Development of a smart glove for affordable diagnosis of stroke-driven upper extremity paresis

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Abstract— **Stroke is the third highest cause of disability-adjusted-life-years (DALYs) and is becoming an important cause of disability in low-and-middle-income countries (LMICs). It has been found that in developing countries, especially in rural areas, patients suffering from disabilities due to stroke do not receive appropriate on-time treatment due to infrastructural limitations and financial barriers. Conventional rehabilitation management systems fail to cater the demanding requirements thereby arousing the need for evolution of wearable m-Health devices for uninterrupted health monitoring of patients with upper extremity paresis. In the present research, we have developed an instrumented glove incorporated with wearable sensors (bend sensors, pressure sensors, and accelerometers) for continuous monitoring of activities of daily living (ADLs) by capturing and transmitting sensory information related to finger bend angle, tip pressure, and acceleration or orientation while doing specified grasps. The sensors were calibrated using standard instruments before installation. Two subjects, a healthy individual and an individual suffering from upper extremity disability after stroke impaired, were employed for experimental validation. The subjects were instructed to perform certain pre-defined tasks and the related finger bending angles, finger-tip pressures, and acceleration were recorded. The trend of the dataset obtained was graphically visualized and analyzed for statistical parameters like mean, variance, maxima, and minima, leading to a generation of appreciably distinguishable results that discriminated against a stroke patient from a healthy individual. Therefore, the present glove-based stroke diagnosis method can be adopted for an affordable and efficient stroke rehabilitation process while promoting m-health at the same time.**

Keywords— m-Health, stroke, rehabilitation, wearable device, paresis, instrumented glove.

I. Introduction

Stroke is the third most common cause of premature death, after cancer and ischemic heart disease. [1] Based on a report from The American Heart Association in 2015, 33 million people worldwide are victimized by stroke every year and two-thirds of all stroke incidences occur in developing countries [2, 3] due to unhealthy lifestyles of people. It is even noted that deaths due to stroke have increased from 35,000 to 605,000 in India in a span of ten years (2000 – 2010). Stroke is the third major contributor to the neurologic disability in India and is therefore a significant cause of disability-adjusted-life-years (DALYs) [4] and is gradually becoming an important cause of disability in low-and-middle-income countries (LMICs).[5] In India, about 1.5 million new stroke cases occur every year and more than one-third of the patients are left with disability [6, 7]. Stroke results in long-term disability in 30%–40% of cases, thereby adding 0.45–0.6 million disabled stroke survivors to the population each year [8].

Limb weakness is one of the most common as well as a significant phenomenon observed in stroke survivors. [9] The upper limb paresis mostly leads to grasping disabilities among the stroke survivors that restricts an individual from the activities of daily living (ADL), as well as social and recreational activities. Affected individuals may regain limb functions through on-time problem-specific and guided rehabilitation therapy. Since such rehabilitation practice starts beyond the inpatient stay in the hospital, it needs frequent visits to the care-giver, is time-consuming and expensive. A large percentage of the rural population are also victimised by post-stroke disability every year and this section of the society are mostly unable to avail requisite rehabilitative measures due to financial constraints and infrastructural limitations. Furthermore, available rehabilitation services are not satisfactory due to lack of trained personnel. [10] The conventional rehabilitation process is time-consuming and monotonous. ~~at the same time.~~ Figure 1 displays a simplified schematic of conventional stroke rehabilitation process indicating traditional rehabilitation procedure that involves frequent doctor-patient interaction, failing which, the recovery of the

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patient is hampered due to discontinuous monitoring of the affected body part. On the other hand, electronic monitoring of affected upper/lower extremity can continuously capture desired impairment related information leading to an improved rehabilitation process. Keeping the above in mind, there is a need of an affordable body mount (wearable) device that can continually monitor the functions related to the grasp of an individual with the ability of correctly identifying any significant anomaly that can be transmitted to the concerned health-care centre in no time for immediate and best possible treatment. To further support this, mobile health or m-Health based devices are gradually gaining importance among medical practitioners and researchers.

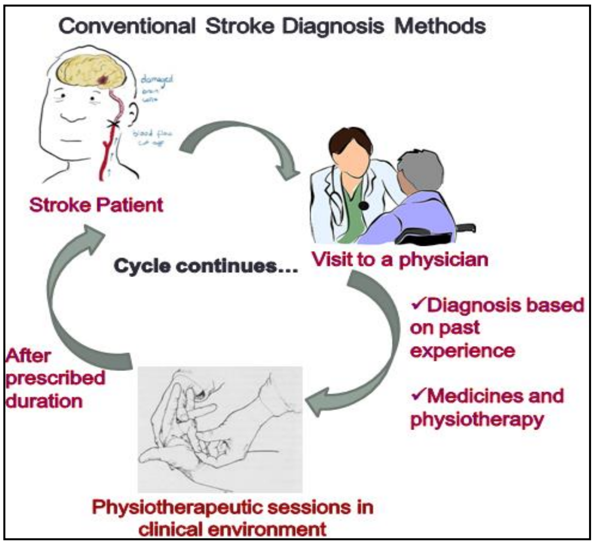

Figure 1: Schematic of conventional stroke rehabilitation procedure (Adapted from [10])

II. LITERATURE REVIEW

Existing literature introduces many devices employed for monitoring abnormal activities of human being, while detection of normal activities is a part of security systems and healthcare. [11] Therefore, such a device that can efficiently monitor daily abnormalities in activity of patients can supposedly contribute significantly towards a more comprehensive assessment of stroke patients with disability even outside hospital setting. The most recent technological advancement in this area lies in the systematic merging of wearable sensor data and transmission hardware on proper software platform for ease of use by patients, researchers, and medical practitioners. [12, 13]

As defined by the Global Observatory for e-Health (GOe), m-Health is a medical and public health practice triggered by mobile devices, such as mobile phones, patient monitoring devices, personal digital assistants (PDAs), and other wireless devices. [14] The contribution of engineering in m-Health is the incorporation of suitable wearable sensors on human body parts to acquire related data for continuous monitoring of the affected part and transmit the same to personal computer or mobile through appropriate technology for further meaningful interpretation [15]. Figure 2 displays the schematic of a standardized m-Health methodology used in clinical practice. Here, the most significant role is played by properly located sensors that generate reliable data about patient's activities. In this context, a vivid analysis has been conducted on position and motion tracking sensors. Accelerometers are widely used for measurement of acceleration and position of concerned body part with respect to gravity. Accelerometers can satisfactorily conclude about the intensity and frequency of human behavior and hence low cost and more effective MEMS based accelerometers are in use nowadays. Traditional inertial sensors have been replaced by inexpensive single chip systems housing accelerometers and gyro sensors on single units.[16] Several innovations constituted wearable sensors based on inertial measurement units (IMUs) with bi-axial, tri-axial, and uni-axial accelerometers and gyro sensors.[17-20] Few researchers included force sensors and bend sensors in their studies. [21, 22, 23]

Data gloves are electromechanical wearables used for tactile sensing and motion control. These devices are in use since long for hand gesture recognition for various applications including diagnosis. Stroke-driven impairment is unique and complex at the same time and therefore an instrumented wearable dedicated to stroke rehabilitation and diagnosis is the present need to cater rising numbers of stroke cases each day. Now, focusing on upper extremity assessment, use of wearable splints or gloves that reflect bending and pressure related information for stroke patients have come into effect. An assistive hand glove was proposed by few researchers for acquiring sensory information from affected part of disabled stroke patients and utilizing the same for useful rehabilitative measures. [25] Bend sensors were incorporated into the developed glove to measure the aperture formed by the thumb and index finger of the user as shown in figure 3. Additionally, interphalangeal (IP) joint angles of the concerned fingers were estimated. Literature revealed a low cost instrumented glove that housed six bend sensors viz., 1 for the thumb, 3 for the index finger, and 2 for palmar and dorsal flexion of the wrist as demonstrated in figure 4. The set-up was utilized to estimate the bending angles of corresponding finger joints (metacarpophalangeal and interphalangeal) to effectively assess stroke patients lacking motor functions. [26]

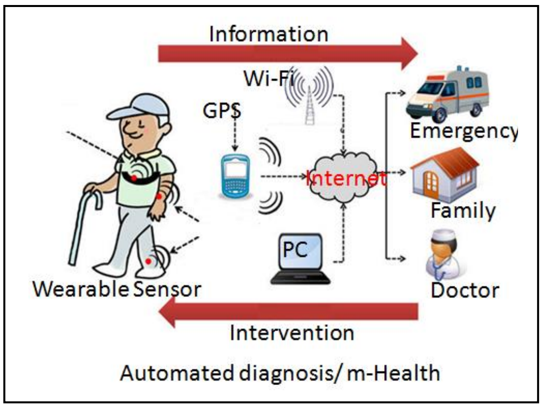

Figure 2: A generalized m-Health based methodology used in clinical practise (Adapted from [15])

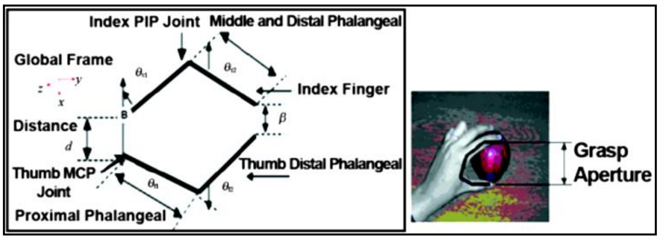

Figure 3: Measurements for instrumented glove used in aperture detection and rehabilitation of stroke patients (Adapted from [24])

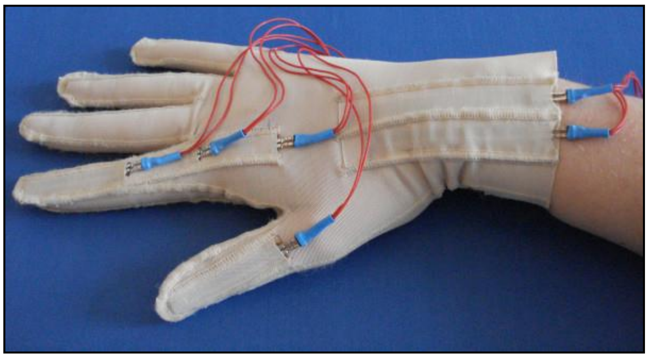

Figure 4: The developed glove for measurement of bending angles of index MCP, PIP, DIP, thumb IP joints and palmar and dorsal flexion of the wrist for diagnosis of stroke affected patients (Adapted from [25])

Further, flex sensors and pressure sensors were used on each finger of an instrumented glove for measurement of bending angle and fingertip pressures respectively, [27] thereby contributing towards the monitoring of upper extremity functions of a stroke patient. Again, in an invention, six accelerometers were used to capture data related to activities of hand, forearm, upper arm, index finger, thumb and sternum of stroke patients while performing certain specified activities. [20, 23] The schematic for the accelerometer set-up has been displayed in Figure 5.

Clinicians and researchers are much aware of conventional stroke assessment scales that are traditionally used to score stroke patients based on their performances through continuous monitoring. Such a method is time-consuming and needs expert supervision. Moreover, the existing literature does not mention a glove based wearable that incorporates bend sensors, pressure sensors, and accelerometers at the same place for stroke rehabilitation monitoring using a graphical user interface (GUI) for performance-based visualization. The present objective of this research is to address the current lacunae thereby replacing conventional time-consuming stroke diagnosis methods with a faster and far more efficient instrumented glove that would monitor the patient continuously with minimum intervention of the healthcare giver. To establish the same, a comprehensive knowledge of parameters such as finger bending angles, finger-tip pressures, and hand acceleration profiles is essential for understanding the behavioral activity of the affected individual. This inspired the authors to fabricate an indigenous and affordable instrumented glove incorporated with flex sensors, pressure sensors, accelerometer assembled with a GUI and data logger for necessary data collection and inference generation.

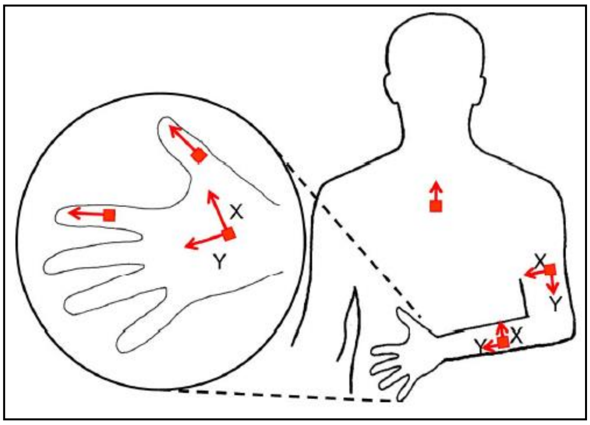

Figure 5: Location of the accelerometer sensors used to monitor human activity (Adapted from [23])

III. Methodology

Considering the need of an automated m-Health based wearable device for improved diagnosis of upper extremity paresis after stroke, the primary objective of this research paper is to fabricate an instrumented data glove incorporating appropriate wearable sensors for capturing essential data from affected hand of an individual thereby contributing towards the process of continuous disability monitoring through reliable inference generation. The sensors were properly calibrated using standard methodology before installation so as to obtain relevant information with the least possible error. The glove houses six flex/bend sensors for finger bend measurement, two pressure sensors for finger-tip pressure monitoring, and a 3-axis accelerometer and gyroscope assembly for detecting abnormality in hand movement and orientation. Further, the wearable hardware has been combined with an interactive GUI for better understanding of a patient's activities. Finally, to test the efficiency of the present invention, the instrumented glove was used to fetch data from a properly functional upper extremity of a healthy individual with no history of stroke or other neurological disease. Once satisfactory sensory information was obtained, the glove was donned by a few stroke patients with residual upper extremity paresis. The data so obtained was compared graphically and statistically to set reliable standards of discriminating stroke data from the control.

A. Fabrication of an instrumented data glove

Human hand glove of stretchable lycra material (Make: B'TWIN 700©) was procured to mount the sensors so as to ensure maximum flexibility while performing specified tasks while data collection. Six 2.2 inch medium resistance bend/flex sensors (make: Spectrasymbol©) were used to acquire finger bend angles of the affected hand. Flex sensors are variable flexible carbon resistors in which the resistance varies with changing bend angle of the substrate, the smaller the radius the higher the resistance value. The thumb, index finger, and middle finger contribute the highest in any grasp-related activity of daily living (ADL) and hence are chosen for a relevant experiment in the present research. Six pockets were stitched on the lycra glove with two on each of the three fingers for accommodating the flex sensors thereby eliminating any possibility of misplacement while experimentation. The flex sensors were placed such that the center of each flex sensor lies on the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints of each finger for the most accurate measurement of bend angles. Three force sensitive resistors (FSRs) of 0.5 inch diameter (make: Interlink Electronics©) were employed to measure fingertip pressures of thumb, index, and middle finger. An FSR is made up of a conductive polymer sheet that changes resistance when a force, pressure or mechanical stress is applied on it. The diameter and thickness of the FSRs were chosen such that reliable forces can be obtained. Like flex sensors, FSRs were also accommodated inside the pockets stitched on finger-tip region of the glove and fixed with glue to ensure unaltered fixation. A motion processing unit, MPU6050 was fixed to the carpal region for capturing acceleration and orientation data. MPU6050 is a 6-axis motion tracking device that combines a 3-axis accelerometer, a 3-axis gyroscope and a digital motion processor. It has I2C bus to communicate with microcontrollers. Arduino MEGA microcontroller board along with additional circuitry was used to collect necessary data from the sensors installed. The circuit diagram used for necessary connections is shown in Figure 6.

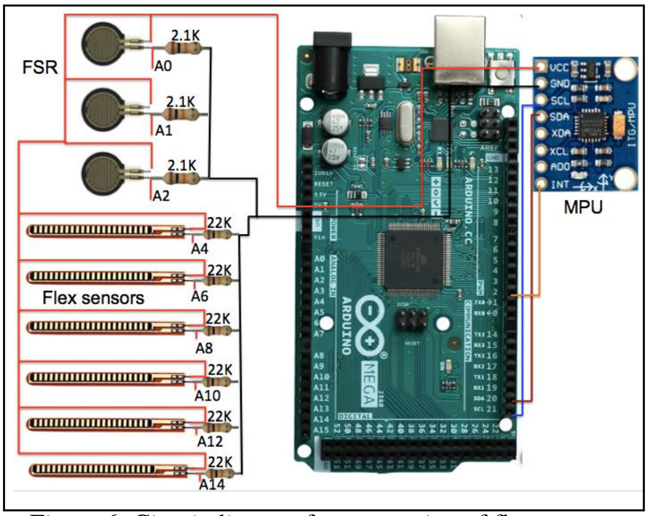

Figure 6: Circuit diagram for connection of flex sensors, FSRs, and accelerometer on an Arduino MEGA platform

Necessary coding for automation of the process was run in Arduino IDE such that the calibrated values of the sensed parameters could be sent to a processing software based GUI in order to display interactive visuals related to motion and position of the hand wearing the developed glove. Furthermore the data could also be stored in CSV format for possible data analysis. The sensor calibration procedure is mentioned in the next section. The developed wearable and the processing GUI are displayed in figure 7.

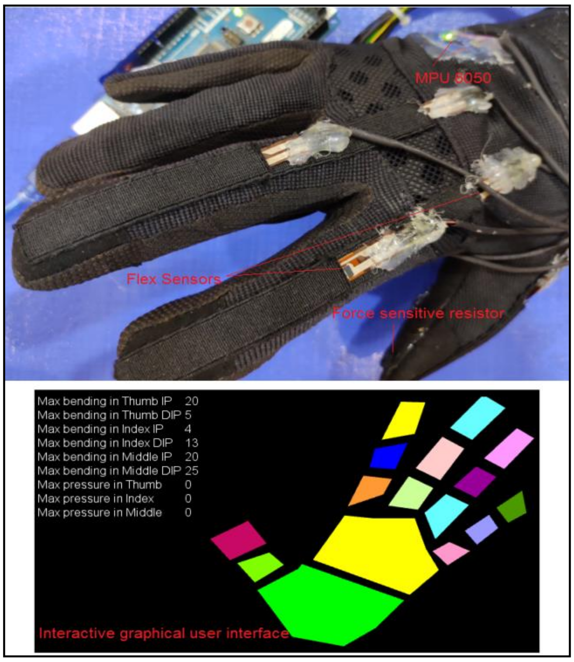

Figure 7: The instrumented glove-based wearable and related processing GUI for stroke diagnosis

B. Calibration of sensors

The sensors employed for the present research were calibrated before installation to ensure reliable data acquisition. The flex sensors were appointed to obtain respective finger bend angles with changing resistances or corresponding voltages upon bend of the substrate. Before installation, calibration of the sensor was done using a goniometer to acquire the resistance vs. bend-angle relationship. Simultaneously, FSRs were calibrated using a force plate dynamometer (make: Kistler©, Model no. 9256C) to generate significant force-voltage relationship. Figure 8 displays the calibration process adopted before the installation of FSRs and flex sensors.

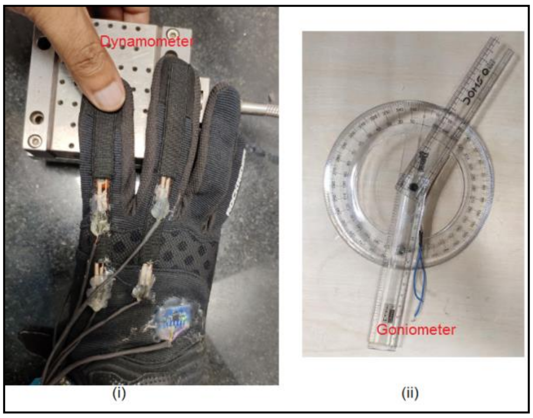

Figure 8: (i) Calibration of an FSR using a force-plate dynamometer (Kistler©, Model no. 9256C); (ii) Calibration of flex sensor using a goniometer.

The voltage-force and voltage-bending angle data were used to characterize the sensors using curve fitting technique available in Matlab©. MPU6050 is a MEMS based 3-axis accelerometer and 3-axis gyroscope that generate 16-bit raw data in 2's complement form. To obtain the desired information from the accelerometer, the full scale range of accelerometer was selected as +/-2g with sensitivity scale factor of 16,384 LSB (Count)/g, where g is acceleration due to gravity. Thereafter, acceleration was noted along X, Y, and Z axes after dividing sensor raw data with its sensitivity scale factor. The purpose of generating suitable acceleration information was to have an idea about the tremor faced, if any, by a participant while doing a particular task. The accelerometer data was then subjected to Fast Fourier Transform (FFT) to quantify the associated tremor.

C. Data collection

Once the sensors were calibrated satisfactorily and reliable data could be obtained, the sensors were mounted carefully onto the stretchable lycra glove platform. The data glove thus fabricated was worn by an abled individual with no history of stroke or other neurological disability. To assess the grasping ability of an individual, two predefined tasks were chosen as follows:

- i) Task I- Grasping a soft smiley ball (Spherical grasp)
- ii) Task II- Gripping a pen and writing the word "getsaakt" without any pen lift (Precision grip).

Spherical or power grasp and precision grip are two significant types of grasps used for performing ADLs and are hence selected for this study. The data so obtained from the healthy individual was treated as control. The experiment was next conducted on a stroke patient suffering from upper right limb paresis. The subject was selected randomly, however satisfying the selection criteria as in Table 1.

Table 1: Selection criteria of a stroke patient for necessary experiments

Sl. No.	Criteria	Eligibility
1	Age(in years)	60-65
2	Gender	Male/Female
3	Post stroke duration	Not less than 6 months
4	Upper limb paresis	Right/left
5	Cause of disability	No other neurological disorder other than stroke
6	No. of stroke attacks	Not more than 1

It was further ensured that the subject chosen for the experiment was able to follow verbal instructions and had minimum abilities to partially perform the ADLs. The subjects chosen approved a consent form before the start of the experiment.

The subject chosen for the experiment was a 62 years aged male suffering from upper right limb paresis for 7.2 months since post-stroke and has regained some mobility to be able to perform the specified tasks. The data so obtained from the healthy individual and the stroke patient was compared and analyzed to conclude significant inferences that distinguish the performance of both.

IV. RESULTS

A. Calibration of sensors

As mentioned in above sections, the sensors were properly calibrated and installed in the wearable to obtain desired sensory information related to certain pre-defined tasks. Data for calibration was collected under standard conditions and scatter plots were constructed for both flex sensor and FSR using Matlab© in order to visualize the trend of the data. Bend angles and forces are characterized against voltage using curve fitting technique on the data obtained. The results are reported in figure 9.

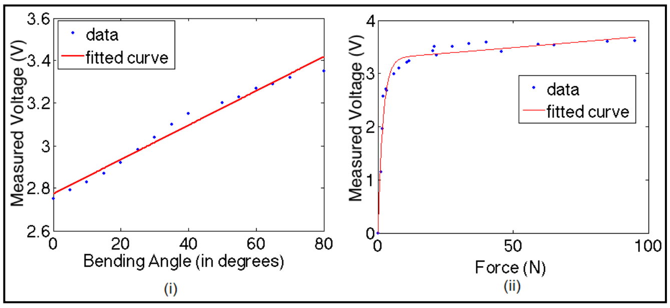

Figure 9: Calibration of- (i) flex sensor using bend angle vs. measured voltage relation and (ii) FSR using force vs. measured voltage relation

The bend angle versus voltage data points were fitted linearly to obtain the following characteristic:

$$f(x) = 0.008063x + 2.772$$

An R-square of 0.9764 and Root Mean Squared Error (RMSE) of 0.03273 determined a sufficiently good fit.

The force and voltage data points were exponentially fitted with the following relation:

$$f(x) = 3.28\exp(0.001228x) - 3.327\exp(-0.5409x)$$

The R-square and RMSE for the above was estimated as 0.9742 and 0.1606 respectively, which indicated a good fit.

The relationships so obtained were incorporated in the functional code to ensure proper interpretation of targeted disability.

The sensors were installed in the glove so as to capture the bending angles and finger-tip pressures of an individual while performing the pre-defined tasks. Also, pre-calibrated fast Fourier transformed acceleration data was obtained for each task.

B. Data collection and interpretation

As discussed before, a healthy and a disabled stroke survivor donned the instrumented glove to perform the pre-defined tasks under expert supervision. Finger bend angle and tip pressure data for each task was collected. Corresponding acceleration data was acquired to detect the amount of tremor, if any. The dataset obtained for the healthy individual and the stroke patient was analyzed and compared with each other. The data plots related to each sensor for both the participants have been displayed in figure 9.

The following observations can be noted from the data profile obtained from the sensors:

- i) For task I, the flex sensor/bend angle data was prominent. The bend angles of thumb, index, and middle finger were much weaker for the stroke patient as evident from figures 10(I) and 10(III).

For task II, the FSR/finger-tip pressure data was a dominating criteria for discrimination. Considering the tip-pressure data profile of the healthy individual to be the ideal, the tip pressures of the stroke survivor deviated significantly from the control and also had noticeable fluctuations along the profile. This can be well understood from figures 10(II) and 10(IV)

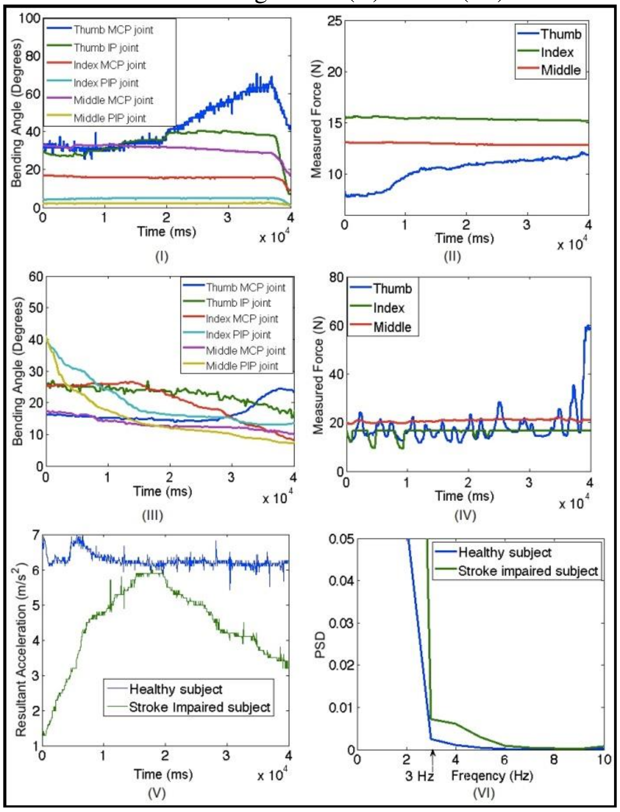

Figure 10: (I) Finger bend angle profile for healthy subject; (II) Finger-tip pressure for healthy subject; (III) Finger bend angle profile for stroke patient; (IV) Finger-tip pressure for stroke patient; (V) Resultant acceleration for healthy subject and stroke patient; (VI) Power spectral density vs. frequency of the acceleration signal for tremor assessment

ii) The frequency content of voluntary movement is generally concentrated at frequencies below 2 Hz, and most forms of tremor occur at 3 Hz or greater. [28] Therefore, as observed from the Fourier transformed acceleration data during task II, data points above 3 Hz were prevalent in the stroke dataset. This proves the presence of tremor in the stroke patient and a much weaker grasping ability compared to the healthy participant. Figure 10(V) and 10(VI) can be referred to understand this phenomenon.

V. CONCLUSIONS

In this research a method for fabrication, calibration and application of an instrumented data glove is demonstrated which could distinguish between a healthy individual and a stroke impaired patient based on finger bending angles, finger tip pressure and tremor profile from acceleration signals. The developed instrumented data glove is particularly beneficial for clinicians in Indian scenario as it promotes m-health based diagnosis for easy recovery of stroke patients recommended with guided therapeutic exercises after in-patient care. This method of diagnosis is home-based, constantly monitor-able, and affordable at the same time. As a future work, internet of things (IoT) integration with the present innovation can trigger its performance thereby finding its use in smart health care of stroke patients. Furthermore, machine learning paradigms may be implemented to predict precise and quantitative grasp related information for an improved diagnosis. Till date, an m-Health based wearable for stroke driven disability care is not available commercially. Hence the developed instrumented glove opens up new vistas towards stroke diagnosis by enabling clinicians to more accurately assess the level of impairment of the stroke survivors relating to conventional assessment scales.

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