FINGER CONTRACTURE PREVENTION SYSTEM DEVICE FOR EARLY POST STROKE REHABILITATION

Mohd Nor Azmi Ab Patar[1,2*], **Hokyoo Lee**[1], **Takashi Komeda**[1], **Jamaluddin Mahmud**[2]
[1]*Graduate School of Engineering and Science, Shibaura Institute of Technology, Omiya, Japan*
[2]*Humanoid Robot and Bio-Sensing Center, Faculty of Mechanical Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia*
*For correspondence; Tel. + (60) 183967319, E-mail: azmi.patar@gmail.com

ABSTRACT: *Physical rehabilitation is key for recovering motor control and function for patients with neurological disorder. 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 paper 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. It is able to assist the subject in flexion and extension movements. Main specification of the device includes a differential system with a current sensing element and a lead screw mechanism which allows independent movement of each finger using small actuators. The device is safe, easy to deploy, integrated with sensing element and offers multiple training possibilities. Further it has been observed to offer an objective and reliable instrumented tool to monitor patient's progress and accurately assess their motor function. Therefore, the device has great potential to be implemented for an individualized rehabilitation session for patients who have to undergo therapy in their home.*

Keywords: Finger Contracture, early acute, post stroke rehabilitation, real-time quantitative monitoring, prevention system

1. INTRODUCTION

In recent years, strokes have been one of the third largest causes of death in the world behind cancer and heart disease. There are many stages in a stroke and the main focus is in acute patient care, which is to perform passive range of motion to prevent muscle contractures [1]. In many countries, finger disabilities and injuries are mostly caused by strokes [2]. A healthy finger is an important aspect in a human's daily life. However, abnormal conditions, such as disabilities, injuries, deformation and diseases of the hand, can impact patients' in their activities of daily living (ADL).

Post stroke rehabilitation at the acute stage usually starts with one-to-one therapies conducted by physiotherapists in acute-care clinics [3]. To reduce the total cost of the treatment, patients are typically sent back to their homes when their ability to walk improves even though they have not fully recovered the function of the upper extremity, especially the distal segments such as hands and fingers. In many cases, it will take a long period of time to recover the function of flexion, extension, abduction and adduction of the fingers [4]. Thus, leaving the fingers in flexed or extended positions leads to difficulties in ADL such as feeding, dressing, grooming and personal hygiene.

One of the approaches in solving finger disabilities and injuries is undergoing finger rehabilitation [5]. The finger rehabilitation is a physiotherapy approach which aims to partially or entirely recover the finger motor function of the patient [6]. The physiotherapy approach is based on how to manipulate the paretic limb which is supported by a physiotherapist. The approach may be accomplished with daily and frequent rehabilitation of up to several months, depending on the severity of the fingers and the condition of the patient [7]. In order to recover to a normal life, the patient requires time and must undergo consistent rehabilitation, assisted by a physiotherapist [8].

However, since the number of physiotherapists is limited, it will not be easy for the patient to do the rehabilitation that requires support from a physiotherapist at all times. Due to the limited numbers of physiotherapists [9], there are needs to develop a rehabilitation system where patients can conduct their own rehabilitation exercises without the aid of therapists [10].

Furthermore, most of the literature reviews on hand rehabilitation robotic devices focus on the recovery of motor functions, specifically the extension and flexion movements of the hand. However, there are limited established approaches or publications available on the recovery of the sensory functions of the hand. In other words, the recovery of the sensory functions of the hand has yet to be explored by researchers. Therefore, improvements in the sensory functions of the hand are just as crucial to the recovery of the motor functions of the hand.

In this paper, the development process of the design concept, simulation and the fabrication of the device were discussed. The initial prototype of the device was also included. Since the exoskeleton only performs flexion and extension through the mechanism, the modification of the exoskeleton was conducted in order to qualify as an index finger rehabilitation device. The design concept determined by these specifications was described in Section II. The choice of materials, the actuation system and the implemented control schemes were detailed in Section III. Experiments were conducted with the interface to evaluate its performance (Section IV).

2. SYSTEM REQUIREMENTS

After stroke, the survivors have different malfunctions which contribute to the impairment of hand and finger function such as muscle weakness and muscle stiffness which can limit the movement of agonists and antagonists muscles at multiple joints. The fingers usually locked in a flexed position and stroke patients cannot control finger motion with sufficient extension force. Therefore, it is a necessary for the robotic exoskeleton to train the extension function of the finger at an early stage of the motor function recovery program [11]. After taking care of the extension function, finger flexion needs to be trained to strengthen the weak muscles.

2.1. System Functionality

This section describes the specific functions [12] of the robotic system in rehabilitating the motor function of muscle in each finger of a human hand. The key function of a hand exoskeleton device is the ability to decrease the stiffness of the contracture finger. The stiffness of the muscle in human finger need to reduce according to the normal human finger orientation, thus the robotic exoskeleton must be able to reproduce the flexion and extension of the finger movement repetitively [13]. Besides, the device must be able to detect the angle of the flexion and extension in order to measure the trajectories [14] for index, middle, ring and small fingers while performing the movement. As shown in Figure 1, the sub-functions of the robotic exoskeleton consist of the ability to control angular velocity and producing a normal range of motion of the finger depend on each input angle on finger joint. The point of view from the occupational physiotherapist and the feedback from the healthy subjects are important to avoid incongruity during training session with real patients.

2.2. Robotic Exoskeleton Prototype Development

This project is a pilot study to improve the finger rehabilitation. The project starts with a mechanical design of exoskeleton for an index finger. The main idea of the design is to perform an extension and flexion of the finger based on mechanisms that can transmit the force from the actuators.

In this study, we investigated a new type of a robust hand and finger rehabilitation device which can control a human hand to do flexion and an extension motion. Our hypothesis by enforcing the correct flexion and extension motion, it can help patients with hand and finger muscle problems to close their hand and open hand correctly and improve healing. Most hand and finger devices for rehabilitation available on the market uses the passive control system. Unfortunately, the active control systems are costly and need a bigger space to install, not portable and not suitable to use at home.

Therefore, the current study for the first time attempts to produce a robust, low cost device employing an active control system with a DC motor integrated with lead screw mechanism. Figure 1 illustrated the overview system architecture in robotic exoskeleton where DC servo motor coupled with lead screw mechanism for index finger rehabilitation module.

An active actuation system consists of a DC servo motor integrated with lead screw mechanism has been developed to realize the functions in aforementioned criteria. The block diagram and system architecture of the control actuation system is illustrated in Figure 2.

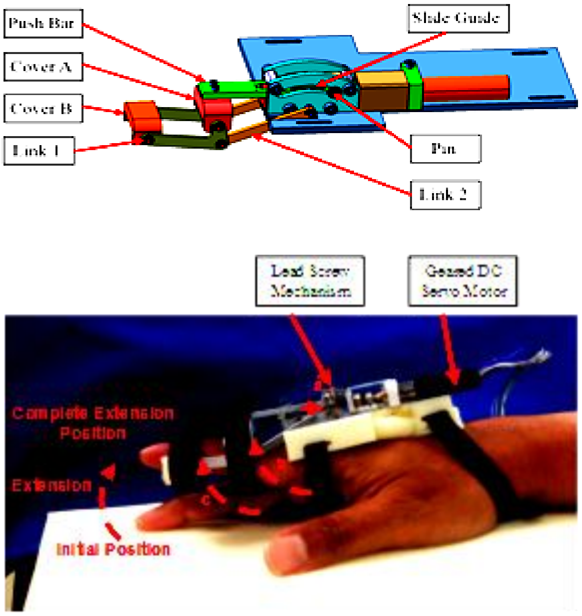


Figure (1) Overview system architecture in robotic exoskeleton where DC servo motor coupled with lead screw mechanism for index finger rehabilitation module.

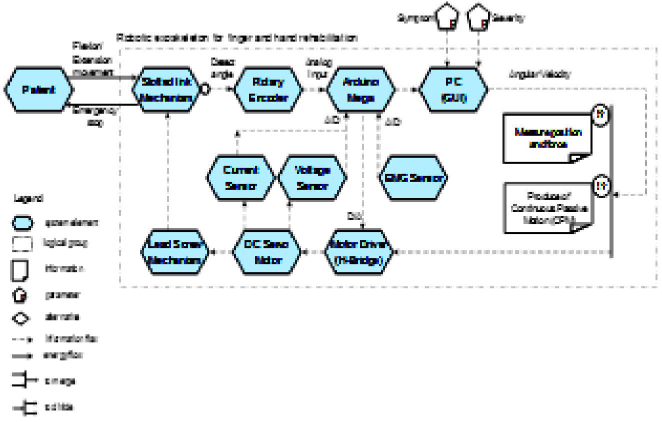


Figure (2) Block diagram and system architecture of a control system in robotic exoskeleton where DC servo motor integrated with lead screw mechanism for finger and hand rehabilitation.

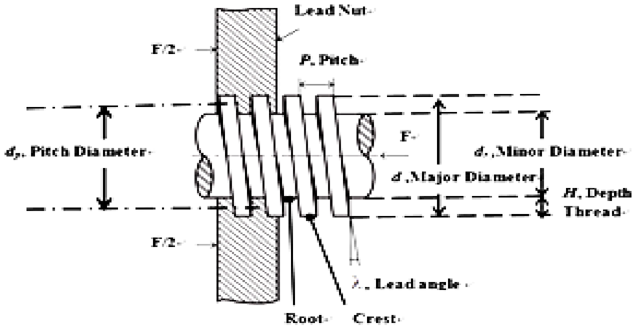


Figure (3) Trapezoidal thread profile, Legends: d: Nominal or major diameter of screw, dr: minor diameter of screw, dp: pitch diameter, Lead angle, λ , P: pitch, L: Lead, H: depth thread of screw.

3. SYSTEM IMPLEMENTATION

3.1. DC Servo Motor

A DC servo motor acts as an actuator to drive the lead nut in lead screw mechanism in order to repetitively flexion and extension a human finger. When the actuator actuates the mechanism, lead screw will convert rotary input motion to linear output motion. The nut is constrained from rotating with the screw, thus as the screw is rotated the nut travels back and forth along the length of the shaft. Depending on the level of severity, the DC servo motor provides a reaction force against the force given by the subject’s finger.

To further realize the real training session, variations in stiffness and angular velocity is added by applying the torque control via DC servo motor to provide continuous passive motion (CPM) helping subjects reduce joint stiffness of the fingers together and individually.

3.2. Lead Screw Mechanism

A lead screw typically is a linear actuator based mechanism that converts an oscillating input torque in the form of an angular displacement into a desired linear displacement. The major benefits of using a lead screw mechanism in linear actuators are inherent mechanical advantages, high stiffness, high strength, and a cost-effective package. Lead screws fall under the category of power screws and can be classified into ball screw, acme/trapezoidal screw and roller screw. A ball screw mechanism, consists of a ball screw and a ball nut with recirculating balls providing rolling contact between the nut and the screw. An acme or trapezoidal screw, which hereafter will be addressed as lead screw, consists of a screw and a nut that are in sliding contact with each other. The screw is generally made up of alloy steel with a trapezoidal thread form, and the nut is typically made of an engineering polymer or bronze. The contact between the nut and the screw is a sliding contact. Therefore, friction plays a very important role in the performance and efficiency of the mechanism. These screws offer low efficiencies due to the relatively greater coefficient of friction in sliding. Figure 3 illustrates trapezoidal thread profile of lead screw mechanism. Consider that a single thread of the screw is unrolled for exactly one turn. When determining the amount of input torque required to produce an amount of output linear force, there are many factors to consider. The following equations provide a practical approach in making force and torque calculation in lead screw mechanism. Equation (1) was used to approximate the total force involving in the system.

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

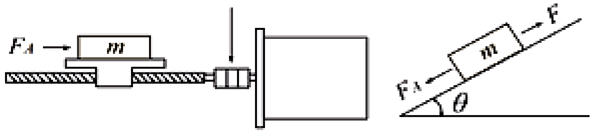


Figure (4) Free Body Diagram (FBD) of lead screw mechanism with force action reaction effect.

Figure 4 demonstrates Free Body Diagram (FBD) of lead screw mechanism with force action reaction effect. Here F is force of moving direction, F_A represents external force, m is the total mass of the lead screw nut and load in kilogram (kg), g is gravitational acceleration, μ is the friction coefficient of sliding surface, and θ is tilted angle in degree. External force due to clockwise (CW) and counter clockwise (CCW) motion of DC servo motor shaft direct connection with coupling in horizontal applications which is the requirements in extension and flexion of the finger. Friction force required to overcome all of the friction in the load bearing system with a low friction bearing system, this can be negligible. The total force must be below the compressive trust rating of the lead screw chosen. A modest factor of safety should be added to the total force. Thus, unexpected dynamic loads are safely handled by the lead screw mechanism system.

The torque, T required to move the mechanism system can be approximated by Equation (2), where F_T is total force exerted on the finger phalanges, P represents pitch of lead screw assembly.

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

The torque required should be well below the torque rating of the motor chosen. A modest factor of safety should be added to the torque required, hence unexpected dynamic loads are safely handled by the driving system.

3.3. Safety Factor Consideration

Safety is the most important element for robotic exoskeleton which involve in the interaction between machine and humans. Both software and hardware precaution implemented as emergency stop to prevent any injuries and damage neither to the system nor the users during the rehabilitation session. Limit switches as a mechanical stop and emergency switch triggered by subjects and a physiotherapist can stop the device motion anytime. All electronics and the drive train mechanism have been sealed off in an enclosed box and external parts have been rounded for safety purpose.

4. EVALUATION MEASUREMENT

4.1. Range of motion measurement

At the early stage of the development, we try to develop the device using only an actuator to assist the MetaCarpo Phalangeal (MCP) joint and Proximal Interphalangeal (PIP) joint. By that way, we can reduce the size of the device as compact as possible. Image processing based measurement is used to measure the relationship between MCP joint angles and PIP joint angle either in the situation of extension or flexion condition. Figure 5 illustrates two images taken from the motion analysis experiments. By using this method the range of motion of the device itself can be determined.

Eight color markers based image processing are attached to a left hand with thumb and index finger, according to the position of MCP joint, PIP joint and Distal Interphalangeal (DIP) joint of the healthy subject to measure the relationship between MCP joint angle and PIP joint angle in the extension or flexion motion. Then, the 3D position of color markers is estimated and recorded using a stereo optical motion capture measurement system. In the experiment, the healthy subjects need to perform the flexion and extension motion and also at the same time need to grasp an object which is a cylinder 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 estimated. Figure 5 indicates the position of the color marker setup of the each joint accordingly. We use a mathematical approach called the dot product where the calculation of the angle joint between vectors is estimated. The joint angle can be extrapolated from Equation (9) and approximated by Equation (10).

$$\underline{A}\cdot\underline{B}=|\underline{A}||\underline{B}|\cos\theta \qquad (9)$$

$$\theta_1=\cos^{-1}\left(\frac{a_1b_1+a_2b_2+a_3b_3}{\sqrt{a_1^2+a_2^2+a_3^2}\cdot\sqrt{b_1^2+b_2^2+b_3^2}}\right) \qquad (10)$$

Here θ is a joint angle, which is located between two position vectors, $\underline{A}$ 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 $\underline{B}$. These vectors are projected from the coordinate position of color markers in 3D space orientation. For index finger, vector of the MCP joint and vector of PIP joint will make the joint angle for MCP joint angle while vector of PIP joint and vector of DIP joint will make the joint angle for PIP joint angle.

4.2. Validation Experiment

The objective of the validation experiment was to evaluate the pressure sensation on the palm after extension and flexion motion training with exoskeleton based robotic. Moreover, the experiment also identified and examined the distribution of the sensory points of tactile sense that exist on the palm.

There are sensory receptors on the skin with a somatic sensation, which are very sensitive to pressure and touch stimulation [15].

The experiment was carried out on 10 mm 10 mm square scales on the palm [11] (Figure 6). Three different types of cylindrical brass rods (probes) with a diameter of 0.8 mm were used. The probe was pushed 100 times on the palm. The validation experiment setup is shown in Figure 7. The probe for the measurement system can move up or down due to the rotation of the DC motor. If the probe touches the palm, the movement will stop when the subject feels the stimulation.

Figure (5) Image processing based marker less motion capture analysis using calibrated stereo camera to determine range of motion normal fingers.

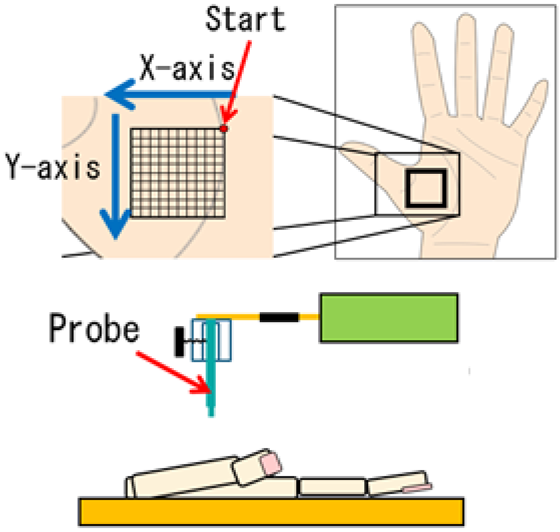
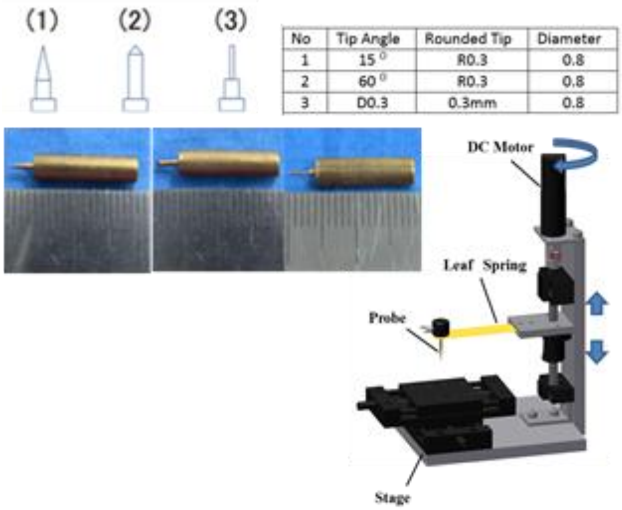


Figure (6) Experiment setup to validate the recovery level of sensory area on the palm



No	Tip Angle	Rounded Tip	Diameter
1	15 °	R0.3	0.8
2	60 °	R0.3	0.8
3	D0.3	0.3mm	0.8

Figure (7) Experiment setup to validate the recovery level of sensory area on the palm

The inclusion criteria for this study included (1) Healthy Subjects recruited from the Rehabilitation Robotics Lab, Shibaura Institute of Technology, Japan (Female; n = 4, Male; n = 5); (2) Velocity of Probe: constant voltage of motor speed (0.58 mm/s); (3) Factor Error: with or without glove; and (4) Shape of Probe : 3 different types.

The measurement was repeated three times in the same place, with the X-Y axis moving constantly. The evaluation of the measured data was optimized by using the Mahalanobis-Taguchi System (MTS). The MTS is a diagnostic and predictive tool for analyzing patterns in multivariate cases.

Figure 9(a) illustrates the model of the sensory area of the palm. Figure 9(b) shows the sensory area of the dorsal part of the hand. When the area of the palm was pressed, the red points indicate the area that reacted to the stimulus. The blue triangle indicates the area where there was no reaction to the stimulus. The palm is more sensitive to stimulus (100%) compared to the dorsal part of the hand (92%). The skin of the palm is glabrous (hairless) and more durable, yet sensitive to touch. There are more touch and pressure receptors such as Meissner's corpuscles, Pacinian corpuscles, Merkel's disks, and Ruffini's corpuscles under the skin of the palm than under the skin of the dorsal part of the hand .

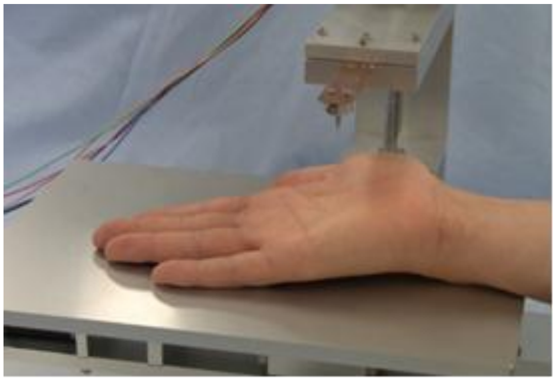


Figure (8) Experiment setup to validate the recovery level of sensory area on the palm

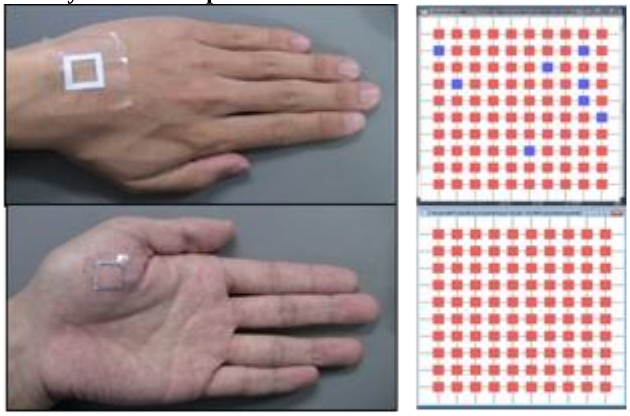


Figure (9) (a) Experimental results of the evaluation of the sensory area of the dorsal part of the hand (b) Experimental results of the evaluation of the sensory area of the palm

5. CONCLUSIONS

A hand rehabilitation device system that can improve the motor functions and sensory receptors of the hand has been developed. A potentiometer and force sensor allowed the patient’s progress to be monitored during the training session [16].

An active actuation control strategy, integrated with geared DC servo motor and lead screw mechanism has been developed to actuate the flexion and extension of the finger in rehabilitation. By independently controlling the DC servo motor and utilizing the behavior of a lead screw mechanism, the system is provided with a range of bandwidth to operate in different modes. In this paper, a robotic rehabilitation device that assists stroke patients in recovering their extension and flexion motions of motor functions was proposed. Also, a novel patient-driven mode based on the intention movement from the patients detected using EMG sensors was proposed in order to engage directly in neuroplasticity. In the proof of concept study conducted by therapists and healthy subjects, it was found that the proposed device actuated with the patient-driven approach could be beneficial for hand rehabilitation.

Our proposed device has several limitations. It is needed to adopt adaptive control strategies for each patient’s capabilities. Further research focused on investigating the rehabilitative effect of the proposed device will be undertaken through working with targeted stroke patients and constructing solid evidence of the proposed device’s benefits using functional sensory devices to validate the level of recovery.

A new interface for hand and finger rehabilitation has been developed based on physiotherapy requirements in terms of the biomechatronics, safety factor, and comfort ability. An assessment of the grasping force (motor function) and sensory function of the hand will help physiotherapists to train the hand and fingers to function effectively. The device has been designed to be adaptable to most hands and was tested with healthy subjects.

However, the limitations of the study were the small sample size and the variation in the subject recruitment.

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REFERANCE

[1] M. N. A. A. Patar, T. Komeda, L. C. Yee, and J. Mahmud, “Model-based systems engineering of a hand rehabilitation device,” *J. Teknol.*, vol. 76, no. 4, pp. 101–106, 2015.

[2] O. Lambercy, Y. Kim, and R. Gassert, “Robot-assisted assessment of vibration perception and localization on the hand.,” *Disabil. Rehabil. Assist. Technol.*, vol. 8, no. 2, pp. 129–35, 2013.

[3] Mohd Nor Azmi Ab Patar, T. Komeda, C. Y. Low, and J. Mahmud, “System Integration and Control of Finger Orthosis for Post Stroke Rehabilitation,” *Procedia Technol.*, vol. 15, pp. 756–765, 2014.

[4] D. A. Nowak, “The impact of stroke on the performance of grasping: Usefulness of kinetic and kinematic motion analysis,” *Neurosci. Biobehav. Rev.*, vol. 32, no. 8, pp. 1439–1450, 2008.

[5] P. Agarwal, J. Fox, Y. Yun, M. K. O’Malley, and A. D. Deshpande, “An index finger exoskeleton with series elastic actuation for rehabilitation: Design, control and performance characterization,” *Int. J. Rob. Res.*, pp. 1–26, 2015.

[6] M. N. A. B. A. Patar, T. Komeda, J. Mahmud, and C. Y. Low, “Model Based Design of Finger Exoskeleton for Post Stroke Rehabilitation Using a Slotted Link Cam with Lead Screw Mechanism,” in *Industrial Engineering, Management Science and Applications 2015*, M. Gen, J. K. Kim, X. Huang, and Y. Hiroshi, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2015, pp. 95–103.

[7] P. Page, “Current concepts in muscle stretching for exercise and rehabilitation.,” *Int. J. Sports Phys. Ther.*, vol. 7, no. 1, pp. 109–19, 2012.

[8] M. N. A. bin Ab Patar, T. Komeda, C. Y. Low, and J. Mahmud, “Patient-Driven Hand Exoskeleton Based Robotic with Active Control System for Early Post Stroke Rehabilitation,” *Appl. Mech. Mater.*, vol. 799–800, pp. 1063–1068, 2015.

[9] P. Langhorne, J. Bernhardt, and G. Kwakkel, “Stroke rehabilitation,” *Lancet*, vol. 377, no. 9778, pp. 1693–1702, 2011.

[10] H. Tanaka, M. Yoshikawa, E. Oyama, Y. Wakita, and Y. Matsumoto, “Development of Assistive Robots Using International Classification of Functioning , Disability , and Health : Concept , Applications , and Issues,” *J. Robot.*, vol. 2013, 2013.

[11] M. N. A. A. Patar, T. Komeda, T. Mori, T. Seki, Y. Saito, J. Mahmud, and C. Y. Low, “Hand rehabilitation device system (HRDS) for therapeutic applications,” in *5th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics*, 2014, pp. 381–386.

[12] M. N. A. Bin Ab Patar, T. Komeda, and J. Mahmud, “Force assisted hand and finger device for rehabilitation,” in *1st International Symposium on Technology Management and Emerging Technologies (ISTMET)*, 2014, pp. 133–138.

[13] A. Rahim, A. Hakim, A. P. Mohd Nor Azmi, A. T. M. Amin, and J. Mahmud, “The Development of Finger Rehabilitation Device for Stroke Patients,” *Appl. Mech. Mater.*, vol. 393, pp. 604–610, 2013.

[14] A. Hamid, M. N. A. A. Patar, and M. A. Ayub, “Force Sensor Detection and Performance Evaluation of New Active System Ankle Foot Orthosis,” *Procedia Eng.*, vol. 41, pp. 510–515, 2012.

[15] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, “A survey on robotic devices for upper limb rehabilitation.,” *J. Neuroeng. Rehabil.*, vol. 11, pp. 1–29, 2014.

[16] M. N. A. Bin Ab Patar, M. H. Mohd Ramli, J. Mahmud, and A. H. Yusof, “Efficacy and Safety Testing of a New Biologically Based Design Ankle Foot Orthosis in Healthy Volunteer,” *Appl. Mech. Mater.*, vol. 110–116, no. 1–7, pp. 1953–1957, Oct. 2011.

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*For correspondence; Tel. + (60) 183967319, E-mail:azmi.patar@gmail.com