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Hand Exoskeleton for Rehabilitation of Stroke Patients (HERSP)

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Abstract

Stroke causes millions of people causalities every year while leaving many survivors with upper limb motor impairment. The treatment methods nowadays are mostly provided in hospitals or rehabilitation centers. However, there are very few hospitals providing them, so their accessibility is quite low. Moreover, the rehabilitation treatment fee is high due to the rehabilitation device's cost. Many post-stroke patients are left with disabling spasticity [12]; thus, some of them might not be able to attend such programs. This project presents a hand exoskeleton for rehabilitation of stroke patients (HERSP) designed to be suitable for all patients including those with spastic muscles. The extension mechanism provides wide range of motion and sufficient resistance for the passive rehabilitation which solves spasticity. The result shows that the ranges of motion (ROM) of the fingers are over the ROM needed to perform gripping.

***Keywords**:* Exoskeleton; finger; hand spasticity; rehabilitation; stroke

1. Introduction

Stroke occurs when blood supply to an area of brain is cut off or clogged. Those exact brain cells are deprived of oxygen and begin to die. Thus, after recovered, stroke patients lose abilities controlled by the affected area of the brain, which is usually a muscle control. Stroke causes long-term adult disability. In Thailand, there are new 154,200 stroke patients per year and 12,600 of them has died [1]. Those who survive from stroke have to suffer living with difficulties. Therefore, they need to be recovered as fast as possible to minimize the muscle disabilities [4]. Ability to control hand muscle movement are various depending on the stroke patients. Spasticity is usually found in stroke patients; it causes tension in the finger and makes patients' hands stay closed. Spasticity makes rehabilitation a lot more difficult and leads to pain in rehabilitation session as it resists the finger motion. Ignoring this problem will develop the resistance in stroke patient joints. A passive hand exoskeleton that is user-friendly will helps patient rehabilitate individually without occupational therapist.

The HERSP will be focused on designing and manufacturing a hand exoskeleton for post-stroke rehabilitation which can alleviate fingers joints spasticity and increase patient's range of motion (ROM) from the rehabilitation. The mechanism must provide full grip ROM with 0-80˚of DIP joint, 0-105˚ of PIP joint and 0-90˚of MCP joint, while passively extending user's hand in the neutral position.

This project will provide an alternative for stroke rehabilitation in Thailand. It not only aims to help the patients but it also reduces workload of psychotherapists. In addition, this project allows the stroke patients to rehabilitate at home which is significant due to the adequate amount of treatment center for stroke patient in Thailand.

This paper describes design and prototype of HERSP. In addition, we briefly reviews prior knowledge required to design HERSP including rehabilitation, biomechanics of hand.

2. Rehabilitation

The goal of rehabilitation is to improve function so that the stroke survivor can live their life less dependently. This can be accomplished by motivating the survivor to relearn impaired basic skills.

Rehabilitation should start in the hospital as soon as possible following a stroke, since it will be more effective that way [2]. Proprioceptive Neuromuscular Facilitation study suggests that repetitive motor activity help with motor learning and recovery [3]. Even after a short period of simple motor training, cortical rearrangements occur. This change reflects kinematic aspects of the practiced movement [4].

3. Biomechanics of human hand

Each hand consists of four fingers and one thumb. Each finger has three phalanges: Distal Phalange, Middle Phalange, and Proximal Phalange, while thumb has only two phalanges: Distal and Proximal. The phalanges are connected by joints called DIP and PIP, and the Proximal Phalanges are connected to Metacarpus with MCP joint. DIP, PIP, and MCP have ROM (range of motion) of 0- 85˚, 0-105˚, and 0-100˚ respectively [5].

Table. 1 Comparison of joints' range of motion while performing different hand motions

	Key	Pinch	Grasp	Grip
1. MCP	62˚ (+/-8˚)	58˚ (+/-7˚)	33˚ (+/-6˚)	72˚ (+/-12˚)
2. PIP	76˚ (+/-8˚)	76˚ (+/-13˚)	39˚ (+/-7˚)	78˚ (+/-5˚)
3. DIP	46˚ (+/-8˚)	33˚ (+/-12˚)	26˚ (+/-5˚)	50˚ (+/-5˚)
Total	185˚ (+/-20˚)	167˚ (+/-19˚)	96˚ (+/-14˚)	208˚ (+/-23˚)

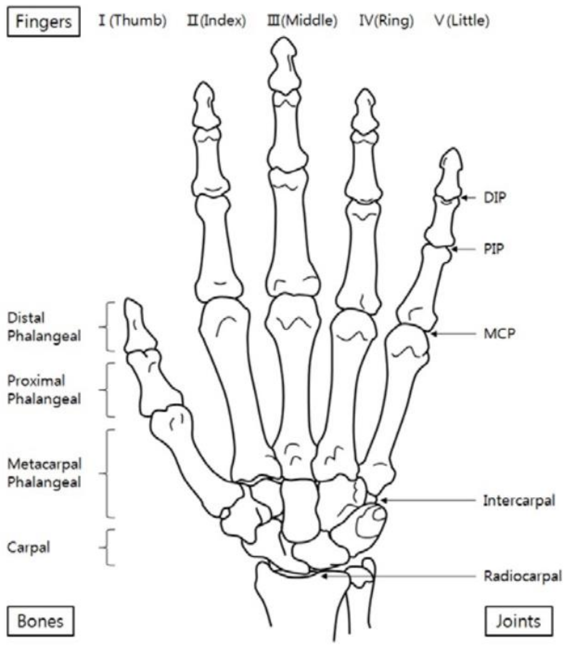

Fig. 1 Biomechanics of human hand [6]

4. Hand exoskeleton for rehabilitation

Hand injuries caused by a stroke give a huge number of patient difficulties in their lives. The injuries take very long to recover. Thus, hand exoskeletons for rehabilitation are designed and develop to reduce time needed and lower the cost of recovery. The efficiency of the rehabilitation is improved significantly.

4.1 Rigid frame exoskeleton

Rigid frame is the most common frame type for exoskeletons which is far better in case of controlling and the variety of mechanism design. The greatest advantage of using rigid-frame exoskeleton is that the force exerted on each joint can be measured and controlled at ease with force sensors. The position of each finger can be controlled by programmed controller, while the transformation matrix can be derived from Denavit Hartenberg parameters.

Even though the rigid frame is better at controlling the system, there are many drawbacks related to human compatibility, for instance, the problem with human fingers' biomechanics. Human fingers are simply divided into three phalanges. Rotation between the phalanges can cause interference between linkage and finger, if the center of rotations does not lie on the right position. Many designs have been published with the task of fixing this problem, for example, the sliding six-bar joint mechanism [7]

Another well-known rigid-framed exoskeleton is a passive exoskeleton. The passive exoskeletons do not need any actuators to operate. The very good example of a passive exoskeleton is Saeboflex [8]. Saeboflex is a device used mainly for rehabilitation of stroke patients which focuses on solving muscle rigidity problem. It is designed to be portable and user friendly; it can be easily worn with one hand, and that's why it is suitable for rehabilitation at home. The patient can put this device on their hand by inserting their finger to the tips cover one by one. The fingers will be stretched automatically by preloaded force from tension spring. The spring is fixed to the arm strap while the other side is attached to cables which transmits tension force to fingertips. The finger-links can be adjusted to make the cables align with fingers.

The device purposes are to open user's hand and to provide small ROM for grasping some objects (e.g. therapy balls). Total ROM of this device is about 15-20 degree because the finger caps completely restrict DIP joint motion.

Fig. 2 Saeboflex [8]

4.2 Soft exoskeleton

Soft wearable exoskeletons are very different from the rigid-frame exoskeletons because their frames are usually based on gloves which make them compact, lightweight, and comfortable to wear.

Since the rigid-framed exoskeleton can cause injuries in case of motor issues and uncomfortable sessions of rehabilitation, Bowden cables have been used to transmit power from the actuator to the mechanism part of exoskeletons by attaching tubes as a path for tendons on the glove as in Exo-glove [9].

However, tendon routing system has a few disadvantages; this system needs to operate with pretension of transmission cable to provide shorter response time and maintain stiffness of the joint. Pretension causes interference and makes device uncomfortable which can lead to injuries. Moreover, the force exerted on each joint cannot be measured because force sensors cannot be attached to the gloves directly.

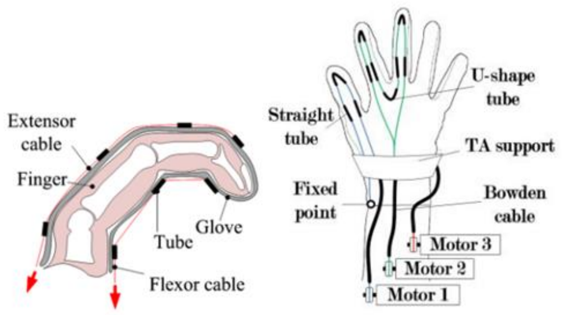

Fig. 3 Tendon routing in soft exoskeleton [10]

5. Extension mechanism conceptual design

Most of stroke patients have spasticity hand and it causes pain and resists fingers' movement. To alleviate stated problems, mechanism of the exoskeleton should be passive element and have full grip range of motion for advantages of rehabilitation.

Normally, the paths of motion of human fingertips are curvatures. From the experiments which show stereotypical trajectory of the fingertip, Humans tended to grab daily life objects with the same trajectory even though their sizes are different.

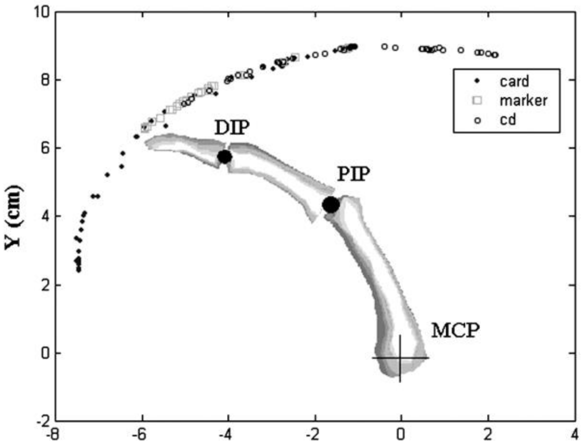

Fig. 4 Trajectory of tip of index finger in the x-y plane in 3 trials (grasping card, CD and marker) [11]

5.1 Mechanism Concept

To solve spasticity problem, patient's hand must be opened and held with their palm free to allow rehabilitation with objects, which passive mechanism can provide to reduce cost and weight. Moreover, with the portable size, patients can rehabilitate anywhere or just wear the exoskeleton to reduce the spasticity pain. To make the exoskeleton works with patient's hand effectively, the mechanism must allow user's hand do the gripping with no interference. Thus, soft exoskeletons with no rigid parts will cause a lot more interference with spastic hand

After reviewing related literature, design requirements and specifications are:

1. Passive mechanism
2. Passively extend fingers with the joint angle below 10˚, 20˚, 10˚ for MCP, PIP and DIP joint respectively
3. Full grip ROM with 80˚ flexion of DIP joint, 105˚ flexion of PIP joint and 90˚ flexion of MCP joint approximately
4. Palm free mechanism

From the design specifications, our design will be focused on improving to full grip ROM.

Consider a mechanism [8] and similar. This mechanism was designed to use in small ROM, to approach design specifications, force transmission must be changed, because the effort of user decreased when θ is increased as shown in Fig. 5.

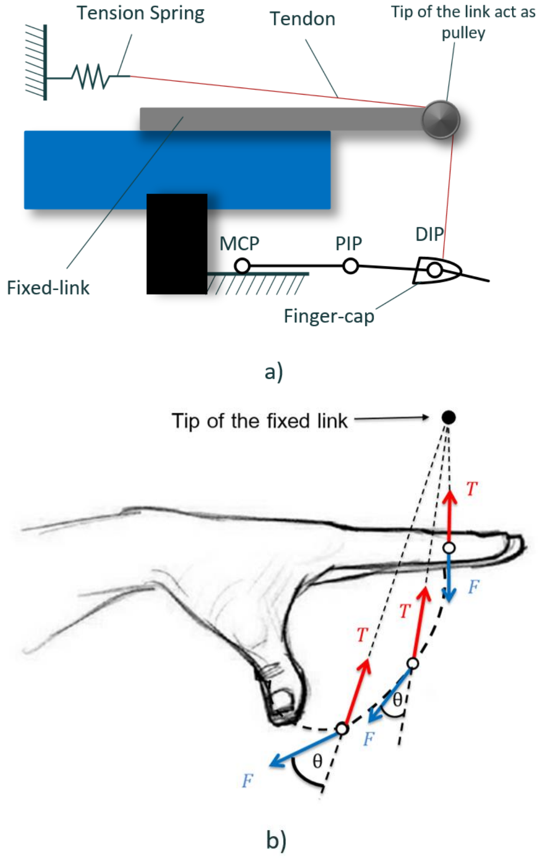

Fig. 5 a) Diagram of Saeboflex's [8] mechanism
b) Force analysis on Saeboflex's mechanism

This mechanism can work properly at small ROM because the exerted force must be in opposite direction with the string tension in order to stretch the tension spring, as gripping goes by, force the exerted force is decreased because of the increased θ (Fig 5b). Another reason is the finger interference with strings. While gripping, tension in the strings has the opposite direction with the fingers and it causes moment around DIP joints which leads to pain and hyperextension of the fingertips which is inappropriate.

To reduce interference and improve grip ROM, tip of the mechanism must follow tip of user fingers. The distance between the fixed link and the fingertip is not constant. From the previous problem, the mechanism must contain moving and expanding part. In the proposed design called HERSP (see Fig. 6). The mechanism has two links, first one is fixed on the exoskeleton body and can be adjusted for various finger lengths, and another can rotate with torsional spring resistance. The rotating link is used as a bush holder which pivots linear shaft with low friction. The linear shaft provides elongation of this mechanism; one tip of the shaft is attached with a guided curve link which allows the user's hand and the mechanism work with no interference.

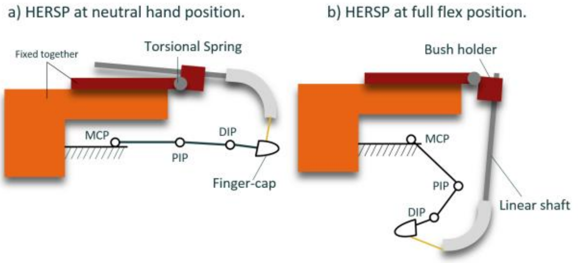

Fig. 6 HERSP's proposed mechanism

HERSP uses the moment of resistance (M_{ts}) from preloaded-torsional springs to maintain extension of user's hand. Force applied to user's fingertips by the finger-caps as illustrated in Fig. 7. While gripping, force exerted on finger-cap (F) which is parallel with the linear shaft ($F\cos\theta$) will provide extension of the mechanism (f_{bush} is the friction between bushing and linear shaft) and the force perpendicular to the distance d ($F\sin\theta$) generates moment around rotating point. The mechanism can provide gripping of every fingertips trajectory because the mechanism can freely rotate and extend with resistance. HERSP has two supports at the palm to maintain distance between fingers and the mechanism, and the other to make HERSP more stable and to open user's spastic wrist.

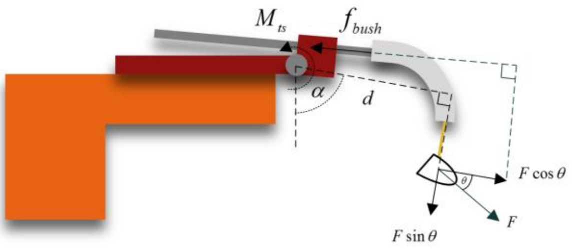

Fig. 7 Force analysis on the proposed mechanism

The mechanism provides 3-5 N force per finger (the torsional spring constant $k_v = 2.79 N.mm/\deg$) which is enough to hold spastic fingers.

The proposed mechanism maximizes the effort of the user because it follows the fingertip path in every gripping position. Thus, HERSP solves spasticity problem passively with full grip ROM and has a palm space to manipulate daily life objects.

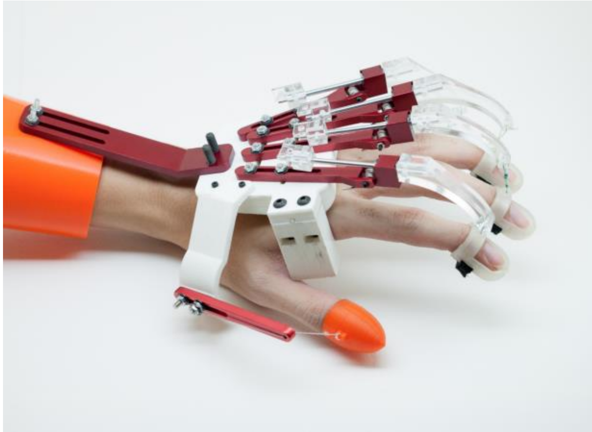

Fig. 8 HERSP holds user's hand at neutral position

7. Evaluation

In order to evaluate the performance of the device, we had a subject performed full grip motion (Fig. 9) started from extended position (Fig. 8) and take 4 snapshots throughout the cycle of motion. The observed data is then used to simulate the movement of each joint of the index finger via MATLAB.

Fig. 9 HERSP while provide full ROM of gripping

The result in Fig. 10 shows that HERSP can extend user’s hand with 9.8˚of DIP joint, 12.9˚ of PIP joint and 7.6˚of MCP joint, while provide full gripping with 72.1˚of DIP joint, 109.6˚ of PIP joint and 93.3˚of MCP joint. Thus, HERSP’s range of motion surpasses the design specifications.

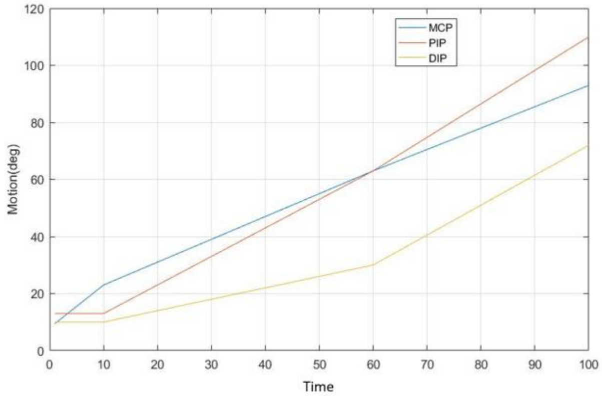

Fig. 10 Motion of each joints of the index finger throughout one cycle of full grip motion. (Four samplings were used to approximate the motion throughout a cycle)

The result in Fig. 11 shows that the device allowed the subject to completely perform full grip motion with 0-80˚of DIP joint, 0-105˚ of PIP joint and 0-90˚of MCP joint (approximately). Moreover, the observed path of full grip motion is very close to the normal one; thus, this device will make patients get used to a motion which is very close to the normal one.

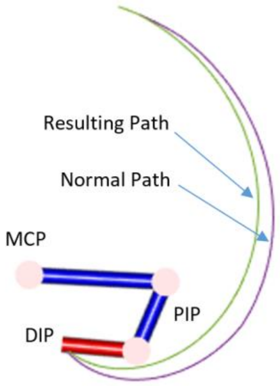

Fig. 11 Comparison between a normal path of motion to the resulting path of motion.

8. Challenges in further development of this device

Future works will be focused on apply HERSP to stroke patients in rehabilitation centers and hospitals in Thailand and we plan to develop the design to be more user friendly in appearance and comfortability

8.1 Comfortability

In the current design, there are some areas on the user hand that receive pressure while performing a rehabilitation tasks. It may cause chafing and discomfort for the users. The current design is weigh 230g. Thus, Alternative materials e.g. silicone or fabric can be replaced to make HERSP lighter and more comfortable.

8.2 Appearance

The materials used in the current design were chosen to test out whether it is functional or not; aesthetic factors are not yet considered in this design. In order to make it practical, the device must look safe and simple that the users will feel comfortable to use it without concerns.

9. Acknowledgement

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