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Research Article

THE DESIGN OF FUNCTIONAL MECHANICAL HAND DEVICE FOR SPASTICITY HAND FUNCTIONS

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ABSTRACT:
Stroke patients usually have disability on body opposite to damaged brain side. Recovery of upper limb is more difficult than lower limb. In addition, the distal parts of limbs are less recoverable and slower than the proximal parts. Moreover, in some cases, no longer recover any hand functions. They are not weakness only, but there are also spasticity that limit hand functions training after stroke. In moderate to severe spasticity, patients cannot open hand by self. So, the functional mechanical hand device is invented for assisting open spasticity hand, allowing patients to practice their hands by themselves every day. The main components of this prototype are springs separating of individual finger. The spring force acts finger extension. Individual finger spring has a unique force like the natural force proportion of any finger. That reason for each finger moves close to the natural fine movement independently while using the device. Also, the wrist of device is in suitable position for using hand. The simulation results of this prototype show that there is strength and safety in use. Especially, it is suitable for this patient type. The biomechanical test results in the healthy subject show that range of motion (ROM) of fingers are in the desired motion range. It is suitable to each task gestures of the finger.

Keywords: *Hand devices, Hand device design, Mechanical hand device, Hand function, Spasticity hand*

1. INTRODUCTION

Stroke remains a major global public health concern. The statistical report of the Ministry of Public Health was found that mortality and stroke rates continued to show an uptrend [1]. It is also the cause of disability. According to statistics, if the disability of cerebrovascular patients admitted to Siriraj Hospital was 95%, divided into 25% of those who had a similar recovery to normal, and 70% of patients will have decreased disability over time [2]. According to the disability statistics of Chulalongkorn Hospital, after ischemic stroke patients admitted to the hospital. The stroke patients were followed up for one year. It was found that 32% of the patients had a disability so severe. These patients needed someone to help them in their daily routine [1]. Usually, arm recovery is worse than the leg [3]. Stroke patients should begin practicing hand and arm movements that use various physical therapy techniques. Also, they may practice with other equipment to help move. Previous studies have shown that training results are noticeable for 3 months or more and should be continued for another year. The recovery phase of the hand and arm requires natural recovery and a learning-dependent process, including brain reorganization that can

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occur in subacute and chronic stages [4]. That is a long period since the onset of the disease. Besides, there are external factors such as the convenience of the caregiver and cooperation of patients, including time-consuming and expenses for both medical and travel expenses. These reasons may lead to lack of opportunity in the appropriate duration and frequency rehabilitation after stroke.

Currently, hands and arms are rehabbed by physical therapy techniques along with various equipment. As a result, the patients trained their hands and arms easier. Also, there was results improvement significantly [5-9] such as Mechanical hand devices and Powered assistive hand devices. Here we discuss mechanical hand devices in previous research that be used for hand posture and hand function such as SaeboStretch [10], dynamic hand-wrist orthosis with Ultraflex hinge [11], Dynamic splinting component [12], Dynamic hand splints [13], SaeboFlex [10], Customized dynamic hand splint [14], Dynamic outrigger extension [15, 16], Leaf spring glove [16], Dynamic wrist–hand orthoses [16]. However, devices for self-hand training of stroke with spastic finger flexor are rare and are not yet widespread in Thailand. Moreover, most of the equipment is foreign and expensive.

Therefore, the primary objective of this study is to develop a hand-training device that is designed for chronic stroke patients with partial hand and arm movement. They often have wrist and finger flexor spasticity. Moreover,the secondary objective is to study the strength and safety of device to suitable for patients this condition. We hypothesized that patients would practice their hands as often as possible by themselves. As a result, patients will have re-learning movement and stimulating brain function during chronic period after stroke. Besides, patient self-training will reduce the burden of caregivers as well.

2. METHODOLOGY

2.1 Material and design method

In conceptual design, the main functionality of the device is pulling the spastic finger flexors to extension. To prepare for handling object and stretching the fingers again to release the object from the hand. The device must be sized for each patient to ensure fit while using the device. Besides, the device can bear the maximum force acting on various parts of it. Initially, the maximum force acting on a component was calculated based on a reference study that studied finger size and force [17, 18]. In addition, the patient must be able to wear-take off or adjust the length for optimal use in each hand job with another hand. The device sub-function is divided into the following:

2.1.1 Power source

Power source is used to stretch the fingers by tension spring, one on each finger separately and each finger uses a different spring force. The force of each spring must be slightly greater than the flexor muscle of each finger to allow the patient who exerts force holding the desired size object without falling out of the hand. The spring force is predicted from a reference study that described the force sharing test of normal human's four fingers in a neutral line position on load cells. The results showed that the index and middle fingers have flexion force of 32%, 22% of the ring, and 14% of the little finger [19]. Then, it was calculated to divide the predicted synergy force level of stroke's finger flexors with moderate to severe spasticity from a reference study. That simulated a station where patients reached for the ball on the monitor and noted flexor synergy forces from load cell in the handle [17]. These two studies became the maximum-predicted synergy force in each finger of moderate to severe flexor spasticity patients as shown in Table 1. Or it can be called the stiffness of the spring extension. That can be used to find a suitable spring for each finger pulling.

Table 1: Grade of predicted extension spring or stiffness of extension spring (Unit = N.)

Fingers	Gr.1	Gr.1+	Gr.2	Gr.2+	Gr.3	Gr.3+	Gr.4
Thumb	4.000	8.000	16.000	20.000	24.000	28.000	32.000
Index	2.500	5.000	10.000	12.500	15.000	17.500	20.000
Middle	2.500	5.000	10.000	12.500	15.000	17.500	20.000
Ring	1.732	3.465	6.930	8.663	10.395	12.128	13.860
Little	1.103	2.205	4.410	5.513	6.615	7.718	8.820

Gr; Grade of extension spring

2.1.2 The force transmitter

The force transmitter pulls the fingers to extension. Using a wire rope connected to the end of the spring on the proximal side. The distal side is connected to the thimble that is made of Thermoplastic Polyurethane (TPU) 3D printing. It is thin but tough. It can resist the force of the fingertips and do not press on the finger's patient to be injured in any way. Also, another part made of TPU is spring tube. That prevents the spring breaking. Wire ropes distal ends are through the holes of the Polylactic acid (PLA) 3D printing plastic. These are the finger parts that put the eyelet inside the hole to reduce the friction of the wire rope and the plastic pieces. The base of the forearm and hand is designed according to the anatomy and biomechanics of the wrist. Two types of plastics are used as the

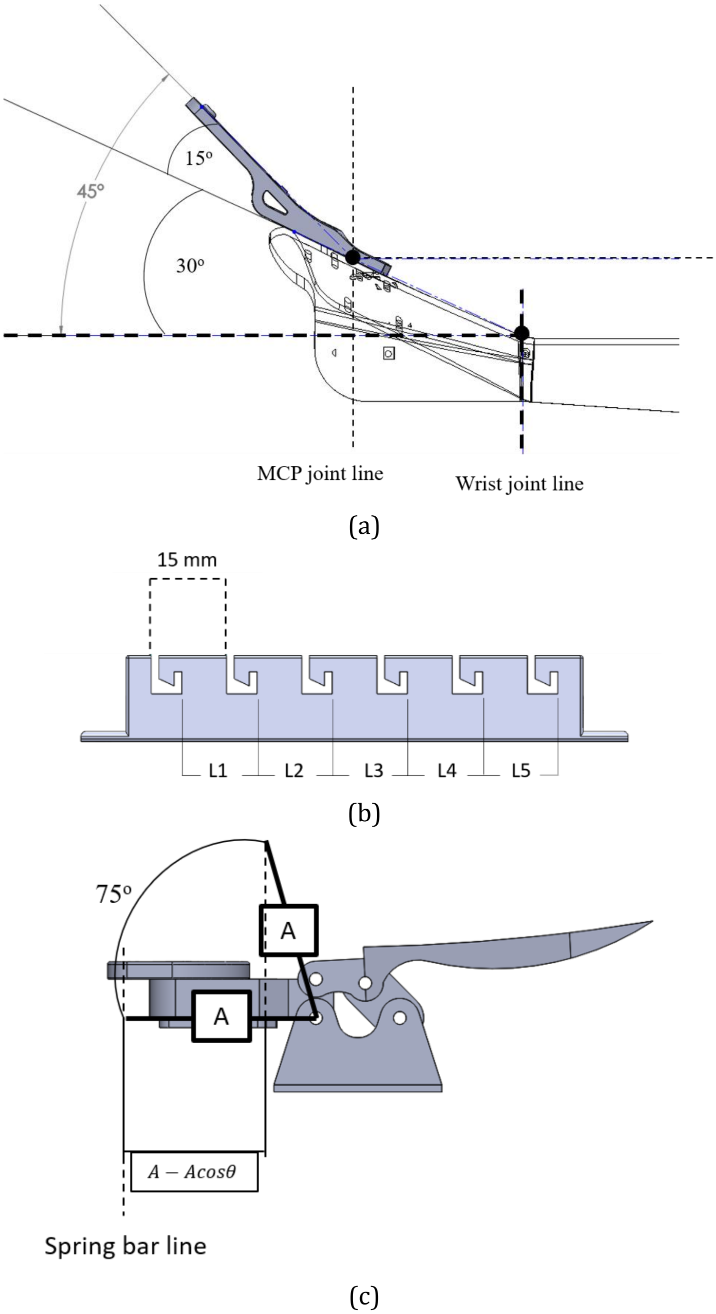


Fig. 1. Show the finger and wrist angle of forearm and palm base with a piece of the middle finger (a), the length of each lock in mm and number of lock position. (b), and the opening length of the toggle clamp to increase the spring elongation (c)

main materials of this base. *i*) Thermoplastic (Klarity Medical and Equipment Co., Ltd.) which can be immersed in hot water and molded according to the specific size of the forearm and palm for each person. It is designed to be in proper posture for hand function position in 30° wrist extension approximately. *ii*) PLA 3D printing is used for various components such as simulated finger bone parts that is connected to the end of the distal palm base. It is in the extension position 15° of metacarpophalangeal (MCP) joints according to the anatomy and biomechanics as shown in Fig. 1 (a). The finger parts can be adjusted the length to suit each person a little more. The sling fixing and locking parts located on the forearm are also made from PLA 3D printing. The forearm and palm base are tightened to the patient's forearm and palm with a strap belt.

2.1.3 Mechanism for holding and easing the pull finger force

The mechanism is designed as a lock that attaches to the spring of four fingers and thumb. To get the appropriate finger extension for the object sizes.

According to the principle of the force in the spring (F), which is proportional to the length of the spring (x), as in Equation (1).

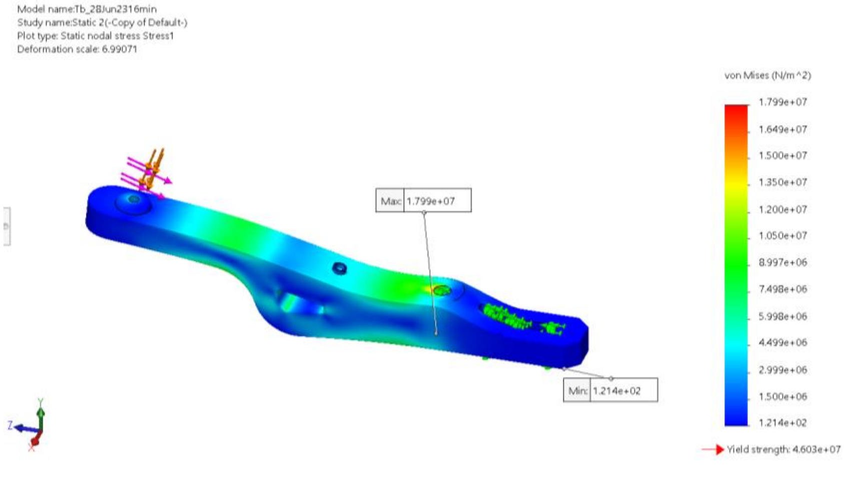
$$F \propto x \tag{1}$$

It was found that extended spring length provides increased grip resistance as well. As a result, the patient's hand force may have insufficient to grasp or pick-up desired object sizes. Including, be unable to release the object due to unstable muscle tone or spasticity. For that reason, the spring force is used to extend the finger that causes a short grip-release range for various object sizes. So, there must be two adjustable mechanisms for increase sling and spring range of motion: *i*) The lock can be adjusted to the pull – relax the length of the sling and spring. This design uses an industry-standard miniature toggle clamp (Model KC-20, 35 g, holding capacity 30 kg, bar open 90°) on a base sliding and be placed in the lock rail. Also, a 1.2 mm diameter steel wire is specially designed for hooking the toggle clamp. The other side of the wire is locked into the groove width 15 mm on a side rail for each lock as shown in Fig. 1 (b). To be able to adjust the sling and spring length and lock for desired distance, and to prevent the toggle clamp moving while training the hand in any position. In addition, *ii*) If the patient is unable to release an object while using the original lock position. The toggle clamp tail can be raised so that the bar that connected to the spring can be opened to 75°. The sling tension and spring length will increase A-AcosΘ mm as shown in Fig. 1 (c) or it is the spring elongation (Δx), when A is the spring bar length. It is the changed force from the increased spring length that can pull the fingers open again shortly. As the relationship in equation (2)

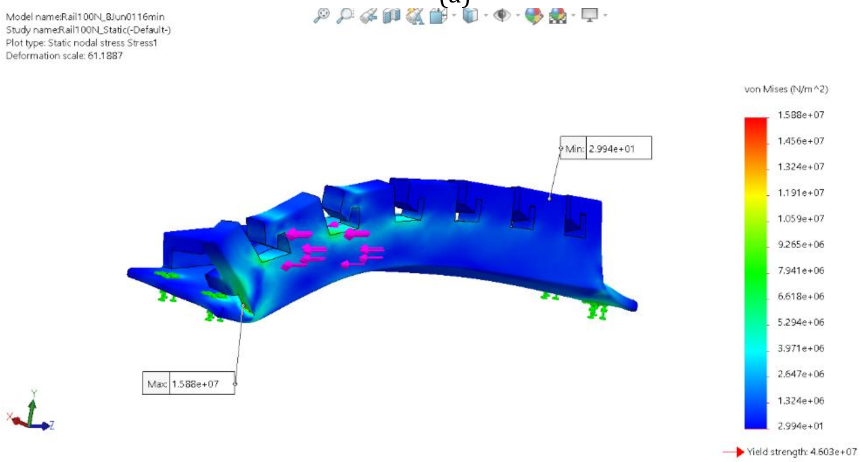
$$F = k \cdot \Delta x \tag{2}$$

2.2 Design results

Drawing and simulating of various part components with Solidworks 2018. The static maximum load on the workpiece that consists of five fingers parts and a two-piece locking system of the thumb and four-finger portion. The static maximum load on four-finger parts total is 100 N and the thumb-part is 50 N. These load values from a reference study that simulated a station where moderate to severe finger flexor spasticity patients reached for the ball on the monitor and noted flexor synergy forces from the load cell in the handle [17]. The static maximum load on each finger part based on a reference study showed that the force sharing test of normal human's four fingers in a neutral line position on load cells. The results showed that the index and middle fingers have flexion force of 32%, 22% of the ring, and 14% of the little finger [19]. Also, the locking system of four-finger and thumb use maximum load values from these references. The locking system consists of *i*) parts with holes for each spring *ii*) Toggle clamp *iii*) Ductile steel wire *iv*) Lock rail. Mesh parameter is curvature-based mesh. Material simulation results as shown in Fig. 2. The Safety factor (SF) value was approximately 3 in the finger pieces, greater than 2 in the lock rail parts, and the other parts had a higher SF value. The various parts are located on the forearm and palm base as shown in Fig. 3 that is the hand-training device prototype in this study.



(a)



(b)

Fig. 2. Show the maximum stress in various parts;
the thumb part (a), the lock rail part of four-finger (b).

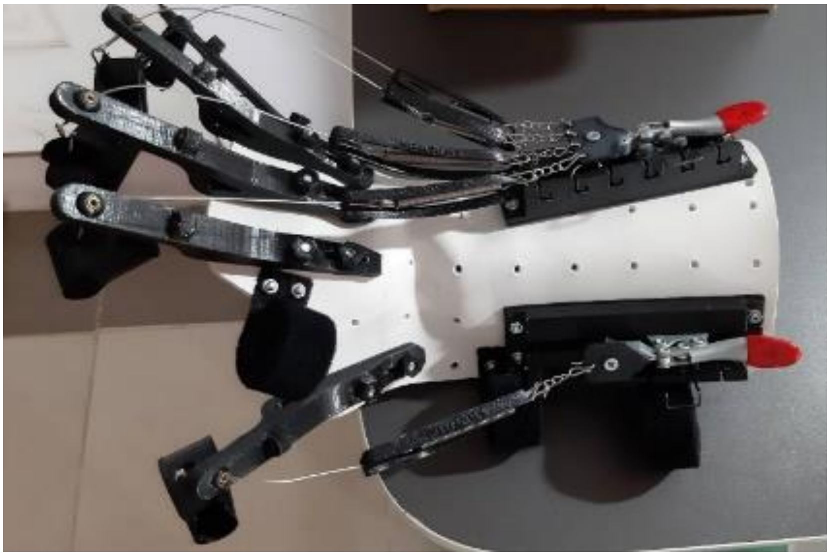
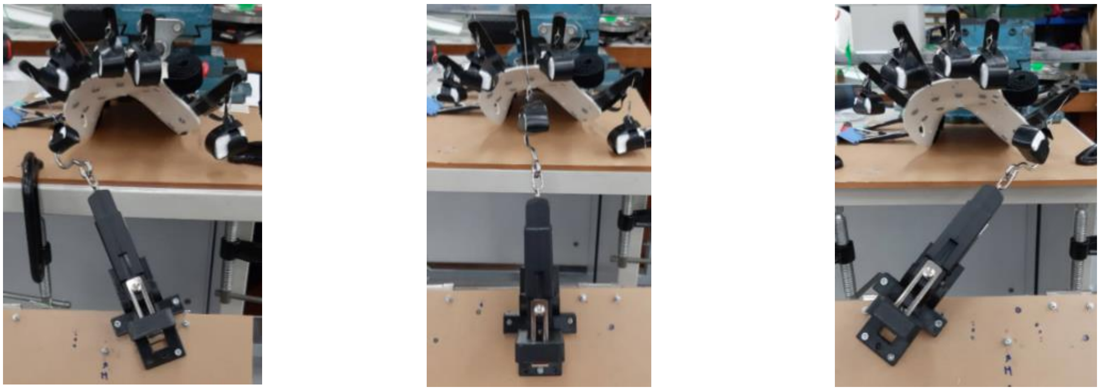


Fig. 3. Hand-training device prototype.

2.3 Research method

2.3.1 Sling and spring tension test and result in various locking positions

Using standard springs (MISUMI Thailand) with an extra light load to medium load type in the finger parts that up to the spring grade as shown in Table 1. First, the hand device is held on the table. Next, the distal end of the sling is attached to the digital weighing scale that is fixed to the vertical incline. Besides, simulate pulling direction of each finger into the palm (Fig. 4a) is similar to the real working direction of the normal fingers while grasping (Fig. 4b) as shown in Figure 4. The station was set firmly.



(a)

(b)

Fig. 4. Show the tensile direction when testing with a digital weighing scale on the little, middle, and thumb finger and normal finger tension direction while grasping.

The test begins by noting the sling tension value of the first lock near the wrist. After that, slide it into the lock further, one by one. Note value until complete the stretch of each spring. Then, the individual spring was measured for 3 times with the same process and was tested on the same model device. The average value of the sling tension of each finger is shown in Table 2.

Table 2: Average sling tension value of each finger of 3 spring grades (N).

Spring	Tb			IF			MF			RF			LF		
grade	2+	3	4	2+	3	4	2+	3	4	2+	3	4	2+	3	4
F_{av} (L1)	.40	.75	.28	.25	.80	1.60	.72	.75	.37	.83	.55	.63	.20	.25	.38
F_{av} (L2)	.60	4.17	3.82	3.00	4.57	5.58	2.42	.52	5.45	2.32	3.03	4.60	1.78	1.90	3.62
F_{av} (L3)	6.50	7.25	8.55	6.13	7.83	9.75	4.72	.87	9.33	4.38	5.80	7.05	3.57	4.50	5.45

F_{av}; Average sling tension, L*i*; Any lock position, Tb; Thumb, IF; Index, MF; Middle, RF; Ring, LF; Little finger

2.3.2 Hand device using test and results

In a healthy participant, male with a 26-year-old, 110 kg body weight, with forearm and palm sizes was similar to the reference study [18] in percentile 95th male workers. This participant was a case study to develop a hand-training device prototype before being administered to the patient later. The participant did not have any abnormalities in the muscles and joints of the hand and forearm during the test. Comparison results with reference data in palm width (included thumb) and palm length can be comparable. However, in the PIP joint circumference, calculated by adding the width and depth of the reference study, then multiply by 2. Therefore, the result is the approximate PIP circumference that can be compared with the actual measurement. The results were found to be similar to the percentage error, as shown in the Table 3.

Table 3: Show the comparison of %error in the forearm sizes, hand and fingers between healthy and reference data.

Measured part	**Healthy subject (mm)**	**95th % ile of reference study (mm)[18]**		**%error**	
Palm width (included thumb)	115	110.05		4.50	
Palm length	100	113.44		11.85	
Finger; PIP jt.	Circumference (mm)	Width(W) (mm)	Depth(D) (mm)	2(W+D) (mm)	%error
Tb	75	20.96	18.07	78.06	3.92
IF	75	19.55	17.47	74.04	1.29
MF	70	18.76	-	72.46	3.39
RF	69	17.82	-	70.58	2.23
LF	60	15.81	15.14	61.90	3.06

Tb; Thumb, IF; Index, MF; Middle, RF; Ring, LF; Little finger, PIP jt.; Proximal interphalangeal joint

In addition, the participant was described in detail of the testing processes. Also, measure the hand and forearm size as shown in the Table 3. Then, the participant has been tested as follows: *i*) To answer the identity questionnaire. The results showed that the participant did not have any restrictions on the study. *ii*) Hand grip strength test (without hand device) with dynamometer grip strength, found that be strong with an average hand force of 37.59 kg. *iii*) To put on the hand device and test hand grip again. The results showed that the average hand force was 26.07 kg of spring grade 2+, 24.37 kg of spring grade 3, and 18.17 kg of spring grade 4. *iv*) To test the hand movement with hand-training device in a fist action and opponent to four fingers was found that is a possibility. *v*) Pick-up and release object test of various sizes to find the limitation of hand functions with this prototype. Various hand and finger gestures are required for daily hand work. So, according to the hand function principles are divided into precision grip 4 actions consisted of pincer, tripod, pinch, and key grip and power grip 5 actions consist of oblique palmar, ball, span, cylinder, and hook grip [3]. It was found that unlimited in any hand functions with hand device as shown in Fig. 5. *vi*) The results of the 7-level attitude gauge questionnaire and opinions toward this hand device after hand device using test showed that the hand device makes participant easier to drop objects out of the hand, easier to use, easier to put off. These scores are in more than a moderate level (5th-6th levels). Also, this questionnaire has been considered by experts before being used. The total test time was two hours.

3. Discussion

The results of comparing actual hand measurement to reference data size were found that can reduce some measurement processes. Width and length of the palm from the reference study [18] were not available in this case although the percent error is not high. Because some dimensions are less than the actual size. It must fit properly or to be slightly larger. Due to the shape of the palm is curved. It should cover the metacarpal bone of the thumb to the little finger. Moreover, wrist and finger flexion spasticity of patient is probably difficult to measure around PIP joint. The reference data size can be used for calculating the finger circumference to make the thimbles. However, forearm and palm should be re-measured.

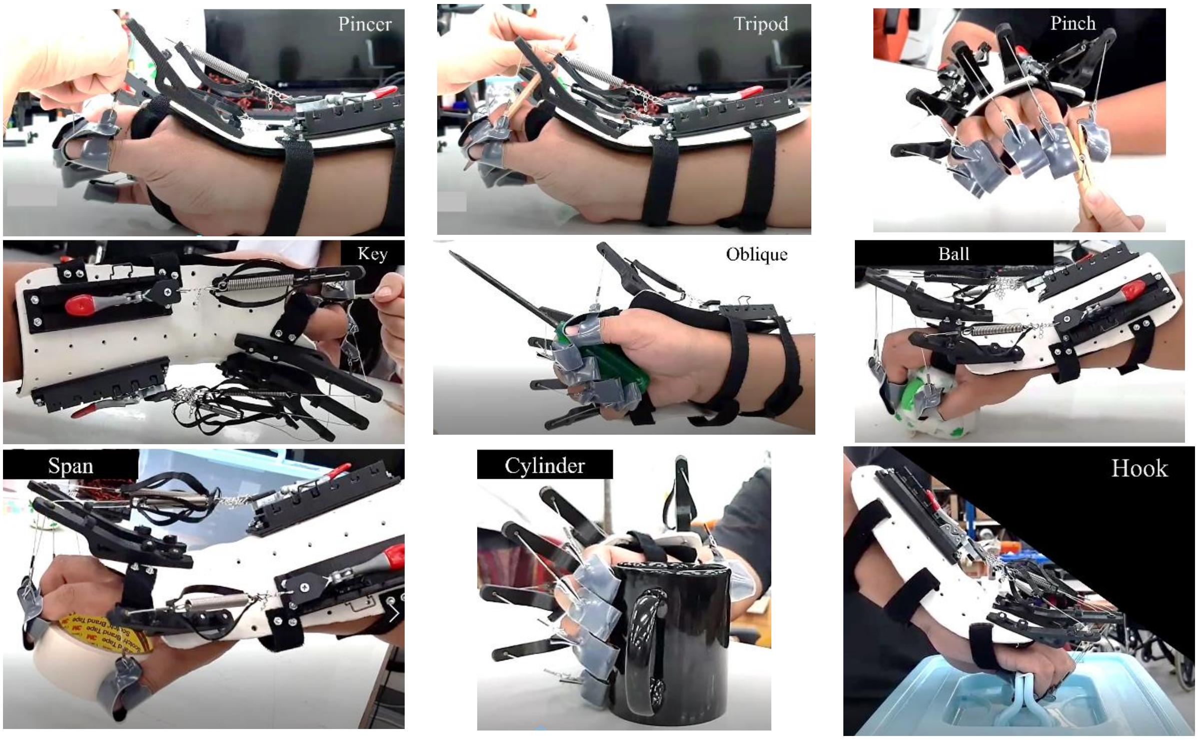


Fig. 5. Show nearly normal hand functions with hand-training device prototype.

From the results of the average each finger sling tension is shown in Table 2. It was found that if moving the lock position further, the sling tension will increase as equation (1). Action in hand function principles with hand-training device is a possibility. Therefore, if the stroke patient cannot act in these hand functions, we could cut the sling length issue off. Although there is no limit to any hand functions, there should be an advanced hand function test. Because the combined movement is required for hand functions in daily life. Moreover, this study found that the thumb thimble rotates because thumb hanging is in combine posture of thumb abduction with extension. However, it is not a negative effect during use. Also, the thimbles must require a silicone or rubber cover on the finger pad for easier handling because the TPU pad has a slip surface. Nevertheless, fine movement of hand also requires wrist and forearm movement. Therefore, combine movement test or advanced test of hand should also be required
.
However, the hand grip force test with hand device which locked in the second lock positions (L2) showed force decreased of grip. It was different from the normal 11.52, 13.22, and 19.42 kg in the spring force grade 2+, 3, and 4, respectively. As in equation (2) that the greater spring force should have higher resistive force. However, the spring assembly may lose force in the mechanical system. It is probably more deformation of forearm and palm base plastic. Including, the presence of friction during the sling moving. However, hand grip dynamometer measures the force of the stroke patient's hand first to predict spring force that be used for pulling fingers to extension.

Attitude gauge opinion is in fair level. However, still many parts should be improved, such as easy to put on the device. Also, it should be careful of plastic wrinkles on the dorsal of the hand and wrist when forming plastic. Because it can press the backhand until pain and swelling.

However, these results can be support data for decision-making to use assistive hand training devices in stroke patients. Because they need to practice the repetitive movements to achieve re-learning and improve hand functional movement [20].

4. CONCLUSION

This study has shown that some hand data should measure from actual case because the hand device must be properly sized to prevent force loss when using or prevent pressure problems from the device. From this study, the device is designed to be strong. It can be used without any movement restriction from the results of the hand function test in a healthy subject. Also, this device has no hazardous material components. However, if the molded hand is wrinkled on the plastic frame, it may cause injury to the tissues when using. In other results, the heavier spring force can reduce the hand grip strength more. Therefore, the predicted spring force may help extend the patient's flexing fingers. However, it must study in real patients' conditions in order to the required spring force. In addition, from this study found that hand grip test can measure synergy flexion force to find the initial spring force before the stroke patient uses the hand-training device.

Limitation of this study is small data of hand sizes, including the test in one case can only found the trend of study results. Besides, forming hand base must be careful because it may wrinkle, causing injury. However, other methods may be used to form instead. For example, hand base molding can be adjusted to the forearm and palm size forming. Because patient hand is often in flexion position that is difficult to extension the wrist during form thermoplastic. Or the other forming method can make the device lighter because the patient also has symptoms of weakness. Including, how to put the hand device easily with another patient's hand. Also, some patients must use another hand to adjust the lock position, maybe it is difficult to change object sizes frequently or use in daily life. So, practical use in stroke patients is required. These issues must be further studied for this hand design. However, further studies will be required on a larger number of subjects in both healthy and fingers spasticity groups. Also, it is required study in many sizes of hand.

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