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Development and control of a home-based training device for hand rehabilitation with a spring and cable driven mechanism

https://doi.org/10.1515/bmt-2019-0267
Received October 12, 2019; accepted January 19, 2021;
published online February 8, 2021

Abstract: Rehabilitation at home is rapidly increasing. Although successful results are achieved with treatment methods applied in rehabilitation clinics, there are also some disadvantages in this process, such as dependence on an expert and high costs. Developments in mechatronic technologies have accelerated the development of assistive devices which are designed for use at home. One of the rehabilitation applications is on a hemiplegic hand. In previous studies, some useful devices have been developed for hand rehabilitation. In this study, we suggest a new, low-cost and wearable robotic glove for hand rehabilitation. The specific component of this device is the spring and cable driven system proposed for transmission of motion and force. The device was tested on both unimpaired participants and patients with the hemiplegic hand, and it was proven to be beneficial for hand rehabilitation. As a result of trials with unimpaired participants, the muscle activation of the extensor digitorum and the flexor carpi radialis were increased by 184.1 and 197.8% respectively. The weight of the device was less than 400 g, thanks to 3D printed parts.

Keywords: clinical trial; conceptual design; robotic glove; Stroke rehabilitation.

Introduction

Stroke is the second biggest cause of disability in the world. In 2010, Patients with Stroke (PwS) numbered to approximately 30 million and the mostly affected were developing countries [1]. Stroke is the principal cause of adult disability in Turkey, with an annual incidence of more than 210,000 people [2]. Approximately 70% of PwS experience altered arm function, and 40% are left with a non-functional arm [3]. Activities of daily living (ADLs) are mostly connected with the upper extremity [4]. The ability to reach and grasp is required in over half of the ADLs [5]. The capacity to achieve ADLs has a direct impact on independence, reducing the social and financial burden of stroke.

Rehabilitation at home is becoming a growing need as cost effective hand rehabilitation is vital for all PwS. Although successful results are achieved with treatment methods applied in rehabilitation clinics, there are also some disadvantages in this process. The main disadvantage is dependence on a certain healthcare centre or experts with which only a limited number of people can benefit from their services. This is so because of the relatively high cost of the rehabilitation processes, and difficulties encountered in accessing rehabilitation services. Thus, rehabilitation-oriented practices should also be developed at home. The World Health Organization's global report on disabilities emphasizes that care and support costs in the rehabilitation process may drop with the use of assistive technologies [6]. In addition, another advantage of rehabilitation at home is that it can speed up the recovery process with high-intensity exercises [7, 8]. On the other hand, distributed and random practise sessions are more beneficial due to a more active participation of the patient in the rehabilitation process [9]. Moreover, distributed training sessions across days also results in enhancement of performance for the remaining training [10]. Distributed and random training can be performed better at home.

Developments in rehabilitation technologies have accelerated the development of devices designed for use at home. One such application is for rehabilitation of hemiplegic hands, which can occur after a paralytic stroke. Studies in this field show that mechanisms, belts, gears, cables and soft actuator systems are used in the transmission of motion and force [11]. Since classic machine parts such as mechanisms [12], gears [13] and belts [14] take up too much space on the hand, they are disadvantageous in terms of both weight and aesthetics. Jo et al. [12] designed a five-bar linkage mechanism for exercising flexion/extension of the finger. They used five linear actuators for fingers' movement. Although the device was light weight (297 g), it

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took up a lot of space on the hand (120 × 195 × 90 mm). A device designed by Worsnopp et al. [13] contained a large number of mechanical parts such as gears and pulleys. Therefore, the control algorithm of the device was complex. In the study by Guo et al. [14], a device with pulley mechanism was suggested. The weight of only finger mechanisms of the device was over 250 g. In this case, systems with a soft actuator are more advantageous because of their lightness, little space needed on the hand and compatibility with soft tissue movements. Prange-Lasonder et al. [15] proposed a soft-robotic glove with a computer gaming environment. Artificial tendons were sewn into the glove to apply force. Polygerinos et al. [16] developed a functional system involving a fibre-reinforced elastomeric glove for finger exercises. Yap et al. [17] used pneumatic actuators for a similar system. For detailed studies on fluid-driven force transmission, the compilation by Polygerinos et al. [18] may be explored. Rehabilitation devices in which force is transmitted by fluid-driven systems are thought to be disadvantageous for use at home. It is thought to be more appropriate for devices used at home to be electrically operated.

In addition to the mechanical and electronic properties of the devices developed for hand rehabilitation, the ergonomic features of these devices are also important. Baier et al. [19] evaluated stroke rehabilitation devices designed to be ergonomic. They suggested that there should be an interdependence between functionality and form.

Our study addressed the design, manufacturing stages and control of a low-cost, wearable robotic glove for hand rehabilitation at home. The specific component of this training device is the spring and cable driven system proposed for transmission of motion and force. The device was tested on both unimpaired participants and PwS with the hemiplegic hand problem, and it proved to be beneficial for hand rehabilitation.

Materials and methods

Design and development of the device

This section details the conceptual design of the training device. The work is done in the following order: A requirement list is identified; Design solutions are presented; The spring mechanism is designed; Biomechanical model is derived; Control scheme is provided and Final design is detailed.

Requirement list of the device

According to the systematic approach proposed by Pahl et al. [20], the design process starts with the requirement list. The features contained in a device for exercise-based rehabilitation of hand muscles are given in Table 1. In determining these features, the factors to be paid attention to in the design of assistive technologies from the viewpoint of rehabilitation engineering were also taken into account [21]. The demands (D) given in Table 1 are the features that the exercise device must definitely have. Wishes (W) represent the features of secondary importance that the device may have.

The major geometric features that the device is expected to have are that it should fit the hand well, easily don/doff, and be portable. As the device will be used by adults, it is expected to fit the hand of individuals with different anthropometric characteristics. From the viewpoint of kinematics and force characteristics, it is desired that the device has a low degree of freedom, which makes it easier to control. In addition, the system is expected to allow for passive (without the patient's involvement) and active (with the patient's involvement) exercises. As it is a system that should be suitable for home use, it should be electrically-operated. Apart from these features, it is desired that the device should meet expectations regarding safety and that its manufacturing cost must be low so that it can be a competitive product in the market.

Design solution for finger exercises

Holding and grasping, which are the most important functions of the hand, are possible with the flexion of the fingers [22]. Therefore, the most suitable movement for hand exercises is extension and flexion. A system that makes the fingers both extend and flex needs to provide the forces of pulling and pushing. Within this scope, studies based on spring and cable driven force transmission [23, 24] have produced successful results. The advantages of spring and cable driven systems

Table 1: Requirement list for the hand training device. D, demands; W, wishes.

Design specifications			
1. Geometry	D/W	**4. Material**	D/W
Suitability for anthropometry of each users	D	Suitability for the skin	D
Easy to don/doff	D	Operating at room temperature	D
Low weight	W	Durability	D
Independent usage	D	Recycling	D
Portability	W		
Suitability for home use	D	**5. Safety**	
Ergonomically	D	Users safety	D
		Device safety	D
2. Kinematics and force			
Low degree of freedom	W	**6. Costs**	
Minimum shear force on the finger joints	D	Being competitive	D
To allow active and passive exercises	D	**7. Control and operation**	
		Easy to assembly	W
		Understandable indicators	D
3. Energy			
Electrical power	D	Position and force control	D
Low voltage	W		

are that they are far much lighter, have a smaller size, and are easier to control.

We determined three different design possibilities. Then, the evaluation criteria were established, taking into account the requirements given in the design specification. These include wearability, suitability for individual use, simplicity and reliability. The criteria are weighted based on their importance, such as wearability 30%, suitability for individual use 20%, simplicity 20% and reliability 30%. In order to evaluate the suggested design solutions, each design was evaluated based on scores (values) ranging from 0 to 4 [25]. The design with the highest score was selected as the best solution.

Upon assessment by our research team, it was decided that all components of the device be placed onto the dorsal surface of the hand in accordance with selected design solution. The device is conceptually composed of a string and cable system, an electrical actuator, and a glove onto which the components are installed. Figure 1 illustrates the conceptual design of the proposed device.

Detailed design for the spring mechanism

In order to ensure that the device allows for finger exercises with flexion and extension movements, the spring system was designed so that there is a spring on each finger joint. Springs generate a force that initially keeps the fingers in the flexion position. By means of the cable force, the fingers are able to extend (Figure 2). Springs are installed to fit the MCP and IP joints on the thumb and the MCP, PIP and DIP joints on the remaining fingers [26]. In order to prevent buckling of the springs, two rows of strings that are tied to each other are installed on each finger.

Final design of the robotic glove

After the design of the spring system is placed onto the fingers, the pulling system was designed. In some previous studies [27, 28], each finger is moved independently. This increases the degrees of freedom, which makes control of the device harder. Furthermore, additional actuators used for each finger increase the cost and weight of the device. Therefore, it was decided to create a design in which the finger exercises are done with a single actuator. Figure 3 shows the final design of the device. The device is composed of the spring system, pulling cables, cable adjustment part, glove, hand support, forearm support, wrist support, linear actuator and control component. In selecting the linear actuator, the analysis of flexion and extension movements of the fingers is utilized [29]. A miniature linear actuator (stroke length: 50 mm, max. force: 50 N, back drive force: 31 N) from the L16 series of Firgelli was used on the device. This actuator also provides a joint angle which will be utilised to control finger joint angles.

The extension movement of the fingers is provided by the back drive force applied by the actuator to the cables. To pull the fingers properly, the cable tension needs to be adjusted. Furthermore, while the fingers are moving to the extension position, the linear displacement of each finger is different. Taking this into account, a cable adjustment part was designed to adjust the cable tension.

Biomechanical model design

The requirement to repeatedly perform an open/close task enables participant to activate hand and wrist flexors. Each movement starts from a fixed initial hand position. The control signal is generated using kinematic joint information as shown in Figure 4(left), in combination

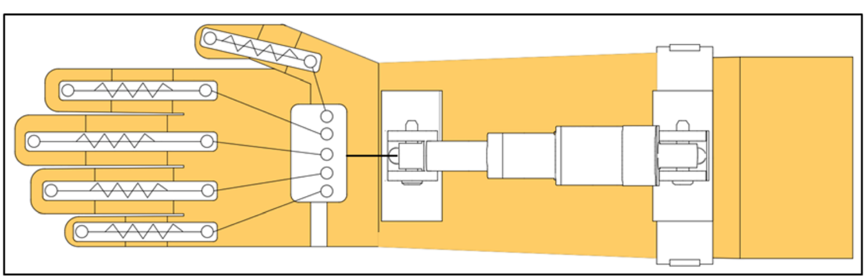

Figure 1: Conceptual design of the device.

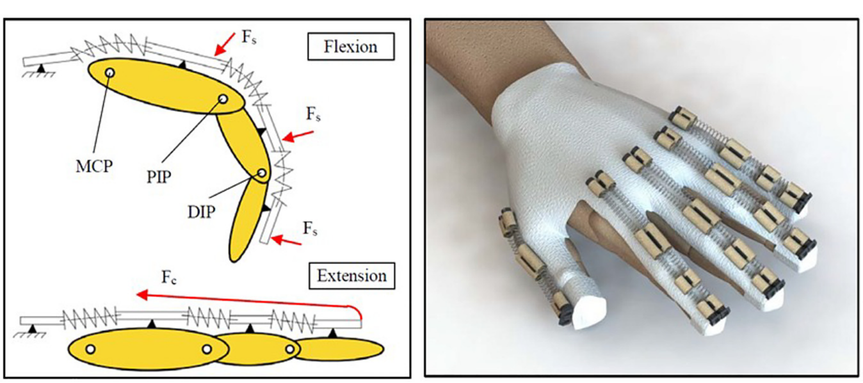

Figure 2: Working principles of springs (left side), and detailed design of the glove (right side). MCP, metacarpophalangeal; PIP, proximal interphalangeal; DIP, distal interphalangeal.

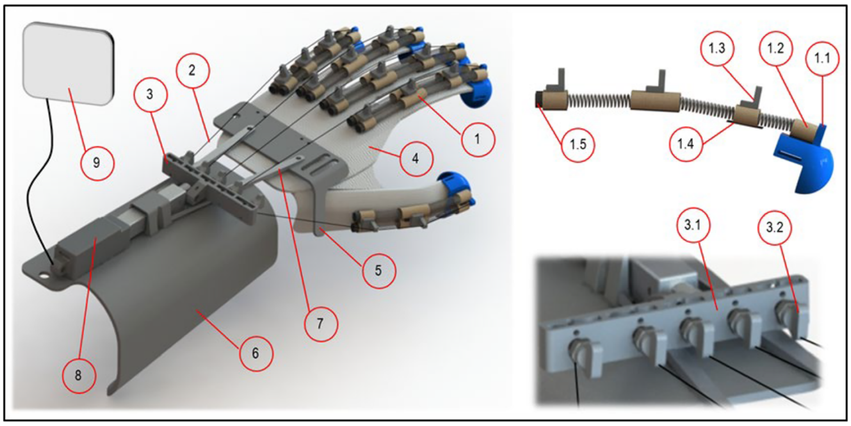

Figure 3: All components of the device. 1, spring mechanism; 1.1, fingertip fitting; 1.2, fiberglass cover, 1.3, pulling cable guide; 1.4, cover fixing part; 1.5, rear connection tube; 2, pulling cable; 3, cable adjustment part; 3.1, body; 3.2, adjustment screw; 4, glove; 5, hand support; 6, forearm support; 7, wrist support; 8, linear actuator; 9, control unit.

with a dynamic model of system which will be detailed in this section. Combined biomechanical model

$$B_h(\Phi)\ddot{\Phi} + C_h(\Phi,\dot{\Phi})\dot{\Phi} + F_h(\Phi,\dot{\Phi}) + G_h(\Phi) = \tilde{g}(u,\Phi,\dot{\Phi}) - J^T(\Phi)h \quad (1)$$

where $B_h(\cdot)$ and $C_h(\cdot)$ are 14-by-14 inertial and Coriolis matrices respectively, $F_h(\cdot)$ and $G_h(\cdot)$ are friction and gravitational vectors, h is a vector of external force and torque due to interaction with device, and $J(\Phi)$ is the system Jacobian. The vectors $\Phi = [\varphi_1, \ldots, \varphi_{14}]^T$ and u respectively denote joint angles and applied force via actuator at time t. The vector $g(\cdot)$, comprising the resulting moments produced through cable, has form

$$g_1\left(u_1(t),\varphi_1,\dot{\varphi}_1\right) = h_1(u_1,t)\times F_{m1}\left(\varphi_1,\dot{\varphi}_1\right),\ldots\ g_5\left(u_5(t),\varphi_5,\dot{\varphi}_5\right) = h_5(u_5,t)\times F_{m5}\left(\varphi_5,\dot{\varphi}_5\right). \quad (2)$$

where $h_i(u_i, t)$ is a Hammerstein structure incorporating a static nonlinearity, $h_{IRC,i}(u_i)$, that represents the isometric recruitment curve, cascaded with linear activation dynamics, $h_{\mathrm{LAD},i}(t)$. The term $F_{m,i}(\varphi, \varphi)$ models the multiplicative effect of the hand joint angle and joint angular velocity on the active torque developed by the muscle. Due to weakness, spasticity and fatigue, stroke patients commonly experience slow restricted movement in their hand and wrist. This means the multiplicative effect of angle and angular velocity can be neglected since it is approximately unity.

The device also supports the hand and its model is given by

$$B_s(\Phi)\ddot{\Phi} + C_s(\Phi,\dot{\Phi})\dot{\Phi} + F_s(\Phi,\dot{\Phi}) + G_s(\Phi) + K_s(\Phi) = 0 \quad (3)$$

where vector $\Theta = [\theta_1, \ldots, \theta_{14}]^T$ contains the joint angles of the spring joints as shown in Figure 2, $B_s(\cdot)$ and $C_s(\cdot)$ are 14-by-14 inertial and Coriolis matrices, and $F_s(\cdot)$ and $G_s(\cdot)$ are friction and gravitational vectors respectively. Vector $K_s(\cdot)$ comprises the moments produced by the spring, which takes the form $[k_1(\theta_1), \ldots, k_{14}(\theta_{14})]^T$. When connected to hand structure (1), a bijective mapping between joint angles, $\Theta = M(\Phi)$, yields the combined model

$$B(\Phi)\ddot{\Phi} + C(\Phi,\dot{\Phi})\dot{\Phi} + F(\Phi,\dot{\Phi}) + G(\Phi) + K(\Phi) = \tilde{g}(u,\Phi,\dot{\Phi}) - J^T(\Phi)h \quad (4)$$

These relationships result by simply combining the hand and device structures (1) and (3) and employing the chain rule. This model is next used by the control system to produce an input signal that results in accurate completion of the task.

Control scheme

A simple proportional-integral-derivative (PID) control system is utilised in the experiment and it is verified to enforce tracking of joint reference $\hat{\Phi}$. The task is tailored to each patient using their underlying hand dynamics. The system has five inputs and 14 outputs. However, each input corresponds to a single output and can be assumed to have minimal dynamic coupling during slow supported movement on each finger. Therefore we assume the controlled hand dynamics are given by the linear forms $\varphi_1(s)=H_1(s)u_1(s)$, …, $\varphi_5(s)=H_5(s)u_5(s)$. Then controller C is selected such that $u_1(s)=K_1(s)(e_1(s) + v_1(s))$, $u_2(s)=K_4(s)(e_4(s) + v_4(s))$ and $u_3(s)=K_5(s)(e_5(s) + v_5(s))$. The resultant closed-loop dynamics are

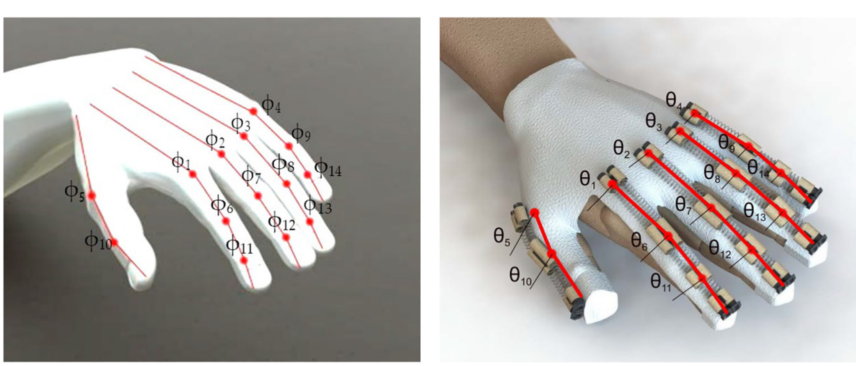

Figure 4: Biomechanical model.

$$G_i:\left(\widehat{\varphi}_i+V_i\right)1\rightarrow\varphi_i:\varphi_i(s)=(I+K_i(s)H_i(s))^{-1}H_i(s)K_i(s)\left(\widehat{\varphi}_i(s)+V_i(s)\right),\quad i=1,\ldots,5 \tag{5}$$

During trials incorporating, the controller assists in the tracking about φ_1 to φ_5 only, and it is assumed that the patient has sufficient control over the remaining axes to adequately perform the task. As the system embeds smart servo motor which has a linear encoder, a simple PID controller is implemented with resulting feedback from motor angle. All data collection was carried out by a team of experienced researchers and each participant PID tuning was performed from clinical feedback from physiotherapists. Please note that for simplicity biomechanical model only utilized for deriving feedback of finger joint angles (Figure 5).

Prototyping the device

The most challenging aspect of the proposed design is the manufacture of a spring system that will keep the fingers in the flexion position. Following several trials, an appropriate method was developed to manufacture the spring system (Figure 6). First, the springs were installed onto a curvilinear guide and compressed to the desired length. Then they were heated and bent. The bent springs were combined with a plastic tube on the ends. Subsequently, they were installed on the glove in fiberglass covers. As a result of the trials conducted to select a spring that would generate a force sufficient to keep the fingers in the flexion position, the compression spring – the features of which are given in Table 2 – was selected.

Table 2: Specifications of commercial compression spring used for force transmitting.

Feature	Symbol	Amount
Wire diameter	*d*	0.80 mm
Mean diameter	Dm	5.60 mm
Initial length	Lo	59.00 mm
Minimum length	Ln	27.03 mm
Spring constant	*k*	0.80 N/m
Maximum force	*F*	25.59 N
Material		Stainless Steel

Following the production of the spring mechanism, the other components of the device were manufactured. Components other than the standard parts were manufactured via a Cubex DUO 3D printer (3D Systems, Belgium). The dimensions of the 3D printed parts can be changed according to the individual properties. The prototype of the device is illustrated in Figure 7. The actuator's position, speed and back drive force can be adjusted by means of the controlling unit. Back drive force is adjusted by the potentiometer on the controlling unit. The device's level of support is set by limiting the operating current of the actuator. It is therefore possible to do passive exercises completely supported by the device as well as active exercises in which the patient is involved. In addition, the linear actuator in the device operates at low current (stall current 650 mA) and voltage (0–15 V, DC). The device was also electrically insulated. Thus, user safety was taken into consideration.

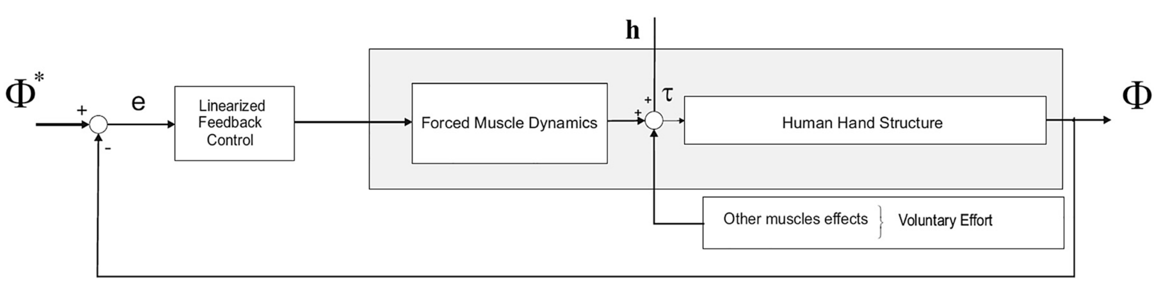

Figure 5: System block diagram.

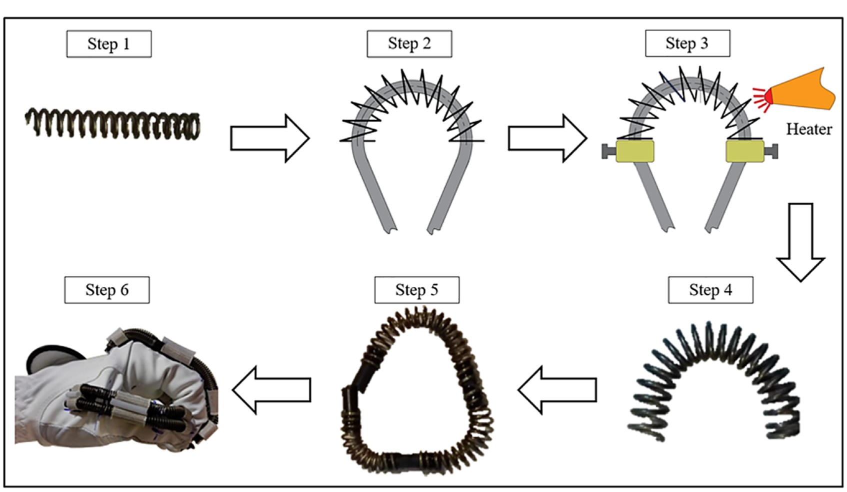

Figure 6: Manufacturing steps of the spring mechanism.

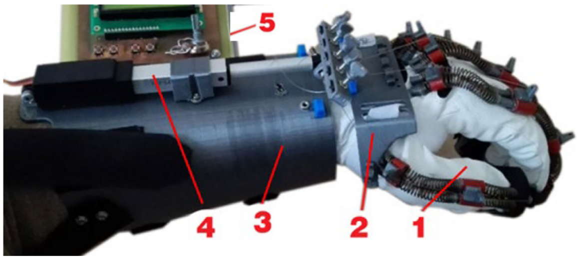

Figure 7: Prototype of the training device. (1) the glove, (2) the hand support, (3) the forearm support, (4) the linear actuator and (5) the controlling unit.

Table 3: Information of unimpaired participants.

Gender (F/M)	Age, years	Height, cm	Mass, kg	Dominant hand
F	26	166	57	Right
F	22	173	51	Right
F	21	167	57	Right
M	22	181	85	Right
M	31	174	73	Left
M	22	171	76	Right
M	22	175	75	Right
M	32	178	82	Right

The palmar section of the glove was cut and removed so that the device can be don/doff easily. In addition, the springs should be in the extension position during wearing. For this purpose, metal rods pass through the springs on each finger. The user removes the rods after wearing the device. Fingers are kept in the flexion position before starting the exercise. Once the exercise starts, the linear actuator of the device carries out a negative (backward) movement to bring the fingers to the extension position. While the actuator carries out a positive (forward) movement, the fingers move to the flexion position again by means of the cable and spring force balance. The finger exercises are therefore done by repeated extension and flexion movements (Figure 8).

Results and discussion

Clinical study

Firstly, ethical approval was obtained for implementing the clinical trials. To test the effectiveness of the device, clinical investigations were carried out both on unimpaired participants and volunteer PwS after obtaining their consent. The purpose of the trials conducted on unimpaired participants was to find out how much the glove (see Figure 6) developed using compression springs which stretched the flexor and extensor muscle groups during active exercises. In this context, the trials were conducted on five male and three female volunteers (see Table 3).

Electromyography (EMG) measurements were conducted to determine the muscular activation of the volunteers. One Delsys DE (Delsys, USA) surface EMG sensor was placed on each of the extensor digitorum muscle and the flexor carpi radialis muscle on the forearm of volunteers [30]. Signals were received by means of a Delsys Bagnoli amplifier (8 channel, total gain of 1,000). Analysis of the data collected was conducted on Delsys EMG-Works software.

Following the electrode placement, the volunteers were instructed to open and close their hands 20 times by repeated extension and flexion movements of fingers while sitting, applying an arbitrary force and speed. They then repeated the same exercise with the glove (see Figure 6) on their hand. The movements were repeated three times with two-min breaks between each trial. Muscular activation during exercises with the glove was compared with muscular activation during exercises without the glove for each volunteer. This process was carried out by the amplitude analysis of EMG signals. The root mean square (RMS) value of the data was obtained in assessing the EMG measurements.

A study was conducted at the physiotherapy clinic of Sakarya University Training and Research Hospital's Korucuk Campus in order to examine the effects of the device on PwS. Three female hemiplegic patients took part in the research at the physiotherapy clinic. The first patient was 63 years old and had hemiplegia in her left hand for two years. The second patient was 47 years old and had hemiplegia in her left hand for two months. The third patient was 50 years old and had hemiplegia in her left hand for a year. The purpose of the research on these

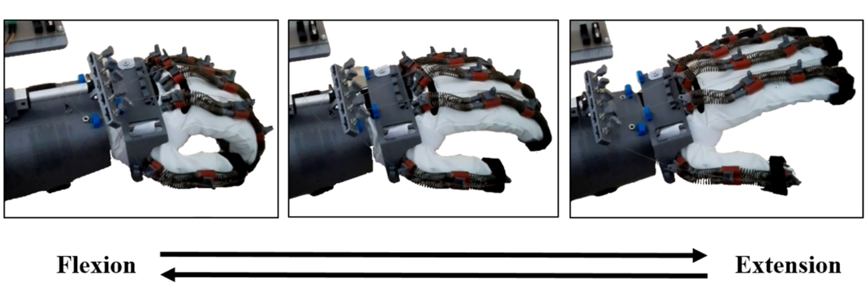

Figure 8: Exercise movement.

patients was to test the device in terms of its suitability for don/doff and exercise movements. The patients were instructed to wear the developed prototype and perform short-term passive exercises (see Figure 9).

A measurement mechanism was designed on the spring system of the glove in order to measure the variation in force generated during the extension/flexion exercises. In accordance with the geometric movement limits of index finger, a finger model was created that is similar to a double pendulum consisting of three cylindrical rods and three rotating swivels. This model was inserted into the index finger part of the glove. The distal end of the glove's index finger part was pulled by a digital hand scale and the finger part was brought to the extension position. This process was shot by a video camera. Using the video footage, the force generated by the spring system was calculated based on the total joint angle ($\varphi_{tot}=\varphi_1+\varphi_6+\varphi_{11}$). Figure 10 shows the force variation on the spring with total joint angle. From the radial spring force measurement conducted, it was clear that the spring system on a single finger generated a force of approximately 6 N in the extension position. As the fingers move to the flexion position, the spring force decreases as expected.

For simplicity a PID controller is designed and embedded in the device. φ_1 is tracked as it can represent all the other finger joints for highly coupled hand system. As shown in Figure 11, a participant performed open hand task correctly. Even though it does not exactly match the motor learning, the device provides an intensive task repetition and it is expected to change the brain plasticity.

The trials carried out on unimpaired participants showed that the exercises with the glove provided a higher muscular activation than those provided by the exercises without the glove (closing and opening the hand). According to the results of the amplitude analysis, the muscle activation of the extensor digitorum increased by 184.1 ± 70.1%. The increase of the muscle activation of the flexor carpi radialis was 197.8 ± 47.5%. This assessment was made taking into account the maximum amplitude in each person during the EMG measurement. Based on these results, the glove proved to be effective both on the extensor and the flexor muscles during active exercises.

Although hemiplegic patients can put on the device on their own, it takes a long time for them to do so. With the help of someone else, a patient can put it on in 5–10 min. Following completion of the exercises, the device can be taken off in 1–2 min. It was understood that the passive exercises were suitable in terms of the range of motion.

The part of the device worn on the hand weighs less than 400 g. In comparison with other similar devices [16, 27, 31], this robotic glove is better in terms of weight. As 3D printing technology was used to manufacture the standard

Figure 9: Clinical trials with PwS.

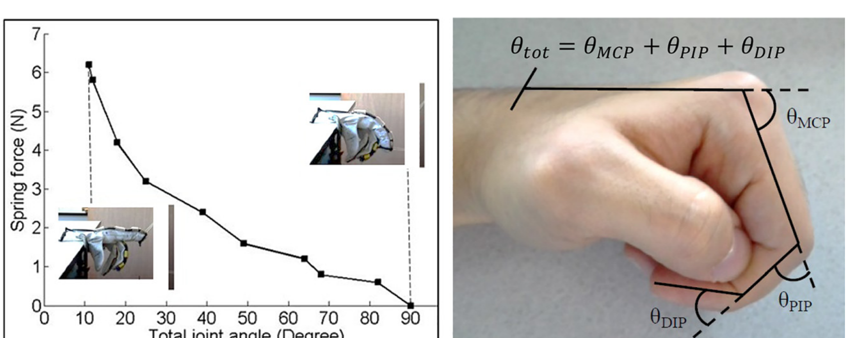

Figure 10: Radial spring force (left) and sum of finger joint angles (right).

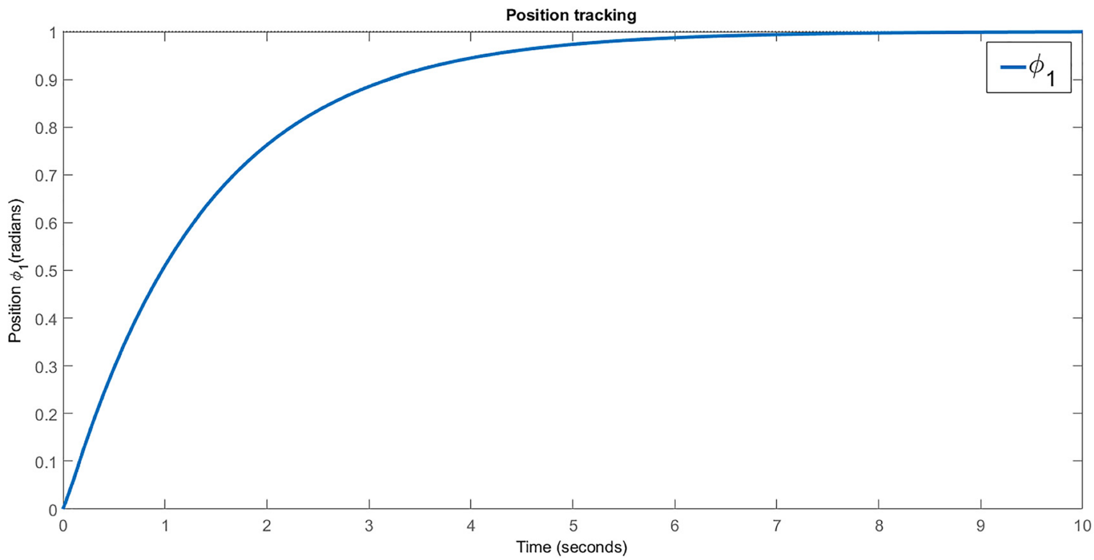

Figure 11: Experimental results of Participant 1.

components, the device can be adapted to personal properties by taking measurements from patients with different anthropometric features. The use of a single linear actuator on the device both reduces the cost and makes it easier to control the device.

The unique aspect of the device is its spring mechanism developed for the transmission of motion. The fact that the method proposed for the manufacture of the spring mechanism is simple and useful is an important advantage. With the spring and cable system, the extension/flexion exercises were done successfully. We believe that a similar system can be applied for wrist exercises as well.

Conclusion

In this study, an original device was developed for use at home. The robotic glove proved to be beneficial for rehabilitation processes. It was also concluded that the glove with the spring mechanism (see Figure 6, Step 6) could be used for completely active exercises (fully patient-attended) by itself. By changing the stiffness of the springs, the level of difficulty of the exercises can be adjusted. For this purpose, the properties of the compression springs can be changed, such as spring constant (k). Thus, the level of radial spring force can be increased or decreased. In addition, leaf springs can be used for completely active exercises. In such a case, leaf springs can be placed on palmar or dorsal side of the hand.

Standard compression springs were employed for the spring mechanism in this study. However, a new spring may be developed for wearable exercise devices. The spring to be developed should not be exposed to buckling due to forces in the radial, tangential and axial directions. The new spring design should also allow soft tissue movements. Thus joint alignment problem can be fixed.

Our goal was to develop a device that would be as simple as possible in every respect. The device has one degree of freedom, so this makes it easier to control. It also reduces the manufacturing cost. However, this situation reduces exercise efficiency. Additional actuator may be used for each finger, but this will increase the cost. As an alternative solution, the thumb movement can be performed with other actuator or the thumb may be fixed at the extension position, and exercises done with the remaining four fingers.

One future study will involve testing the device on patients for a longer period of time and demonstrating the device's impact on recovery. After that there are plans to develop the device commercially. A utility model registration certificate (application number: 201602827) was issued for the device from Turkish Patent and Trade-mark Office for this purpose.

Acknowledgments: A special thanks is extended to Assoc. Prof. Dr. Arno H. A. Stienen of Northwestern University for his contribution to spring mechanism design.
Research funding: This study was supported by The Scientific and Technological Research Council of Turkey (TUBITAK) with project No. 115M622.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.
Competing interest: Authors state no conflict of interest.

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