stroke survivors and have movement impairments; thus, the Hawthorne effect will not increase the movement score beyond a subject's true functional capability, although it might increase the amount of his or her movement in comparison to regular days. This brings us back to another argument: it is helpful if these individuals with movement impairments feel they are being watched so that they move more according to their functional capability. In addition, by being watched and getting positive visual feedback of their movement (like the feedback by the LEDs in FMED), the subjects become more engaged in daily life functional activities, more than they averagely do. This is believed to be helpful in avoiding the learned non-use phenomena in stroke survivors in which the less the individuals use their impaired limbs, the harder it gets for them to recover their motor skills due to brain remodeling over time [9]. These results are promising due to their effect in validating the use of the FMED and other similar devices in patients with an impaired hand. This study demonstrates that the FMED can be a useful tool to track and monitor the use of paretic hand during daily activities in home environment. It was demonstrated that it is feasible as well as accepted by patients with stroke. Additionally, it was shown that this device could be used to motivate patients to improve their hand movements in daily life and more importantly, do exercises at home (home-based therapy).

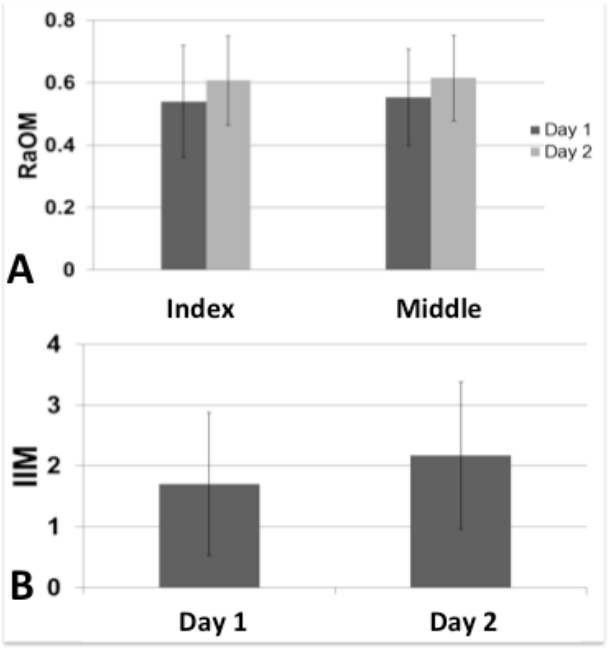


Figure 5. A. Average value of range of motion angle for each joint during the two days, B. Integral of Individuated Movement for the two days of testing the device

B. Two Weeks Home Based Therapy Study

This section discusses the results of a two-week clinical intervention on one stroke subject. The subject was given a set of exercises to do at home based therapy on pre-assigned schedule and she was asked to use FMED while performing the exercises.

1) Clinical Assessment

The WMFT clinical score for the set of 17 timed exercises was 174 seconds before the two-week training and 106 seconds after training, showing a 61% improvement in clinical score.

2) Movement Kinematics Assessment

The data shown in Figure 4 was collected in 1 week of using the device during the home-based therapy. The collected data corresponds to 12326 seconds of device use, which is equivalent to around 205 minutes (3.4 hours). This concludes that the subject complied with therapist's instructions to do 30 minutes of exercising, 5 days a week. RaOM values were 0.89 and 0.87 for index and middle fingers respectively, implying that the subject was exercising while using the device. Values 0.89 and 0.87 imply that during exercising, the subject was performing a minimal impaired hand index finger and middle finger flexion during 89% and 87% of the exercising time, respectively.

Visual observation of the data also shows that the subject was active during the recording time. The average flexion angle of the recorded data was 61.5 degrees for the index finger and 60.5 degrees for the middle finger. However, in the first half of the dataset, the sensors' values ranged from 50 to 100 degrees while in the second half, the sensor's values were between 0 and 50. This indicates that the linear relationship between bending angle and recorded voltage changed during the experiment, either due to a change in the setup or location of the sensor on the finger joint, or damage to the sensor's material due to excessive use for hundreds of repetitions. In this design of the device, a routine calibration was not required, which was a major limitation that leads to corruption in the data collection during the experiment.

At the end of 2nd week of training, the subject reported that the LEDs were not always flashing. Inspection of the data shows improper functioning of the device during training. Similar to week 1 data, the sensors' values were abnormally high due to an error in calibration. However, the device did not record all episodes of movement. The total recorded time was less than 30 minutes so the conclusion was that this set of data was corrupted and was discarded from further analysis. Another conclusion was that the flex sensor is not useful for this application; monitoring the use of an impaired hand in a home-based therapy protocol, due to the uncertainty in the performance of the sensor after an excessive number of repetitions. This conclusion led to recommendations for the creation of a new design of FMED and the termination of the clinical study to avoid wasting time and resources.

Based on the results of the feasibility and clinical study, a new vision for the device was deduced. Accordingly, a new prototype of the device was designed using customized stretch sensors, 5 of which were used to track the 5 MCP joints of the hand in addition to a 6th sensor used to track thumb abduction/adduction movement. The sensors were designed by Dr. Ali Hage-Diab at LIU using graphite powder as conductive material soaked in alcohol and laminated with oil.

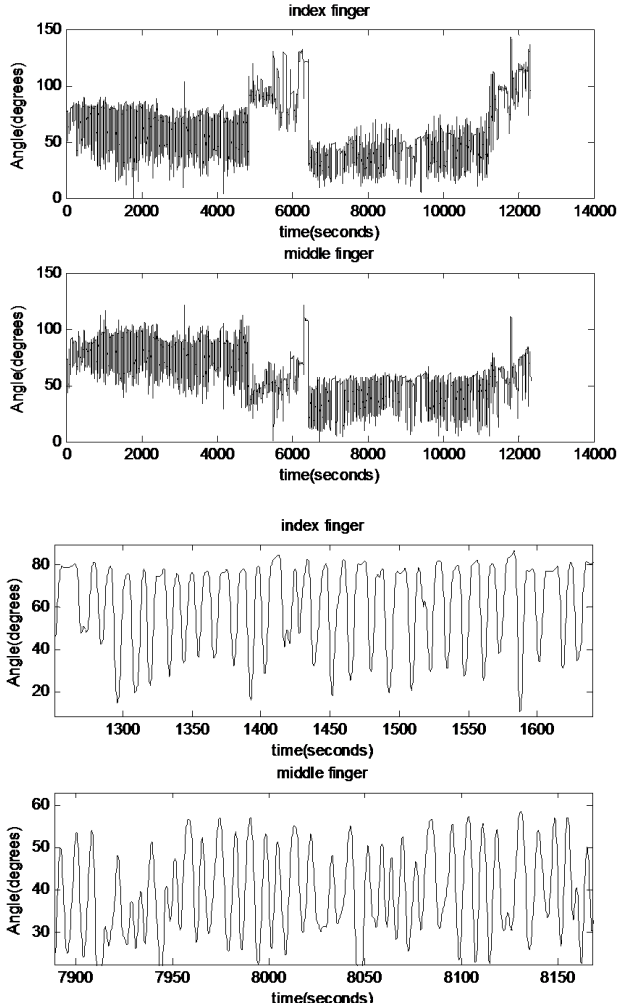


Figure 6. . A. Data recorded by FMED during the first week of training. B. Segment of data shown in A. scaled out to show details of finger flexion.

The sensor was named GO (Graphite Oil) sensor. Detailed description of its design is published in [33]. Sensor performance was tested and results show a linear relationship with bending angle (see Figure 7A). Testing also shows sharp step response of the sensor with bending (see Figure 5B) and repeatability that is better than the flex sensor used in the first prototype (see Figure 8). In this version of FMED, Atmega2560 microcontroller was replaced with Atmega328. In addition, the real-time visual feedback circuitry was replaced with an LED bar that displays the average of whole-hand finger flexion angle during movement. A calibration procedure was designed so that every time a user would wear the device, he or she had to keep the hand in a flat position for 5 seconds and then switch it to a fist position for another 5 seconds. FMED saves the numbers (for each finger) that are acquired during flat position as minimum input values corresponding to 0 degrees bending angle. Similarly, the values recorded during the fist position are assigned to 90 degrees bending angle. Input data between the minimum

(during flat) and maximum (during fist) values are mapped to a range of angles between 0 and 90 degrees.

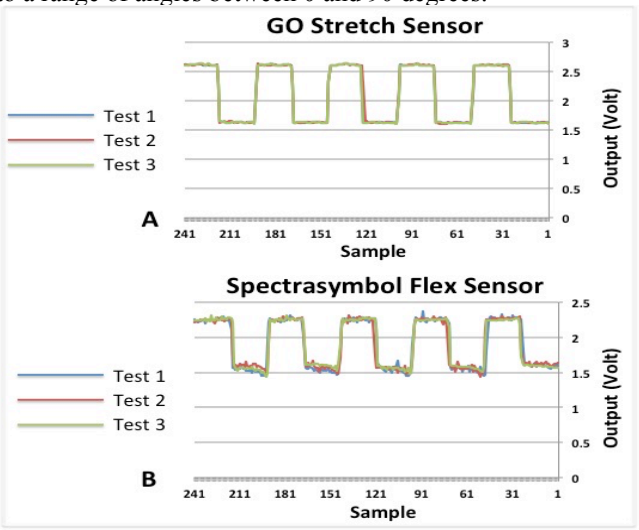


Figure 7. Repeatability test of the sensors. A. Results of the GO sensor. B. Results of the Flex sensor used in the 1st prototype of FMED

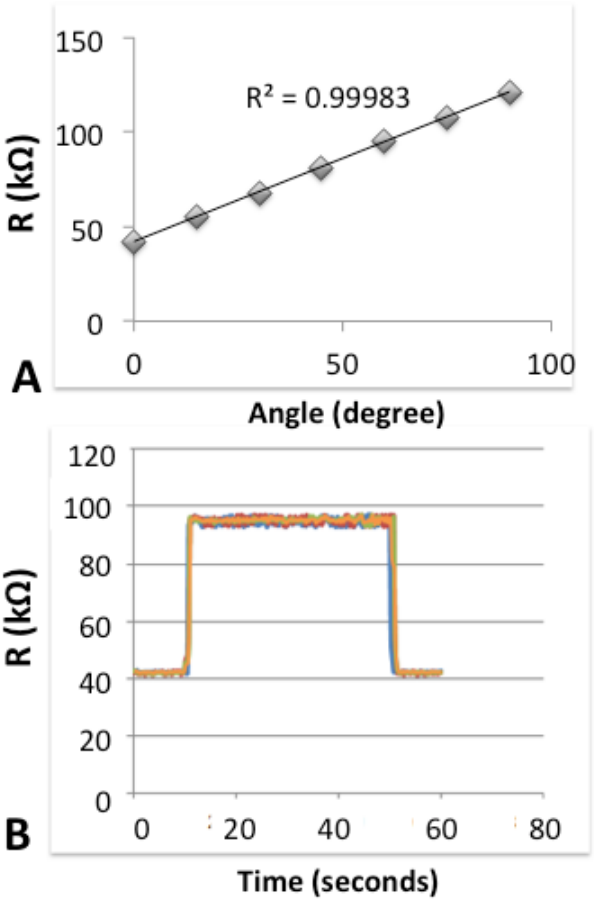


Figure 8. A. Results of Linearity test of the GO sensor. B. Results of the step response test of the GO sensor where the sensor is flexed from 0 to 60 degrees.

VI. CONCLUSION AND FUTURE WORK

FMED allows clinicians to evaluate the improvement of hand function in the context of home environments. It can be a useful tool to complement the role of standardized outcome measures by assessing hand use in real life so that clinicians are not limited to the clinical setting. The high rate of acceptance of FMED by the participants in this study and high enthusiasm of patients to continue using it for therapy due to the presence of visual feedback, suggested the need to test the usability of FMED in a home-based rehabilitation therapy intervention so that it can be produced with a very low cost (~$100).

Home-based therapy study on one stroke survivor showed high competency; however, it revealed issues in the initial design of FMED, specifically weakness in the performance of the flex sensors. An important modification on FMED, as stated previously in this study, involves replacing the flex sensors with the stretch (GO) sensor and increasing the number of sensors to 6 to measure all five finger flexion angles and thumb abduction/adduction movement. The new prototype of the FMED is under development and testing.

Low cost, user-friendly, and low weight are the main advantages of FMED in comparison to other hand motion tracking gloves that are available in the market. The presence of visual feedback setup also allows FMED to be useful as a therapeutic tool and not just as a movement recording device. In the future, the second version of the device will be used in a clinical study to evaluate FMED as both an assistive tool during home-based therapy of impaired hand function and as a research tool that captures significant data of stroke survivors' use of their impaired hands during daily life activities.

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