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Research paper



System Integration of Finger Contracture Prevention System Device for Early Post Stroke Rehabilitation

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Abstract

Physical rehabilitation is the key for recovering motor control and function for patients with neurological disorders. Conventional therapy procedures tend to be labor intensive and non-standardized, especially in the area of hand and finger rehabilitation. Robotics technology offers a way to reduce the burden of the physiotherapists in a repeatable and measurable manner. This work describes a novel finger rehabilitation approach for hand motor functions recovery targeting early acute stroke survivors using an active exoskeleton robotic device. The device is designed based on anthropometric measurement data of hand ergonomics. The device is able to assist the subject in performing flexion and extension movements. The main specification of the device includes a differential system with a current sensing element and a lead screw mechanism which allows for the self-governing movement of each finger through the usage of small actuators. The device is safe, easy to deploy, integrated with sensing element and offers multiple training possibilities. Moreover, it has been observed that the device could offer an objective evaluation of the patients' motor function activity, suggesting its potentiality for a customized home-based therapy program for patients.

Keywords: *Early Acute; Finger Contracture; Post Stroke Rehabilitation; Prevention System; Real-Time Quantitative Monitoring*

1. Introduction

It has been reported that in 2013 there were approximately 6.5 million stroke-related deaths, making it stroke the second-leading cause of death after ischemic heart disease. It is worth noting that nearly 60% of stroke deaths transpired outside the walls of an acute hospital care [1]. Therefore, the best possible treatment is only plausible under the care of a dedicated stroke unit in which vital aspects that expedite motor recovery could immediately be carried out. Common indicators of an upper extremity motor impairment include the change in muscle tone, muscle weakness, joint laxity as well as impaired motor control.

In general, there are six stages of stroke recovery according to the Brunnstrom Stages of Stroke Recovery. The first stage is flaccidity which in essence is essentially paralysis. In this stage, no active movement of the affected limb is possible, hence a pure passive treatment is required. The second stage no voluntary movement is present, and spasticity exists. In this stage passive rehabilitation treatment is required. Spasticity increases in the third stage, at this stage active movement does transpires whilst the spasticity comes to a peak. The muscle begins to communicate with the brain. The fourth stage indicates substantial motor control is developed whilst spasticity decreases. The fifth stage, the patient is able to make complex movements as the spasticity diminishes. Finally, at the sixth stage, coordination reappears. In this stage, spasticity does not exist any longer and the coordination improves significantly and beyond this stage, normal function is completely restored. Needless to mention, that the key for motor recovery lies in acute patient care, in which passive range of joint movement is performed to prevent and correct muscle contractures [2]. More often than not, finger deformity disorders are associated with stroke [3]. A healthy finger is a vital part of a human's activities in daily living (ADL), and the effect of stroke does considerably affect the patients' lives.

Post-stroke rehabilitation typically begins with individual treatments carried out by physiotherapists in acute-care hospitals [4]. Nonetheless, it is worth noting that more than half of the patients are discharged immediately as their lower-limb ability shown some improvement, primarily to decrease the overall expense of the rehabilitation treatment, although the function of the upper extremity is not fully recovered, specifically the distal parts such as hands consists of the wrist, palm, and fingers [5]. Therefore, leaving the fingers in flexed or extended positions, that in turn, limits the ADL of patients.

One of the methods in resolving such finger deformities is through performing the motor recovery treatments as suggested in Brunnstrom stages [6],[7]. The physical therapy is dependent on the usage of the muscle strength of the paretic limb which is often under the care of a physiotherapist. The duration of such therapy depends on the stroke severity of the fingers as well as the medical condition of a given patient [8]. Therefore, a continuous monitoring and active sessions are required in order to improve patients' motor function skills supported by physiotherapists [9]. Nevertheless, owing to the limited number of physiotherapists limits the

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accessibility of the patients to the physiotherapist at all times [10]. Due to such issues, rehabilitation robotics are sought after in order to mitigate as well as addressing the matter [11].

Although there exists literature that reports on the functionality as well as the ability of hand rehabilitation robotic devices in recovering the motor functions through different guided movements of the hand, i.e., flexion and extension as well as the anterior or posterior movements. However, there is limited established methods or studies that are accessible on the recovery of the tactile sensory of the hand. It is noteworthy to mention that tactile sensation of the hand is non-trivial towards motor recovery functions of the hand.

This paper sought to examine the tactile sensory for hand functionality recovery. The realization of the device is based on several development procedures which are demarcated through the respective sections of the paper. The design concept is illustrated in Section II. The selection of materials, the actuator system with sensing elements and the executed control schemes are detailed in Section III. The performance of the developed prototype is assessed in Section IV.

2. Needs Statement Specification

After a stroke attack, survivors would have a different experience in term of muscle weakness, paralysis, stiffness, or changes in the sensation which in turn, debilitate both the hand as well as finger function. It could limit the motion of both the agonist and antagonist muscles at different joints. More often than not, the fingers are rigid in a flexed posture and the patients are not able control their finger movement as they could not provide the required extension force. Accordingly, it is essential for the proposed system is able to provide to repetitive extension movement of the finger at the initial stage of the rehabilitation program [12]. Once the extension function has been considerably recovered, the flexion training is carried out, this training regime involves intensive grip strength training to strengthen the motor control of weak intrinsic hand muscles.

2.1. System Functionality

This segment defines the detailed functions of the proposed robotic system [13]. The main role of the system is to reduce the finger's spasticity stiffness. Therefore, the robotic exoskeleton system ought to replicate the repetitive motion of the flexion and extension motions of the fingers in order to reduce the rigidity of the finger muscles [14]. In addition, the prototype must be able to sense the angular displacement of the extension and flexion motion of the index, middle, ring and small fingers in order to quantify its trajectories [15]. As illustrated in Figure 1, the sub-functions of the proposed system consist of the capability of the device in regulating the angular speed as well as providing the typical range of motion of the finger based on the input angle of the finger joints. Informed opinion from professional physical therapists as well as healthy subjects are important to avert any untoward incidents during the actual rehabilitation program.

2.2 Finger Contracture Prevention Prototype

In the present investigation, a novel type of a robust finger contracture prevention prototype which can control flexion and extension in the range of motion is developed. The hypothesis is, by implementing the normal range of joint motion, patients will be able close and open their hands properly. Most rehabilitation device that are available in the market such as static finger splints are often employs passive control system. It is worth noting that the active control systems are often expensive, requires a larger space for installation, immobile and hence, inappropriate for home rehabilitation.

Therefore, the current study attempts in developing a robust, cost-effective prototype that incorporates an active control system of a DC geared servo motor that utilizes a lead screw mechanism. Figure 1 illustrated the overview system architecture of the proposed exoskeleton system where the DC geared servo motor is coupled with a lead screw mechanism specifically for the index finger module. The block diagram and system structure of the control actuator system is demonstrated in Figure 2.

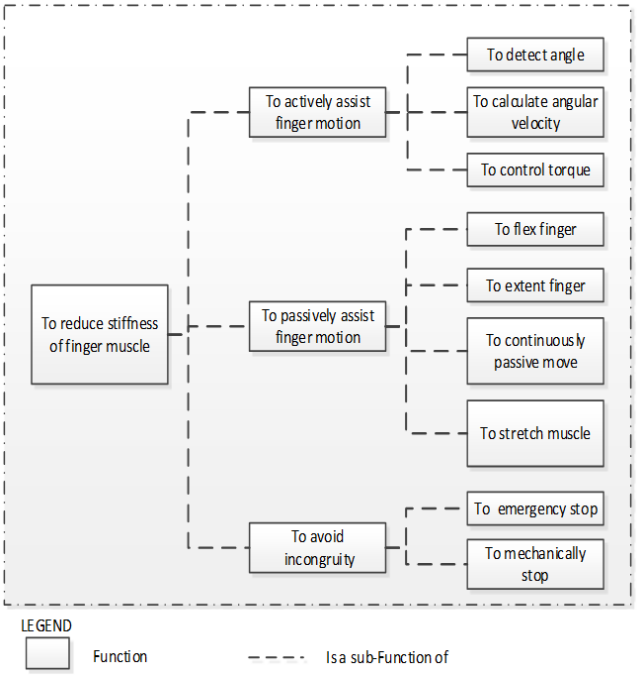


Fig. 1: The functionality of the proposed exoskeleton system.

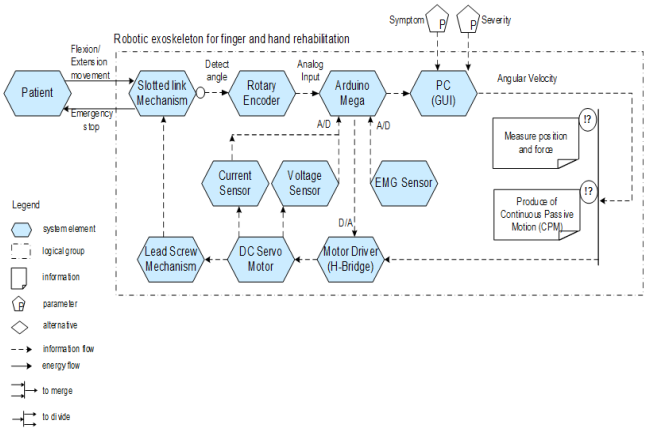


Fig. 2: The control system block diagram and system architecture of the proposed exoskeleton system.

3. System Implementation

3.1. Actuation

The actuation of the system is governed by a DC geared servo motor that drives the lead nut in the lead screw mechanism to produce the flexion and extension motion of the index finger. The mechanism allows for the conversion of the rotary motion from the actuator to a linear motion. In essence, the DC geared servo motor provides a reaction force against the flexion force given by the subject's finger.

To gain further insight on the actual training session, a variation of stiffness and rotating speed is simulated by employing torque control on the DC geared servo motor to offer continuous passive

motion (CPM) in assisting the patients to decrease the joint stiffness of the fingers.

3.2. Transmission System

A lead screw is a type of power screw which provides an economical solution for linear motion requirements. The lead screw mechanism converts a rotating input torque in the form of a rotary motion into a rectilinear motion. The nut and the screw experiences sliding contact. Nonetheless, it is worth noting that such screws offer low efficiencies primarily owing to the relatively greater coefficient of friction it experiences during sliding. Figure 3 demonstrates a trapezoidal thread profile of lead screw mechanism. Equation (1) was employed to approximate the total amount of force involved in the system.

$$F = F_A + mg(\sin\theta + \mu\cos\theta) \quad (1)$$

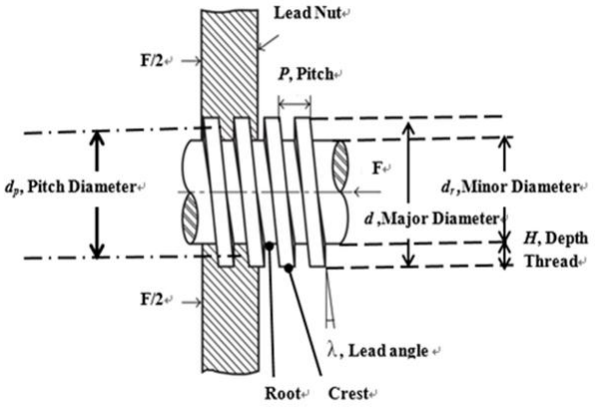


Fig. 3: Trapezoidal thread profile, Legends: d: Nominal or major diameter of screw, dr: minor diameter of screw, dp: pitch diameter, Lead angle, λ P: pitch, L: Lead, H: depth thread of screw.

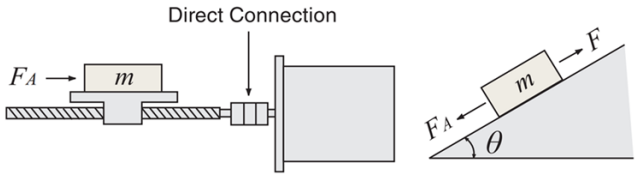


Fig. 4: The Free Body Diagram (FBD) of the proposed mechanism.

Figure 4 demonstrates the Free Body Diagram (FBD) of the proposed mechanism. The symbols F, F_A, m, g, θ, μ denote the force, external force, the total mass of the lead screw nut and load in kilogram (kg), gravitational acceleration (m/s^2), tilted angle (°) and the coefficient of friction of the sliding surface, respectively. The external force is due to clockwise (CW) and counter-clockwise (CCW) motion of DC geared servo motor that is coupled to the mechanism, that enables the flexion/extension of the finger. The total force experienced by the system must be below the compressive trust rating of the selected lead screw. In addition, a reasonable factor of safety should be included to the total force in order to ensure the system is able to withstand unpredicted dynamic loads.

Conversely, the torque, T necessary to drive the mechanism may be computed through Equation (2). F_T is the total force exerted on the finger phalanges, and P represents pitch of lead screw assembly. The computed torque should not exceed the torque rating of the selected motor. Similarly, a safety factor should also be included.

$$T = F_T \frac{P}{2\pi} \quad (2)$$

3.3. Control System

A lead screw nut, driven by a closed loop positioning system in the robotic exoskeleton-based device, consists of a small DC geared servo motor equipped with an optical encoder, connected to a lead screw mechanism with flexible coupling. The lead screw has a pitch of 0.4 millimeters (mm) and is coupled to the motor shaft with three different set of gear ratio which are 16:1, 64:1 and 4096:1. The different set of gear ratio is used owing to the different stiffness and severity experienced by the patients. In early acute phase patients, low gear ratio (16:1) is used as the system would actuate a high speed and less torque. Conversely, for chronic stage, high gear ratio (4096:1) is used to actuate with low speed and high torque in order to avert any form of pain exerted to the patients.

The DC geared servo motor is governed by a series of electrical pulse signals that are transmitted from the input module. Each pulse allows the motor to rotate a fraction of one revolution. This fraction is known as step angle, θ (°) and is defined by Equation (3), where n_s is the number of step angles for the motor.

$$\theta = \frac{360}{n_s} \quad (3)$$

The DC servo motor is directly connected to the lead screw with a gearbox. The angle of rotation of the lead screw is given by Equation (4).

$$A = n_p\theta \quad (4)$$

Here, A is the angle of leadscrew rotation in degrees, n_p represents the number of pulses received by the DC servo motor, and θ is defined as degrees per pulse.

The movement of the nut in response to the rotation of the lead screw is calculated in Equation (5).

$$S = \frac{pA}{360} \quad (5)$$

Where, S is the distance moved or position relative to the starting position in mm, p is the pitch of the lead screw in the unit of millimeter per revolution and A per 360 is the number of revolutions of the lead screw.

From the equations, the number of pulses, n_p required to move a predetermined position can be expressed in Equation (6).

$$n_p = \frac{360S}{p\theta} \quad (6)$$

The pulses are transmitted at a certain frequency, which drives the leadscrew nut at a specific velocity. The rotational speed of the lead screw, N depends on the frequency of the pulses as defined in Equation (7).

$$N = \frac{60 f_p}{n_s} \quad (7)$$

Here, N is the rotational speed in the unit of revolution per minute, f_p is pulse frequency in the unit of pulses per seconds.

The nut travel speed in the direction of the lead screw axis is determined by the rotational speed as defined in Equation (8).

$$v_t = f_r = Np \tag{8}$$

Where v_t is the lead screw nut travel with speed in millimeter per minute, it can also be considered as feed rate, f_r and p is the pitch of the leadscrew in millimeter per revolution.

The proposed prototype was developed with three control modes, i.e., active assisted, passive and active mode. Different control modes are available to cater for the different levels of spasticity. The state diagram of the system is illustrated in Figure 5.

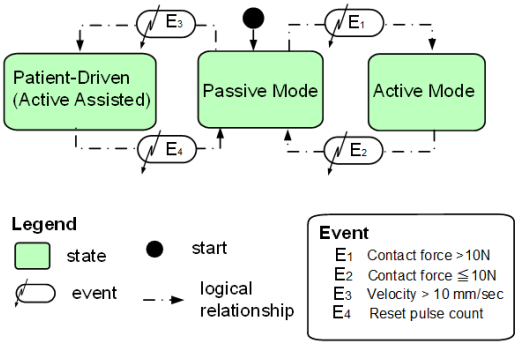


Fig. 5: State diagram for a foolproof robotic exoskeleton-based system

For the passive training mode, the proposed system will guide the extension and flexion motion for patients who does not possess any form of voluntary hand and finger movement. For this stage, the patient's hand and finger are placed in a fixed position of the device with the aid of a Velcro strap. The active training mode is made available for patients that does not require the assistance of the device to perform typical movements as their motor skills are almost recovered. In the event that the patient attempts to move their finger or hand, the readings of the electromyography (EMG) sensor increases to exceed a threshold value. However, if the readings do not exceed the threshold value, it suggests that the user could not complete either the passive and active training mode. Conversely, the active assisted or patient-driven mode is based on the movement intention for patients from the EMG readings with minimal voluntary hand and finger movements.

3.4. Risk Management Precaution Consideration

Safety and risk management is one of the most vital component as such system involves in the interaction between humans and collaborative robot to promote motor relearning. The proposed system is equipped with both software and hardware emergency stop functions to avoid any untoward incidents to occur especially to the patients during the rehabilitation session. Moreover, the electronics, circuitry and the transmission components are sealed off in an enclosed. The sharp edges of the device is also rounded off as a safety precaution to both the patient as well as the physiotherapist.

4. Evaluation Measurement

4.1. The Range of Motion Measurement

The proposed system is designed to assist rehabilitation of the Metacarpal Phalangeal (MCP) and Proximal Interphalangeal (PIP) joints allowing the system to be as compact as possible. The quantification of joint angles of the MCP and PIP is attained via image processing technique. Eight color-based segmentation markers are overlaid to the left hand with the thumb and index finger, based on the position of MCP, PIP and Distal Interphalangeal (DIP) joints of a healthy subject as shown in Figure 6. A stereo camera optical system is used to record the motion. The subjects are required to imitate the stretching movement during rehabilitation sessions as well as performing gripping motion with a cylindrical object with a diameter of 50 mm. DIP, PIP and MCP joint angle of the index finger, MCP and IP joint angle of thumb finger are assessed. The joint angle is estimated through the dot product formulation demonstrated via Equation (9) and Equation (10).

$$\underline{A} \cdot \underline{B} = |\underline{A}||\underline{B}| \cos\theta \tag{9}$$

$$\theta_1 = \cos^{-1}\left(\frac{a_1 b_1 + a_2 b_2 + a_3 b_3}{\sqrt{a_1^2 + a_2^2 + a_3^2} \cdot \sqrt{b_1^2 + b_2^2 + b_3^2}} \right) \tag{10}$$

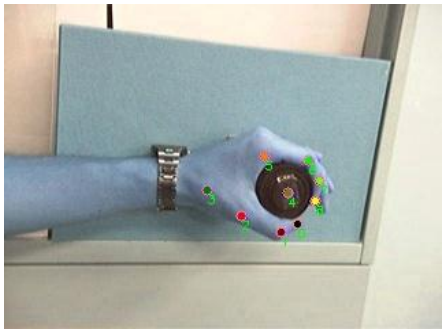
The joint angle, θ is located between two position vectors, i.e., $\underline{A}$ and $\underline{B}$. Whereas a_1, a_2, and a_3 are the position vector elements of vector $\underline{A}$, while b_1, b_2, and b_3 are the position vector elements of vector $\underline{B}$, respectively. The vectors are projected from the position of color markers in 3D. As for the index finger, the vector of the MCP and PIP joints will result to the joint angle of the MCP while vector of the PIP and DIP joint will result to the joint angle of the PIP.



Fig. 6: Image processing based on markerless motion capture analysis using the calibrated stereo camera to determine the range of motion normal fingers.

4.2. Reaction Force Measurement

Four healthy subjects (20-year-old males) were recruited to evaluate the functionality of the proposed system. The grasping force of subjects were measured prior to the functionality test. Figure 7 depicts the results obtained from the measurement. Three fingers namely thumb, index finger and middle finger were measured by means of five force sensors (Flexi Force A201, Nitta Industries Co., Ltd.) that are positioned in tandem with the direction of the grasping force [5]. The sensors are positioned between the IP joint and the MCP joint of thumb finger, between the MCP and the PIP joint of the index finger, between the PIP and the DIP joint of the index finger, between the MCP and the PIP joint of the middle finger and between the PIP and the DIP joint of the middle finger, respectively (Figure.7). The subjects were instructed to grasp a cylinder with a diameter of 50 mm with a varying mass of 0.2, 0.3, 0.4, 0.5, and 1 kg, respectively.



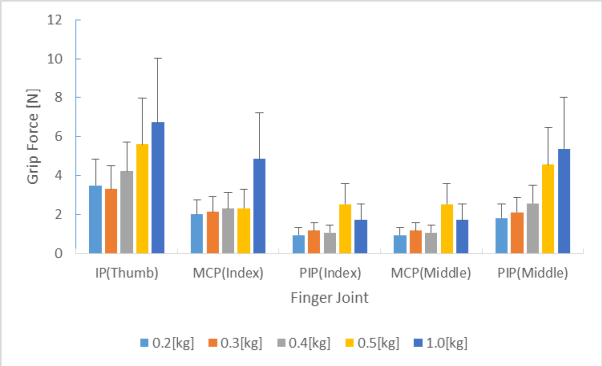


Fig. 7: Reaction force recorded using force sensor during grip motion analysis according to finger joints

4.3. Motion Control Implementation

The DC geared servo motor is equipped with a rotary encoder. The DC servo motor can be positioned based on the encoder pulse signal from 0 to 360 degrees. However, the implementation for finger motion was only focused within the range of 0 to 190 degrees. PWM signals sent to the DC servo motor are translated into position commands by the feedback circuitry inside the servo. Once the servo is commanded to rotate to a certain position, the motor will rotate until the rotary encoder reads and attains the value of the corresponding commanded position. Figure 8 shows the ON-OFF control based on the input response of rotary encoder during the flexion movement.

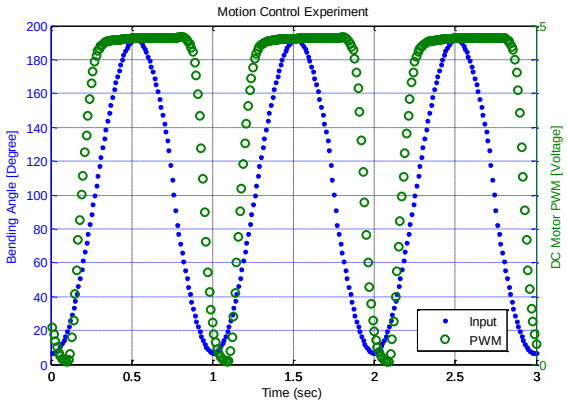


Fig. 8: ON-OFF Control based on the input response of bending angle from flexion movement.

4.4. Validation Experiment

The primary objective of the validation experiment is to appraise the pressure sensation of the palm after the extension and flexion motion training with the proposed system has been carried out. This is performed to identify and scrutinize the distribution of the sensory points of the palm tactile sensation as there are sensory receptors that are sensitive towards pressure and touch [16]. The experiment was performed on a 10 mm by 10 mm square scale on the palm [12] (Figure 9). The test is conducted by utilizing three different types cylindrical probes that is made of brass with a diameter of 0.8 mm that is pushed on the palm for 100 times. The experimental setup for the validation experiment is depicted in Figure 10. The motion of the probe (up or down) is governed by the rotation of a DC motor. In the event the probe touches the palm, no further movement will transpire as the subject sense the stimulation.

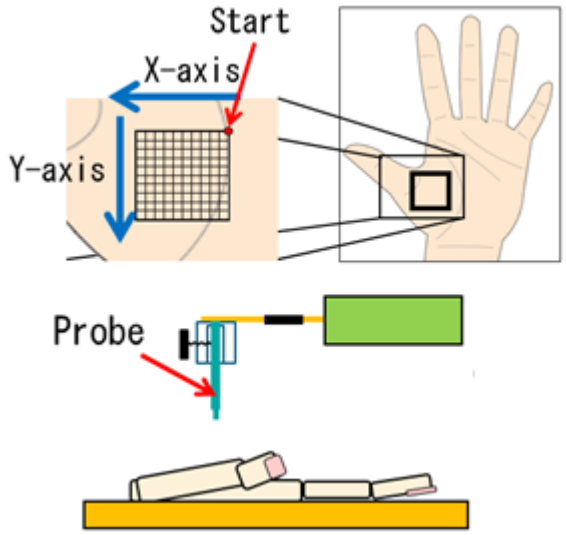


Fig. 9: Experiment setup to validate the recovery level of sensory area on the palm

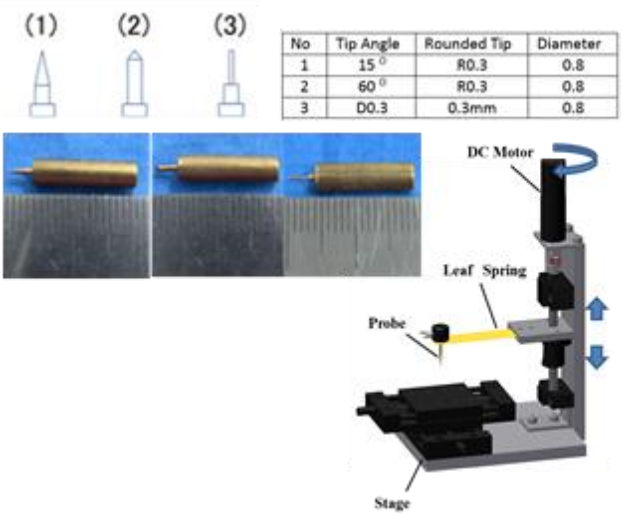


Fig. 10(a): Experiment setup to validate the recovery level of sensory area on the palm

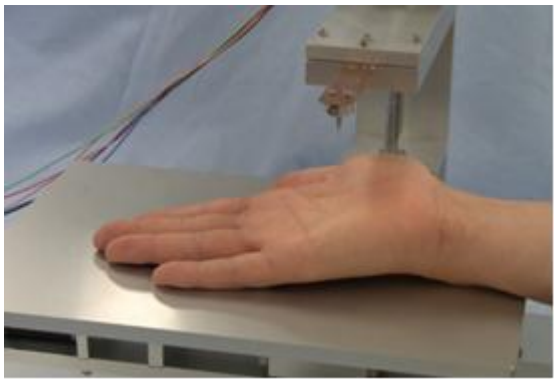


Fig. 10(b): Experiment setup to validate the recovery level of sensory area on the palm

The following inclusion criteria was considered in the present investigation (1) Four female and five male subjects (healthy) were recruited from the Rehabilitation Robotics Lab, Shibaura Institute of Technology, Japan; (2) Velocity of Probe: motor speed of 0.58 mm/s (constant voltage); (3) Factor Error: with or without glove; and (4) Shape of Probe : 3 different types (as depicted in Figure 10(a))

The measurement was repeated three times in the same exact location. The evaluation of the measured data was optimized by using the Mahalanobis-Taguchi System (MTS). Figure 11(a)

and Figure 11(b) exhibit the model of the tactile space of the palm and the dorsal part of the hand, respectively. In the event that the palm is pressed by the probe, the red points indicate the area is responsive towards the stimulus, conversely, the blue points suggest that the area is unresponsive towards the stimulus. It was established form the present investigation that the palm is more sensitive to stimulus (100%) in comparison to the dorsal part of the hand (92%). This observation could plausible due to the skin glabrous (hairless) nature of the palm that is sensitive towards touch. Moreover, it is worth noting that there exist more sensory receptors i.e., Meissner's corpuscles, Merkel's disks, and Ruffini's corpuscles amongst others under the skin of the palm than the dorsal part of the hand [17].

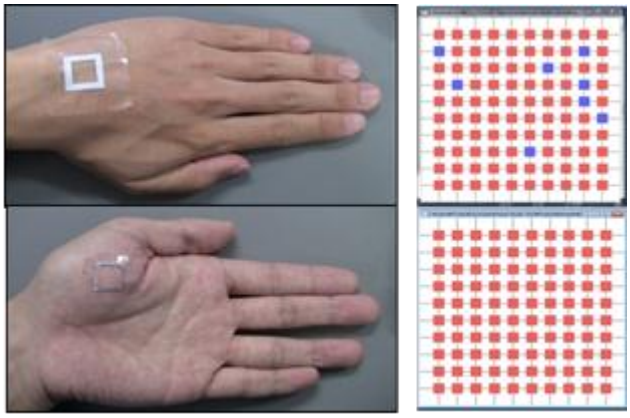


Fig. 11: (a) Experimental results of the evaluation of the sensory area of the dorsal part of the hand (b) Experimental results of the evaluation of the sensory area of the palm

5. Conclusion

The paper discussed on the development of a hand rehabilitation device system that can improve the motor functions and sensory receptors of the hand. The system is based on a novel lead screw driven mechanism coupled with a DC geared servo motor that enables the actuation of the flexion and extension of the finger. The system allows for three different modes of control, i.e., active assisted, passive and active. In addition, a sensory module is also included in the proposed system to evaluate the sensory level of the affected limb upon carrying out the rehabilitation session. Nonetheless, it is worth noting that the proposed device has several limitations. The system should further adopt adaptive control strategies to tailor towards the capabilities of the patients. Moreover, further investigation focused on the rehabilitative effect of the proposed device will be undertaken by means of working with targeted stroke patients to evaluate the efficacy of the system.

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