



POLİTEKNİK DERGİSİ

*JOURNAL of POLYTECHNIC*

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)

URL: <http://dergipark.org.tr/politeknik>



# Design, development and evaluation of a new hand exoskeleton for stroke rehabilitation at home

*Yazar(lar) (Author(s)):* Kasım SERBEST<sup>1</sup>, Osman ELDOĞAN<sup>2</sup>

ORCID<sup>1</sup>: 0000-0002-0064-4020

ORCID<sup>2</sup>: 0000-0001-9236-8985

**Bu makaleye şu şekilde atıfta bulunabilirsiniz (To cite to this article):** Serbest K. ve Eldoğan O., “Design, development and evaluation of a new hand exoskeleton for stroke rehabilitation at home”, *Politeknik Dergisi*, 24(1): 305-314, (2021).

**Erişim linki (To link to this article):** <http://dergipark.org.tr/politeknik/archive>

**DOI:** 10.2339/politeknik.725310

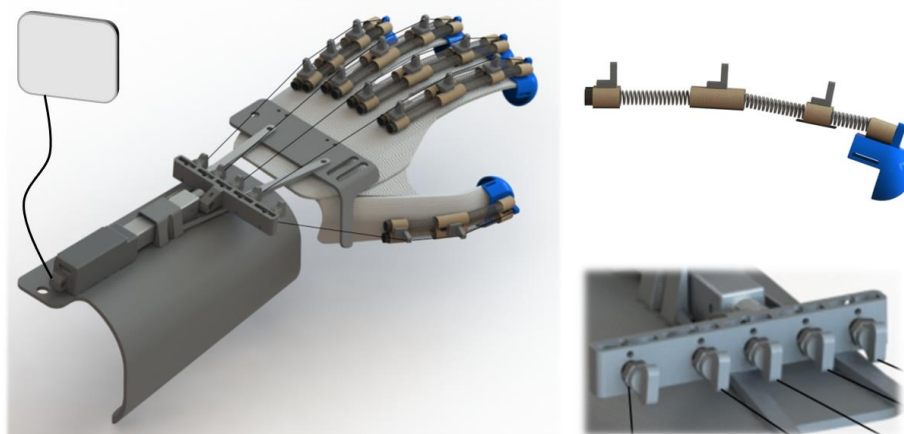
# Design, Development and Evaluation of a New Hand Exoskeleton for Stroke Rehabilitation at Home

## Highlights

- ❖ A new hand exoskeleton with spring mechanism
- ❖ Detailed design studies for spring mechanism
- ❖ It was clinically tested on both unimpaired individuals and hemiplegic patients

## Graphical Abstract

In this study, we present design and development process of a new hand rehabilitation device using at home. The device, designed according to the conceptual design principles, has been clinically tested.



**Figure.** Hand exoskeleton with cable and spring mechanism.

## Aim

The aim of this study is to design and to develop a novel hand rehabilitation device, which is portable, wearable and low cost, using systematic approach.

## Design & Methodology

Firstly, design specifications of the device was determined. Then possible design candidates were suggested. Some evaluation criteria were determined. An evaluation was made according to these criteria and the best design solution was determined. A prototype was manufactured and it was evaluated in terms of exercises, ergonomics, users' observations and market. Finally, the device was tested clinically.

## Originality

The device has a custom made spring and cable mechanism for force transmitting. Commercial compression springs were used in the manufacture of the spring mechanism.

## Findings

The device is low cost (less than \$150), lightweight (345 grams), easy to control (1 DOF) suitable for finger exercises and suitable for individual use.

## Conclusion

As a result of the clinical study, it was understood that the device would be useful in hemiplegic hand rehabilitation. In addition, the device can be commercialized.

## Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

# Design, Development and Evaluation of a New Hand Exoskeleton for Stroke Rehabilitation at Home

*Araştırma Makalesi/Research Article*

**Kasım SERBEST\*, Osman ELDOĞAN**

Faculty of Technology, Department of Mechatronics Engineering, Sakarya University of Applied Sciences, Turkey

(Geliş/Received : 22.04.2020 ; Kabul/Accepted : 11.05.2020)

## ABSTRACT

Rehabilitation at home is a growing need worldwide. Previous studies have suggested different devices in terms of motion and force transmission. In this study, we present design and development process of a novel hand exercise exoskeleton. The main advantages of our device that are portable, wearable, light weight (345 grams) and suitable for home use. The greatest feature of the device is the force transmitting mechanism. The spring mechanism manufactured by using commercial compression springs has some advantages in terms of size and weight. In design studies of the device, we have made use of the systematic approach. In this way, the best of three possible design solutions has been determined. Then the best design solution was selected. A few prototypes of the device were manufactured. The device has been tested clinically on both unimpaired individuals and hemiplegic hand patients for a short time. It was reported that the exoskeleton was suited to passive exercises. The result section gives an evaluation of the device in terms of exercises, ergonomics and the market. Additionally, a patent registration certificate was issued to our device for our country.

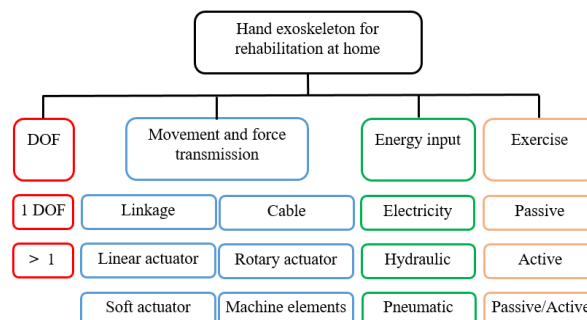
**Keywords:** Engineering design, hand exoskeleton, rehabilitation at home, hemiplegic hand, spring mechanism.

## 1. INTRODUCTION

The main benefits to be gained from rehabilitation at home relate to the high correlation between intensity of exercise and recovery of lost functions [1]. Furthermore, conventional treatments under the direction of a physiotherapist can have some restrictions [2], and the number of studies investigating the use of wearable robotic systems for the rehabilitation of hand muscles within the home is increasing. Nevertheless, the number of commercial applications in this area is still very limited. One of the most successful products on the market is the system developed by Tong et al. [3], while other devices are usually suitable for laboratory use. For detailed information on wearable devices for hand rehabilitation, see the review by Heo et al. [4].

Commercial devices developed for the rehabilitation of hand muscles at home should be low cost, aesthetic in appearance, ergonomic and easy to control, and should also ensure functional exercise. In the daily routine, holding and gripping are the most important functions of the hand, both of which rely on the flexion of the fingers [5]. Accordingly, the majority of devices developed for exercise-based rehabilitation involve the flexion/extension of the fingers, but one of the key points that should be taken into attention during flexion/extension exercises when using such devices is the alignment of the centres of rotation of the device and the finger joints. Different motion and force transmission systems have been suggested for this purpose [4]. The devices developed to date vary in terms of their energy requirements and the degree of freedom (DOF), and the features of the devices developed in previous studies are

summarized in Fig. 1. Previous studies has been reported that linkage, belts, gears and other classic machine parts are used in the transmission of motion and force. They are disadvantageous in terms of both weight and aesthetics. Also, these devices focus mainly on the effectiveness of exercises, which can lead to other features that should be expected from commercial devices being overlooked. In this regard, there is a need to develop of a low-cost, ergonomic and aesthetic exoskeleton that ensure effective exercise.



**Fig. 1.** Some specifications of hand rehabilitation devices.

The primary aim of this paper is to design an original hand exercise device which is suitable for rehabilitation at home. The secondary aim of the study is to develop a low-cost hand rehabilitation device that can be used commercially. In this study, we suggest a new wearable robotic glove for hand rehabilitation. The device has a novel force transmission system that is a cable driven spring mechanism. The advantages of the mechanism are reduction of the number of DOF and has a simple control algorithm. Our device is a low cost, lighter, more ergonomic and easier to control compared other devices. In addition, this device has been tested clinically on both unimpaired and impaired subjects with stroke.

\*Sorumlu yazar (Corresponding Author)  
e-posta : kserbest@subu.edu.tr

The present study includes design studies for a novel hand exoskeleton. The systematic approach is used for the design process of the device. One of the recommended designs has been manufactured. The original part of this device is the spring mechanism for the force transmission.

**2. DESIGN METHODOLOGY**

Developing a new and an original product can be complicated, and so to ease the process, we have made use of the systematic approach suggested by Pahl and Beitz, and improved later with the contributions of Feldhusen and Grote. This approach binds the design in some rules and scientific fundamentals. Systematic Approach is divided into the followings four sections. Clarification of the task, conceptual design, embodiment design and detailed design. Clarification of the task and conceptual design forms an important part of the product design. The final product is related to these two stages directly. The purpose of the conceptual design determines a design solution which is the best way to satisfy the required functions. The conceptual design also offers useful tools in the product development process [6]. Based on the systematic approach suggested for engineering design, the design process is no longer an intuitive process, but is based rather on systematic techniques.

**2.1. Conceptual Design of the Exoskeleton**

The purpose of a conceptual design is to identify the design solution that satisfies the necessary functions in the best way. A conceptual design starts with a design specification, and the features that should be incorporated into an exoskeleton for the exercise-based rehabilitation of hand muscles are presented in Table 1. It can be said that if a device is developed taking into consideration the features listed in Table 1, it will satisfy with user expectations.

**2.1.1. Function structure**

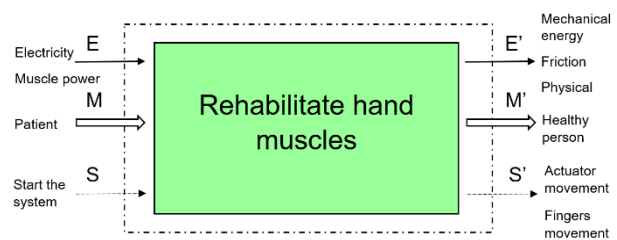
In the design process, the concept of function can be defined as the relationship between the inputs and outputs of the system to be designed. The overall function of a system can be defined by reducing the specification requirements to general statements. In a sizable or complex design problem, the division of the overall function into subfunctions makes the solution-seeking process more straightforward [6].

The overall function of the hand rehabilitation device developed on the basis of the design specification can be described as shown in Fig. 2. Here, the axis lines represent the boundaries of the system, with E being the energy input and E' being the energy output of the system. The energy input of the rehabilitation device comes from electric power, but as the device will enable both passive and active exercises, the muscle power of the user is also included as an energy input. Electric

**Table 1.** Requirement list for the exoskeleton.

Design Specifications
<b>1. Geometry</b>
Suitability for anthropometry of each adult users
Easy to wear and take off. No more than 20 minutes
Light weight. Less than 1 kg
Using without the help of someone else
Portability
Suitability for home use
<b>2. Kinematics and force</b>
Low degree of freedom. 1 DOF if possible
Lower shear force on the finger joints
To allow active and passive exercises
<b>3. Energy</b>
Electricity input
Low voltage. Less than 50 V
<b>4. Material</b>
Suitability for the skin
Operating at room temperature
Durability
Recycling
<b>5. Safety</b>
Users safety
Device safety
<b>6. Costs</b>
Being competitive in the market. Lower than \$1000
<b>7. Control and operations</b>
Easy to assembly
Understandable indicators
Position and force control

power is converted into mechanical energy by means of the actuators within the device. Frictional losses may occur during the use of the device, and muscle fatigue may be experienced when the user operates the device with his/her own muscle power. The material input (M) is the patient, and the material output (M') is the rehabilitated and unimpaired individual. The signal input (S) represents the operation of the system by means of the control unit, and signal output (S') represents the muscle activation and motion of the actuators.



**Fig. 2.** Overall function of the exoskeleton.

The overall function refers to the general functioning of the system, and the details of the system can be represented by means of subfunctions. The subfunctions of the device developed in this study are the wearing of the device on the hand, the flexion exercises, the extension exercises and the adjustment of the operational parameters of the device. Fig. 3 shows how the identified subfunctions are turned into the function structure.

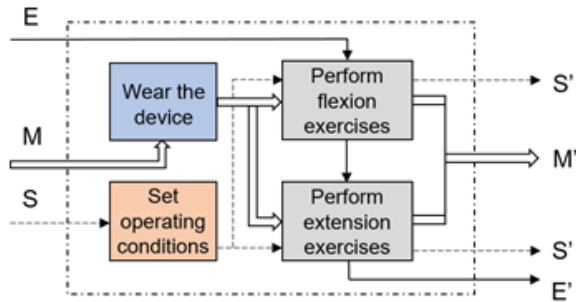


Fig. 3. Subfunctions of the exoskeleton.

### 2.1.2. Possible solutions for functions

Prolonged examinations have been made to develop a device in accordance with the design specification and function structures, with some decisions taken as a result of these examinations. The device is expected to be wearable without the need of assistance from others. In this scope, exposing the underside or surface of the part of the device that is worn on the hand may facilitate the wearing of the device, meaning that patients with different disorders or hand problems can put on the device using only one hand. Moreover, the device is designed to be suitable for adults with different anthropometric characteristics, and so the part of the device that is worn on the hand can be manufactured in different sizes (small, medium, large, etc.) or for a specific patient, ensuring a perfect fit to the patient's hand. After the dimensions of the patient's hand have been measured, 3D printing technologies can be used to manufacture the parts of the device. Furthermore, the connection of the device to the hand and forearm can be made adjustable, or manufactured to different sizes. A microcontroller-based electronic control unit may be developed to adjust the operating conditions.

We consider that it would be better for the exoskeleton to be operated by electric power, as systems operating under hydraulic and pneumatic power [7, 8] are not usually appropriate for use at home. Furthermore, as the mechanisms and classical mechanical elements used to transmit motion and force take up considerable space on the hand, they are also unsuitable from an aesthetic point of view. Considering that lightness is another essential feature, a new motion and force transmission system needs to be developed.

The development of a system relying on the transmission of motion based on springs and cables [9, 10] was deemed to be appropriate. Furthermore, it was decided that the device would have a single degree of freedom,

thus making the exoskeleton easier to control. The spring system can be located on the palmar surface or on the dorsal surface of the hand, and different systems operating incorporating different springs can be used in the system (e.g. compression springs, extension springs, leaf springs, elastic cords, etc.). An actuator drives the spring and cable system, and can move in a linear or rotary motion. The flexion and extension motions can be carried out by both the actuator force and spring force in the system.

Taking into consideration the abovementioned requirements, three different design solutions (DS) are suggested, as shown in Figure 4. In DS1, the spring system is located on the palmar surface and the cable system on the dorsal surface of the hand. The actuator that will provide the force necessary for the flexion/extension exercises is located on the dorsal surface. In this solution, the fingers begin in the extension position. In DS2, the spring system, cable system and actuator are all located on the dorsal surface of the hand, and the motion of the fingers is from the flexion position to the extension position. In DS3, the spring system, cable system and actuator are all located on the palmar surface of the hand, and the fingers begin in the extension position.

Linear or rotary actuators can be used in all three solutions, although they should be operated by electric power. Any component with spring-like properties can be used in the spring system, while products made from polymer, metal or textiles can be used in the cable system.

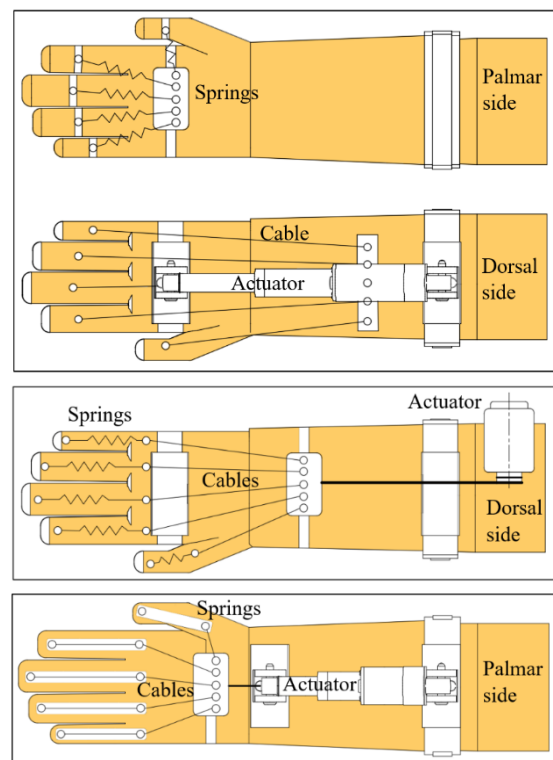


Fig. 4. Three different design solutions. Top; DS1, middle; DS2, bottom; DS3.

### 2.1.3. Evaluating design solutions

The three different design solutions are all functional, however an evaluation was made to find out which offered the best solution. To this end, the evaluation criteria were established, taking into account the requirements given in the design specification, including wearability, suitability for individual use, simplicity and reliability. The expectations from a device that meets these criteria are explained below.

**Wearability:** This criterion refers to how easy it is to wear the device on the hand. A device with high wearability should be easy to wear, while a device with low wearability would be more difficult to wear.

**Suitability for individual use:** This criterion refers to the extent to which the device can be used without assistance from others. A patient can use a device with high suitability for his/her own individual use, and this is important when the patient has functional loss in a single hand. In the case of functional loss in both hands, the suitability for individual use criterion cannot be met.

**Simplicity:** This criterion concerns the number of components (parts) in the device, the degree of freedom, and the installation and control processes. A device with high simplicity is likely to be composed of a limited number of parts, have a minimum degree of freedom and require easy installation and control processes.

**Reliability:** This criterion is an indicator of user and device safety. A hand rehabilitation device is expected to offer a maximum level of safety. In a device with high user safety, all safety measures are addressed and any undesired shear forces are kept to a minimum during the exercises. A system with high device safety would be expected to be durable and not subject to failures.

A tree of objectives was created as part of a quantitative evaluation, and is given in Fig. 5 showing the evaluation criteria. The criteria are weighted based on their importance for the developed device. Wearability and reliability are deemed to have slightly higher importance than the other criteria, and so are given a weight of 30%, while suitability for individual use and simplicity have been assigned a weight of 20%.

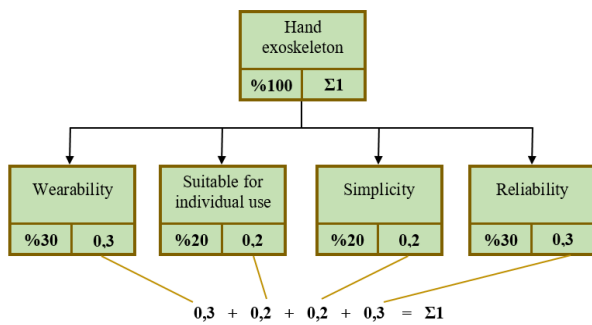


Fig. 5. A tree of objectives for the exoskeleton.

In order to evaluate the suggested design solutions, each design was evaluated based on scores (values) ranging

from 0 to 4, given according to the extent to which they meet the criteria. The criteria are scored as follows [11].

0: Unsatisfactory solution.

1: Acceptable solution.

2: Satisfactory solution.

3: Good solution.

4: Very good solution.

Here, an unsatisfactory solution refers to a solution that is of little or no use to the user, and which has structural deficiencies. An acceptable solution refers to a solution that benefits the user but also has structural deficiencies, whereas a satisfactory solution refers to a beneficial solution that has the necessary structural condition despite having some deficiencies. A good solution is a structurally smooth solution that is convenient for the user, and finally a very good solution refers to a superior and almost ideal solution [12].

The total scores evaluated for each design solution are shown in the evaluation diagram in Table 2. The criterion weights (w) of the designs were calculated by multiplying the percentage weight set in the tree of goals by the value analysis score, after which, the weights calculated for each criterion were added to find the total weight value (Σw) of the designs.

Table 2. Evaluation diagram of the three design concepts.

Evaluation	DS1		DS2		DS3		
Criteria	Weight	Value	w	Value	w	Value	w
Wearability	0,3	1	0,3	2	0,6	3	0,9
Suitability for individual use	0,2	1	0,2	2	0,4	2	0,4
Simplicity	0,2	2	0,4	3	0,6	3	0,6
Reliability	0,3	3	0,9	3	0,9	3	0,9
	Σ=1		Σw=1,8		Σw=2,5		Σw=2,8

As can be seen in the evaluation diagram above, DS3 has the highest total score, given the criteria set, and the total score of DS2 is close to that of DS3. In terms of total scores, the worst solution is DS1, and particularly in terms of meeting the wearability criterion, DS1 is evaluated as being more disadvantageous than the other solutions.

The evaluation results show that DS1 far from meets the expected requirements, although some examinations need to be made into the physical structure of the system in order to find out whether DS1 is suitable for finger and wrist exercises. If the device developed on the basis of

DS1 can ensure effective exercises, the other disadvantages of the system may be reconsidered. Accordingly, DS1 cannot be ruled out fully.

## 2.2. Detailed Design for the Exoskeleton

In the previous section, three conceptual designs are suggested that are based on similar principles, and that are in accordance with the design specification and function structures. This section deals with the detailed design of the exoskeleton that provides finger exercises in line with the design solutions, and focuses initially on the force and motion transmission systems of the three design concepts.

### 2.2.1. Development of the DS1

In the system developed for DS1, the linear actuator and elastic cord will ensure finger movement (Fig. 6, left). In when manufacturing the model's prototype, focus was on the system providing finger movements, and to this end, the structure used to pull the fingers was created first (Fig. 6, right). In the following stage, trials of the system were made in which the fingers were kept in the flexion position, with elastic cords with spring-like properties tried first (Fig. 6, right). When the elastic cords are placed on the palm, the final length of the cords will be up to 2-3 times longer than their initial length when the fingers are at full extension position. This produces very high tensile forces, and consequently, the actuator force required to bring the fingers to the extension position increases. In an attempt to decrease the tensile forces and the required actuator force, the elastic cords were located as far away as possible (somewhere close to the elbow). This decreased the tensile force, but led to an appearance that was not aesthetically pleasing. Either cords that are less stiff, or suitable extension springs can be used to provide both a low tensile force and a more aesthetically appealing design.

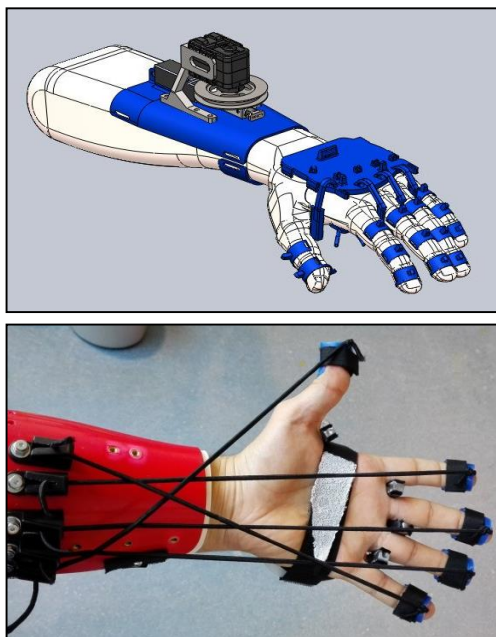


Fig. 6. CAD model and movement transmission system of the DS1.

Although this system is functional, locating the components on a single surface of the hand can result in a simpler and aesthetically superior system. The system developed for DS1 was also lacking in terms of wearability and suitability for individual use.

### 2.2.2. Development of the DS2

In the DS2 solution, all of the components of the device were located on the dorsal surface of the hand. For DS2, a spring system needs to be developed that will keep the fingers initially in the flexion position. The system design, to be worn on the dorsal surface of the hand, features a spring on each finger joint that generate forces that keeps the fingers in the flexion position. The springs are installed to fit the MCP and IP joints on the thumb and the MCP, PIP and DIP joints on the remaining fingers. Taking into account the anthropometric characteristics of an adult hand, it was decided to have two rows of springs on each finger. Fig. 7 shows the force transmission system of the suggested design and the glove that was designed accordingly.

The spring system is fixed to a leather glove, with the springs glued to the glove at a couple of points. In order to bring the fingers from their initial flexion position owing to the force of the spring to the extension position, actuator force is utilized. The actuator can operate in both linear and rotary motions.

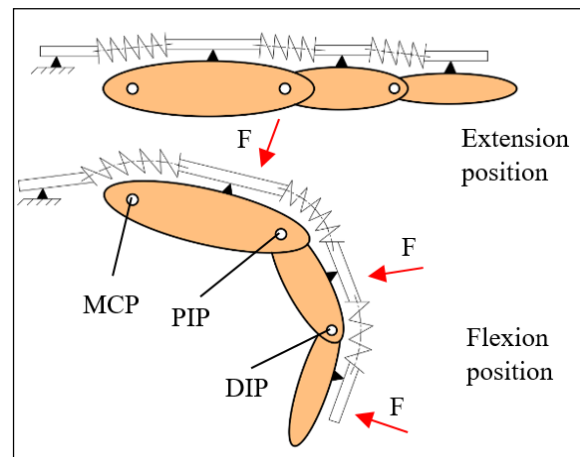


Fig. 7. Spring mechanism design (top) and CAD model (bottom) of the glove.

To create the spring system, numerous trials were conducted with commercially available compression springs, and by bending the standard compression springs, it was ensured that the springs produced the necessary flexion force. The springs were bent by installing them onto a curvilinear guide and heated, and after cooling, the springs assumed the shape of the guide. Fig. 8 shows the glove with the spring mechanism manufactured according to the DS2. The hollow plastic cylindrical parts were used to combine the abutting springs, the bent sections of which located on the finger joints. Fiberglass coverings were added to the glove to act as guides for the springs, and the springs were passed through these coverings. In an attempt to prevent buckling on the spring when the fingers were brought to the extension position, the two rows of springs on each finger were attached together.



Fig. 8. The glove with spring mechanism.

It is apparent that the glove developed for DS2 meets both the effectiveness of exercises and the evaluation criteria.

### 2.2.3. Development of the DS3







In DS3, it is suggested that both the spring system and the actuator are located on the palmar surface of the hand. The main challenge in DS3 is the development of the spring system to be located on the palmar surface. As the system is to be located on the palmar surface, it was deemed appropriate to keep the fingers initially in the extension position. For the design of the spring system that will keep the fingers in the extension position, several trials were conducted using leaf springs, torsion springs and extension springs. In the trials with torsion springs, axial deformities occurred in the spring and an asymmetrical appearance was obtained when the fingers are brought to the flexion position, which may be attributed to be the manufacturing method of the spring. Since the spring can only be fixed at the linear sections at its ends, it is unable to maintain its cylindrical shape under flexion forces. To overcome this problem, different fixation methods need to be developed.

The trials with extension springs were relatively more successful. While extension springs are capable of resisting greater forces in an axial direction, as their radius decreases they are far less inflexible against forces in a radial direction. Therefore, in the trials with springs that had high axial rigidity and a relatively small radii, a structure was designed that would keep the fingers in the extension position and would provide the necessary flexion. Nonetheless, the difficulty that needs to be tackled here is the arrangement of the section that will act as a guide to the spring in such a manner that it permits effective movement.

The trials with leaf springs were deemed to be the most successful. As they are very thin, it is easier to attach them to the glove and the weight of the glove is reduced. A critical point that must be taken into account is that the springs must have sufficient flexibility against bending, otherwise they will deform and fail to come to the fully straight position.

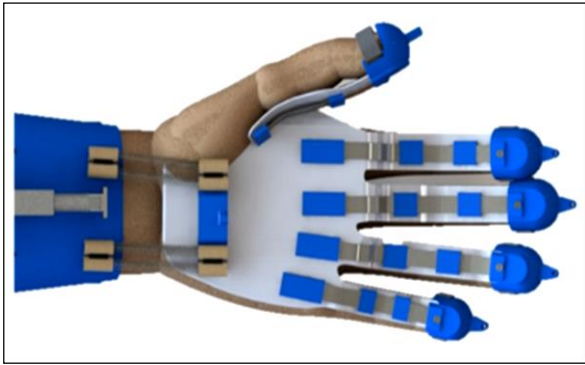
Table 3 shows the results of trials with different types of springs. As a result of the evaluation, it was concluded that the most suitable components for the system to be placed onto the palmar surface of the hand were leaf springs.

Table 3. Trials with different springs for DS3.

Spring type	Figure	Description
Leaf spring		Photos from the trials with leaf springs are shown here. The leaf springs perform a sliding movement within a channel located on the fingers, and bend at the finger joints. When the tensile force is eliminated, the fingers are restored to their open position.
		
Torsion spring		As is seen in the photos from the trials with torsion springs, one spring was used for each joint on each finger. As the fingers, which are initially in the open position, come to the extension position, the springs perform a torsion motion around the axis of rotation.
		
Extension spring		The extension spring shown in the photos moves within a cylindrical channel on the fingers. The spring both bends and performs a sliding motion. One extension spring is used for each finger.
		

The greatest difference between the system located on the palmar surface and the one located on the dorsal surface is the use of leaf springs rather than compression springs. Besides the spring system, similar components can be used in devices located on the dorsal and palmar surfaces of the hand. The detailed design of the spring system suggested for DS3 is given in Fig. 9.





**Fig. 9.** CAD model of the DS3.

One of the requirements stated in the design specification relates to the ease of wearing and removing the device. It is easier to wear a device that is located on the palmar surface than on the dorsal surface of the hand. Since leaf springs are initially in a straight position in the design worn on the palmar surface, the hand can be easily inserted into the device. Furthermore, as the springs will be at their initial open position once the exercises are completed, it is relatively easier to remove the device. Novelty of DS3 is leaf spring mechanism which is located on the palmar surface of the hand. DS3 has advantageous in terms of weight and space.

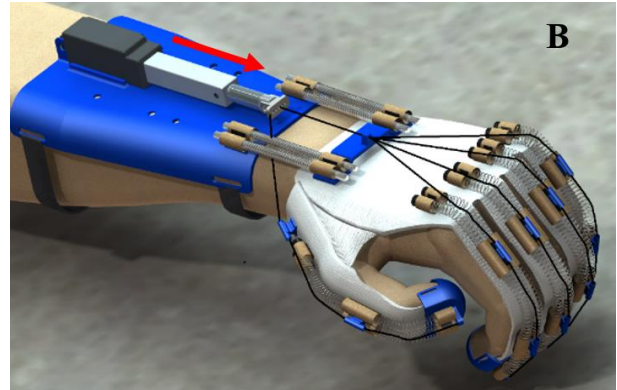
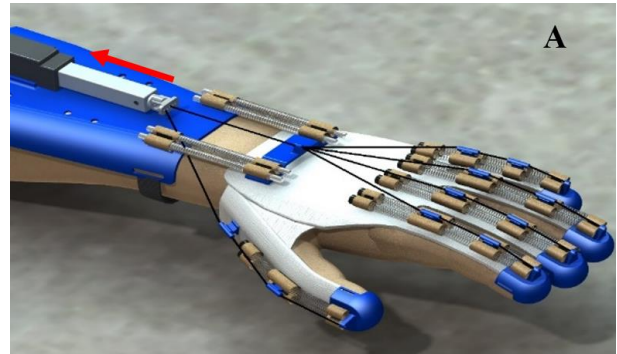
The glove manufactured according to DS3 is shown in Fig. 10. Pulling the cables drives the leaf springs located on each finger, and these cables can be connected to a linear or rotary actuator.



**Fig. 10.** Spring mechanism for DS3.

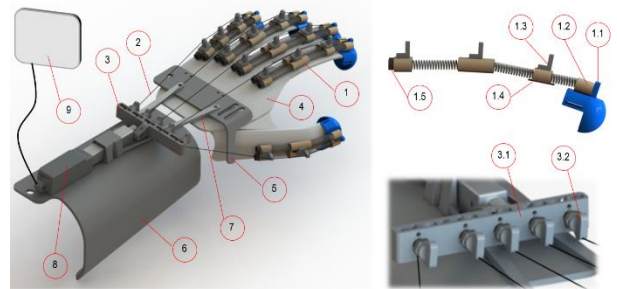
### 2.3. Final Design of DS2

The pre-design study indicated that DS2 was the best solution in terms of both effectiveness of exercises and the other criteria. The use of a linear actuator to drive the glove with a spring mechanism is deemed to be appropriate, and so the system occupies a smaller space on the hand. The pulling cables controlling the spring system are connected to a single actuator. As the pulling cable connected to the actuator overbears the spring force when the device is operated, the fingers move from the flexion position to the extension position (Fig. 11A). Once the device reaches the maximum extension position, the actuator starts its positive (forward) movement. As the force on the cable is less than the spring force, the fingers will return to the flexion position under the spring force (Fig. 11B). By repeating these processes successively, the fingers are encouraged to perform the extension/flexion exercise.



**Fig. 11.** Finger exercises with DS2.

The back drive force applied by the actuator to the cables provides the extension movement to the fingers, and to extend the fingers properly, the cable tension needs to be adjusted. Additionally, as the fingers move towards the extension position, the linear displacement of each finger is different. Taking these factors into account, a cable adjustment device was designed for the adjustment of cable tension. The final design of DS2 is given in Fig. 12. The hand support (part 5) and forearm support (part 6) are fixed to the arm using adjustable bands.



**Fig. 12.** All components of the device. 1; spring mechanism, 1.1; finger-tip 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.

### 3. MANUFACTURING THE EXOSKELETON

As a result of experiments on spring and cable placement, DS2 has been the most appropriate design solution. Flexion and extension movements can be performed with DS2 properly. Therefore, the first prototype of the

exoskeleton was manufactured on the basis of DS2. The parts 1.1, 1.3, 1.5, 3.1, 5, 6 and 7 (see Fig. 12) were manufactured using a 3D printer (Cubex DUO, 3D Systems, Belgium). PLA filament was used in the manufacturing process. The commercially available compression spring used in the spring mechanism had a wire diameter of 0.8 mm, a mean diameter of 5.6 mm, an initial length of 59.0 mm and a spring constant of 0.8 N/mm. 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 in the exoskeleton. A microcontroller-based control circuit was manufactured to regulate the operating conditions (position, speed, force control, etc.) of the actuator. The position and the speed of the actuator is controlled by means of the potentiometer feedback. The circuit has an LCD screen, controls and a potentiometer, and the operating current of the linear actuator can be adjusted by means of the potentiometer. This allows the tensile force of the actuator to be adjusted, meaning both passive exercises and active exercises requiring patient participation can be made. Fig. 13 shows the first prototype of the exoskeleton.

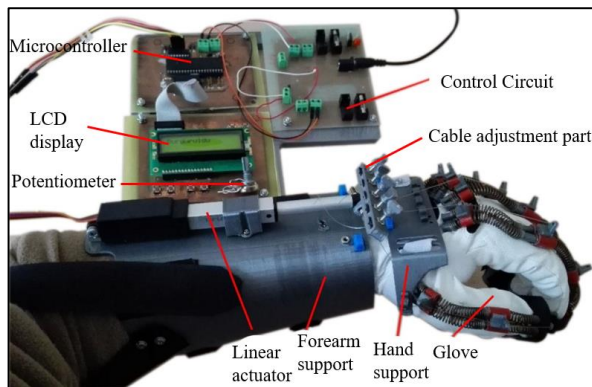


Fig. 13. The first prototype of the exoskeleton.

The palmar side of the glove was cut away and removed so that the device could be worn easily. While worn, the springs should be in the extension position, and for this purpose, steel rods pass through the springs on each finger that are removed by the user after putting on the device. The fingers are kept in the flexion position until the exercise begins, and once the exercise starts, the linear actuator of the device carries out a negative (backward) movement to bring the fingers to the extension position. The actuator carries out a positive (forward) movement, and the fingers move to the flexion position, again, by means of the cable and spring force balance. Thus, the finger exercises are made through repeated extension and flexion movements.

## 4. RESULTS

### 4.1. Evaluation of the Exercises

It is clear that the developed exoskeleton is beneficial for flexion/extension exercises. The range of motion of finger joints when the linear actuator of the exoskeleton is operated at its maximum stroke length during passive

exercises is shown in Table 4. Range of motions (ROM) of the fingers at its maximum stroke length during passive and active exercises is shown in Table 4. Our results are similar to the study in [4]. The ROM of joints resembles the cylindrical grasping movement performed very frequently during daily routines [13], and increases significantly during the active exercises that are made principally through the use of muscle power. Analysing the motion analysis data, the exoskeleton can be said to be well suited to finger exercises.

The operating current of the linear actuator on the device is regulated by means of the potentiometer on the control circuit. By adjusting the current to maximum during passive exercises, the force required to drive the spring system is provided by the device's actuator; and by reducing the current by means of the potentiometer, the force required to drive the spring system can be adjusted by the actuator and the user's muscle power.

Table 4. Range of motions (ROM) of the fingers.

Segment	Joint	DOF	ROM/ Passive	ROM/ Active
Thumb	MCP	Flexion/Extension	35°	65°
	IP		15°	50°
Index, Middle, Ring, Pinky	MCP	Flexion/Extension	25°	40°
	PIP		45°	55°
	DIP		55°	60°

During the rehabilitation process, the device's actuator connection can be completely removed, allowing the exercises to be carried out based on user's muscle power only. The spring system designed specifically for the exoskeleton produces a force of approximately 6 N on the tip of each finger when the fingers are at the extension position. The distal end of the glove's finger was pulled a digital hand scale and the finger was brought to the extension position. This process was recorded by a video camera. The spring force was calculated based on total joint angle. Using springs with different stiffness values can change the amount of force, meaning that active exercises can be made at different levels of intensity.

### 4.2. Ergonomics Evaluation

The ergonomics of the developed exoskeleton can be evaluated through an analysis of such features as wearability, suitability for individual use, weight and the volume utilized on the hand. The exoskeleton can be worn easily and fits the hand perfectly when manufactured according to the anthropometric characteristics of the user. If one of the user's hands is unimpaired, it can be used without the assistance of others.

The exoskeleton has also an advantageous in terms of its geometric properties, taking up only as much space as the hand and forearm breadth on the coronal plane. On the sagittal plane, it occupies a space to a height of 2–3 cm on the forearm. In terms of its geometric dimensions, the exoskeleton offers a significant advantage over systems

that transmit motion via a mechanism [14, 15]. In terms of size, it is similar to systems with a soft actuator [7, 8]. The part of the exoskeleton worn on hand weighs 345 grams, and the entire system, including the control circuit and adapter, weighs less than 750 grams. These values indicate that the device is light. The weights of the wearable hand rehabilitation devices developed in previous studies are given in Table 5. Since the exoskeleton is light, it can be carried with ease and used at home.

**Table 5.** Weight of some previous rehabilitation devices.

Ref.	Force transmission	Weight (g)	Description
[3]	Linkage	500	Excluding control unit
[7]	Soft actuator	3600	Glove + Hydraulic system
[16]	Tendon driven	700	Glove + Power unit
[17]	Linkage	1500	Exoskeleton + Actuation
[18]	Linkage	400	Excluding control unit

#### 4.3. Users' Observations

Both unimpaired (3 females and 5 males, mean age  $24,75 \pm 4,43$ ) individuals and patients (3 female, mean age  $54,66 \pm 7,09$ ) with a hemiplegic hand tested the developed exoskeleton. The unimpaired individuals were able to wear the device easily and, in general, found the device to be comfortable. They stated that they felt a slight pressure on their fingertips when doing protracted exercises exceeding 20 minutes, for which the design of the fingertip part (see Fig. 12, part 1.1) can be improved. The users also noted that the parts constituting the exoskeleton could be in different colours.

The exoskeleton was tested by three adult female patients in the Physiotherapy and Rehabilitation Clinic at Sakarya University Faculty of Medicine Hospital (Fig. 14), all of which had a hemiplegic problem in their left hand. First, the patients were asked to put on the exoskeleton by themselves. As the patients were only able to control their right hands, it took them 20 minutes to put on the device, but only 5 minutes when assisted by someone else. After putting on the device, they engaged in short passive exercises under the supervision of the clinic physician. The physician reported that the exoskeleton was suited to passive exercises.



**Fig. 14.** A hemiplegic patient with the exoskeleton.

#### 4.4. Market Evaluation

We are planning to develop the exoskeleton commercially. The manufacturing cost of the prototype is less than \$150. The fact that the device lacks biofeedback control reduces the cost, but this case decreases the device's functionality. Devices with biofeedback control, and thus high functionality [3], usually have a high price. The device distributed in Turkey under the name "Hand of Hope" sells for \$72,000. As these devices are no longer needed when the rehabilitation process has been completed, the high price prevents their widespread use. There are about 9 million people around the world suffering from paralysis annually that are in need of rehabilitation [19]. Producers of devices for individual users need to balance between functionality and price, and from this perspective, the exoskeleton we have developed can be considered advantageously.

#### 5. DISCUSSION

This study suggested that the development of an original wearable exoskeleton that is suitable for use at home, portable, low-cost, and allows for active and passive exercises. The initial trials of the exoskeleton on patients presents appropriate results, and the next step will be to explore the effects of the long-term use of the exoskeleton, particularly for hemiplegic hand rehabilitation, on the treatment process.

It is clear that both DS2 and DS3 are original designs. In future studies, focus will be on the improvement of the designs with a view to developing a commercial product.

The glove with the spring mechanism developed on the basis of DS2 can be used unaided, and allows patients to do engage in exercises to increase muscle power. When the fingers are in the extension position, a slight buckling occurs on the spring system, and in order to mitigate the buckling, two rows of springs were tied to each other in this study. To overcome this problem, special springs may be manufactured for use in rehabilitation systems.

The fact that the exoskeleton has a single degree of freedom makes it easier to control, while also reducing cost. The fact that all finger movements are supported by a single actuator limits the range of motion of the thumb joints during passive exercises, and so an additional actuator may be used for the thumb that moves on a different plane from the other four fingers, although this will increase the cost. As an alternative solution, the thumb may be fixed at the extension position, and exercises done with the remaining four fingers.

#### ACKNOWLEDGMENT

This study supported by The Scientific and Technological Research Council of Turkey (TUBITAK) with project No. 115M622. We thank Prof. Dr. İbrahim Tekeoglu of Sakarya University for contribution to patient trials and Assoc. Prof. Dr. Arno H. A. Stienen of

Northwestern University for contribution to spring mechanism design of DS2.

## DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

## REFERENCES

- [1] Kwakkel G., "Intensity of practice after stroke: More is better", *Schwizer Archiv für Neurologie und Psychiatrie*, 160(7): 295-298, (2009).
- [2] Amirabdollahian F., Ates S., Basteris A., Cesarino A., Buurke J., Hermens H., Hofs D., Johansson E., Mountain G., Nasr N., Nijenhuis S., Prange G., Rahman N., Sale P., Schatzlein F., van Schooten B., and Stienen A., "Design, development and deployment of a hand/wrist exoskeleton for home-based rehabilitation after stroke – SCRIPT Project", *Robotica*, 32(8): 1331-1346, (2014).
- [3] Tong K. Y., Ho S. K., Pang P. M. K., Hu X. L., Tam W. K., Fung K. L., Wei X. J., Chen P. N., and Chen M., "An intention driven hand functions task training robotic system", *International Conference of the IEEE Engineering in Medicine and Biology*, Argentina, 3406-3409, (2010).
- [4] Heo P., Gu G. M., Lee S., Rhee K., and Kim J., "Current hand exoskeleton technologies for rehabilitation and assistive engineering", *International Journal of Precision Engineering and Manufacturing*, 13(5): 807-824, (2012).
- [5] Hume M. C., Gellman H., McKellop H., and Brumfield R. H., "Functional range of motion on the joints of the hand", *The Journal of Hand Surgery*, 15A(2): 240-243, (1990).
- [6] Pahl G., Beitz W., Feldhusen J., and Grote K. H., "Engineering Design", *Springer-Verlag*, London, (2007).
- [7] Polygerinos P., Wang Z., Galloway K. C., Wood R. J., and Walsh C. J., "Soft robotic glove for combined assistance and at-home rehabilitation", *Robotics and Autonomous Systems*, 73: 135-143, (2015).
- [8] Yap H. K., Lim J. H., Nasrallah F., Goh J. C. H., and Yeow C. H., "Characterisation and evaluation of soft elastomeric actuators for hand assistive and rehabilitation applications", *Journal of Medical Engineering & Technology*, 40(4): 199-209, (2016).
- [9] Duan Q., Vashita V., and Agrawal S. K., "Effect on wrench-feasible workspace of cable-driven parallel robots by adding spring", *Mechanism and Machine Theory*, 86: 201-210, (2015).
- [10] Mao Y., Jin X., Dutta G. G., Scholz J. P., and Agrawal S. K., "Human movement training with a cable driven arm exoskeleton (CAREX)", *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 23(1): 84-92, (2015).
- [11] Borille A., Gomes J., Meyer R., and Grote K., "Applying decision methods to select rapid prototyping technologies", *Rapid Prototyping Journal*, 16(1): 50-62, (2010).
- [12] Birch A., Hon K. K. B, and Short T., "Structure and output mechanism in Design for Environment (DFE) tools", *Journal of Cleaner Production*, 35: 50-58, (2012).
- [13] Buchholz B. and Armstrong T. J., "A kinematic model of the human hand to evaluate its prehensile capabilities", *Journal of Biomechanics*, 25(2): 149-162, (1992).
- [14] Ertas I. H., Hocaoglu E., and Patoglu V., "AssistOn-Finger: An underactuated finger exoskeleton for robot-assisted tendon therapy", *Robotica*, 32(8): 1363-1382, (2014).
- [15] Taheri H., Rowe J.B., Gardner D., Chan V., Gray K., Bower C., Reinkensmeyer D. J., and Wolbrecht E. T., "Design and preliminary evaluation of the FINGER rehabilitation robot: controlling challenge and quantifying finger individuation during musical computer game play", *Journal of NeuroEngineering and Rehabilitation*, 11(10): 1-17, (2014).
- [16] Nilsson M., Ingvast J., Wikander J., and von Holst H., "The soft extra muscle system for improving the grasping capability in neurological rehabilitation", *IEEE EMBS International Conference on Biomedical Engineering and Sciences*, Malaysia, 412-417, (2012).
- [17] Cempini M., De Rossi S. M. M., Lenzi T., Cortese M., Giovacchini F., Vitiello N., and Carrozza M. C., "Kinematics and design of a portable and wearable exoskeleton for hand rehabilitation", *IEEE International Conference on Rehabilitation Robotics*, Seattle, 1-6, (2013).
- [18] Iqbal J., Khan H., Tsagarakis N. G., and Caldwell D. G., "A novel exoskeleton robotic system for hand rehabilitation-conceptualization to prototyping", *Biocybernetics and Biomedical Engineering*, 34: 79-89, (2014).
- [19] <http://www.world-stroke.org/advocacy/world-stroke-campaign>