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A one-DOF passive glove for thumb rehabilitation

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Abstract. Wearable robots are becoming increasingly practical to use to rehabilitate wounded parts of the body as the number of injuries to the hand, particularly fingers, has increased. Wearable robots are designed to help people save time and money. This exoskeleton is intended to rehabilitate the thumb such that it may do an opposing movement with one Degree Of Freedom (DOF) and a cable system. Two drums, one on the thumb and the other on the tip of the assistive finger place the cables, which feature a cable adjusting screw that can be adjusted for fingers of various lengths. To choose the assistive finger from 4 intact fingers, the two perspectives of the cable length changes and finger forces are compared. Finally, with the help of these comparisons, the middle finger was selected as the assistive finger. Furthermore, the cable traction forces do not hurt the fingers joins due to a safety factor of 36.78. The biggest angle difference between the thumb and middle is at 140 degrees; yet, the thumb performs better at the third joint due to the smallest angle difference.

1. Introduction

According to epidemiology studies conducted in America, stroke is the fourth cause of death and the first cause of American society disablement. Based on Oybiagele estimation in the year 2009, stroke costs about 68.9 billion dollars directly and indirectly for the country [1]. One of the most vulnerable body points to stroke is the fingers. This is because fingers are exposed to physical injuries from work with risky types of equipment in the workplace. According to epidemiology studies, about 21.44 percent of triage referrals consist of individuals with hand and wrist injuries [2]. Moreover, damages can result from accidents or other special conditions.

Usually, after surgery, rehabilitation steps need to be performed so that individuals can do the Activities of Daily Living (ADLs). Therefore, using exoskeletons is a proper choice. An exoskeleton is used for purposes of rehabilitation and motion assistance so that patients can do their ADLs and quicken the rehabilitation process. Xiang, based on his studies [3], concludes: "EMG (electromyography-driven rehabilitation training using the soft robotic hand with flexion and extension could be effective for the functional recovery of the upper limb in chronic stroke subjects with mild or no spasticity". Also Basar [4] compared the outcome of patients receiving rehabilitation with those who did not, after surgical treatment of acute and chronic tears of the Ulnar Collateral Ligament (UCL) of the thumb, and the results were that although there was not a significant change in pinch or grip, there were better results in flexion and extension of the thumb.

The point to consider during designing a wearable robot is its appropriate weight and portability. In addition, it can be adjusted for different people with different finger sizes. Exoskeletons are divided into

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two branches of active and passive in terms of their operator. Robots that have the active operator have the external force, and robots with the passive operator do not have this force, but they supply their required force from other sources to drive the mechanism. This property makes robots with passive operators, cheaper.

For thumb rehabilitation, limited robots are manufactured and designed, which are wholly dedicated to thumb movement. Correct thumb opposition and pronation movements are devised in these robots. Hence, a robot is desired that is light, cost-effective, and portable so that individuals can use it at home, and additionally, it should have a passive operator to prevent device complexity and be adjustable for various individuals. Furthermore, it should be suitable for individuals who are unable to move their thumbs, such as elder or disabled people.

We designed a robot to improve and treat the thumb that conducts the thumb opposition/reposition movement appropriately and takes the necessary force from other intact fingers to perform this movement. To this end, we selected one or more fingers among four intact index, middle, ring, and little fingers as an assistive finger capable of moving the thumb.

Among manufactured exoskeletons with pneumatic operators, the Burdea robot [5,6] can be mentioned in which pistons are placed inside the palm. The fact that the patient palm area must be free so that palm nerves can touch the objects is not considered in this robot. Noritsugu [7] and Hung [8], on the other hand, employed rubber tubes, which are known as rubber muscles, and operate as a muscle, giving the user more freedom.

In addition to exoskeletons with pneumatic operators, we also examined robots with electric operators, some of which include a bar power transmission system. Sara Koglou [9] designed a seven-degree-of-freedom exoskeleton to move the index, middle, ring, and thumb fingers. Iqbal [10,11] designed a bar mechanism for hand rehabilitation that is optimized for weight reduction, comfort, unrestricted motion, and simplicity. He considered one degree of freedom for each finger. Additionally, Bn Abdallah et al. [12] designed a 5-DOF robot for stroke patients, which is controlled by EMG sensors. Shiota et al. [13] proposed a soft thumb rehabilitation device that is based on a parallel-link mechanism and two different types of actuators into a 5-digit assist system.

Ito et al. [14] provided a rehabilitation system so that patients can easily use them. This robot has a thumb movement assisting mechanism with a parallel link structure. Furthermore, most produced robots are immobile, resulting in their large size. For portability and lightness, a small low-weight design is required, with the hand palm having the freedom to grip and position objects so that it can perform double-sided opposition for the thumb, as Lambercy [15] did in his robot. Jo et al. [16] built a one-degree-of-freedom robot with a passive operator that uses a spring to provide force and can flex and extend four fingers (except the thumb). Sanjuan et al. [17] examined the cable-driven exoskeleton for upper-limb stroke rehabilitation, focusing on the arm, shoulder, elbow, wrist, fingers, and thumb.

Robots with a cable power transmission system, in addition to robots with an electric operator and a bar power transmission system, are developed and designed one of which is described below. Stergiopoulos et al. [18,19] and Fontana et al. [20] built robots with cable mechanisms for rehabilitating the index and thumb fingers, and there are operators on hand. Overall, this system is huge and heavy. Unlike these two robots, Worsnopp et al. [21] designed and built an AFX exoskeleton, which is just for the thumb and index finger, but the mechanism of this robot can be used for all fingers. Unlike the Fontana robot, this one has operators on the hand as well as away from it. Conti's [22] robot is designed for rehabilitating index and thumb fingers, but the operators of this robot are not on the hand. This robot has a cable mechanism so that the individual can do abduction/adduction motions. Additionally, Marconi et al. [23] designed a HandeXos-Beta (HD-B) exoskeleton to rehabilitate index and thumb fingers by using SEA elastic sensors to do flexion/extension and opposition movements for the index and thumb fingers. Komeda and Mohamaddan [24] designed an exoskeleton for fingers that does flexion/extension movements and has a cable mechanism acting as a tendon and can perform a repetitive flexion/extension motion. The robot operator allows the patient to control the device. Li et al. [25,26] modeled an 8-DOF exoskeleton with a combined bar-cable system for the index and thumb fingers. The force is supplied to each of the joints through the cable and the shell, from a motor located at a distance from the hand, and these cables cause the bar mechanism to move on the joints.

Heo et al. [27] proposed a mechanism for rehabilitating fingers in which cables operate as tendons, with a cable running from a set of sheaths to fingertips, and fingers being opened and closed by pulling these cables.

We have examined active robots so far; now we will look at passive robots, which are closer to our aim, and one of the osteoarthritis models used for hand rehabilitation. This robot is designed to be passive so that the hand can execute grabbing actions. This robot drives its fingers by wrist motion, allowing fingers to grab objects by opening and closing the wrist [28]. Hernández and Cuenca-Jiménez [29] presented the architecture and kinematics of a new 2-DOF 9-bar spatial mechanism that can be utilized as a prosthetic thumb to mimic the 5 movements of human thumb joints. The mechanism replicates the movements of the interphalangeal (IP), metacarpophalangeal (MCP), and carpometacarpal (CMC) joints, with the limitation that only the movements of the CMC joint are independent, while the movements of the remaining joints are dependent on CMC movements.

This paper is organized as follows: Section 2 shows the parts of the device and the designed exoskeleton components. Section 3 introduces results and discussion which consists of three parts: 1) Obtaining the cable traction force to select the auxiliary finger, 2) Analyzing the force applied to the joints of each finger by simulation, and 3) Device performance testing. Finally, conclusions are given in Section 4.

2. Device

According to the explanations given in the previous section, the thumb opposition movement is one of the most important hand movements. Humans and other animals are distinguished by this movement. Because with this movement, the thumb is placed in front of other fingers and gives the ability to lift objects. Hence, a large number of devices for thumb mobility rehabilitation have been developed, with only a tiny percentage of them being passive.

The mechanism used in this wearable robot is a creative mechanism designed for rehabilitation exercises for injured people.

Figure 1(a) shows the view of the palm of the hand and Figure 1(b) shows the view of the back of the hand, which shows the connection between the two thumb and middle fingers.

In Figure 1(a) and (b) two "dashed line" and "straight line" cables are shown. These two cables, respectively are labeled flexion cable and extension cable. The flexion cable is responsible for bending and the extension cable is responsible for stretching the thumb. To do the opposition movement, the thumb must touch one of the index, middle, ring, or little fingers. The middle finger is selected by calculating the amount of force on each finger and simulating the force. According to Figure 1(a), the "straight line" cable is attached to the tip of the thumb, which after passing through sheath 3 on each phalange, reaches the palm of the hand and is transferred to the back of the hand by sheath 4. This cable is attached to the tip of this finger in the back of the hand, after passing the sheaths on the middle finger phalanges (5 in Figure 1(b)). In this way, by bending the middle finger, the flexion cable ("straight line" cable) is stretched and causes the thumb flexion. The lengths of sheaths 5 and 3 are calculated in a way that the change rate of cable length on the middle finger is equal to the change rate of cable length below the thumb. This means that flexing the middle finger cause the thumb flexion and vice versa. In this case, the two fingers are flexed in equal proportion to reach each other. The opposite process occurs in extension cables ("dashed line" cable). The beginning of the cable is connected to the tip of the thumb, then after passing the sheaths on this finger phalanges (6), in Figure 1(b)), it is directed to the back of the hand. It is transmitted to the palm of the hand by sheath 7 on the back of the hand. Afterward, it is connected to the middle finger by passing through sheath 8 in Figure 1(a). In this way, when the middle finger is extended,

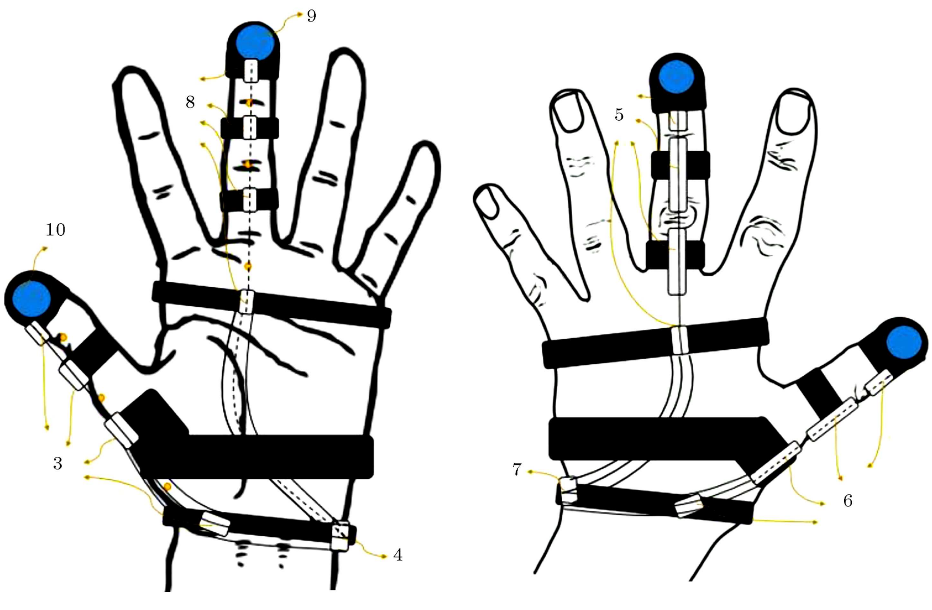

Figure 1. View of the palm and back of the hand; "dashed line" cable is labeled flexion cable, and "straight line" cable is labeled extension cable.

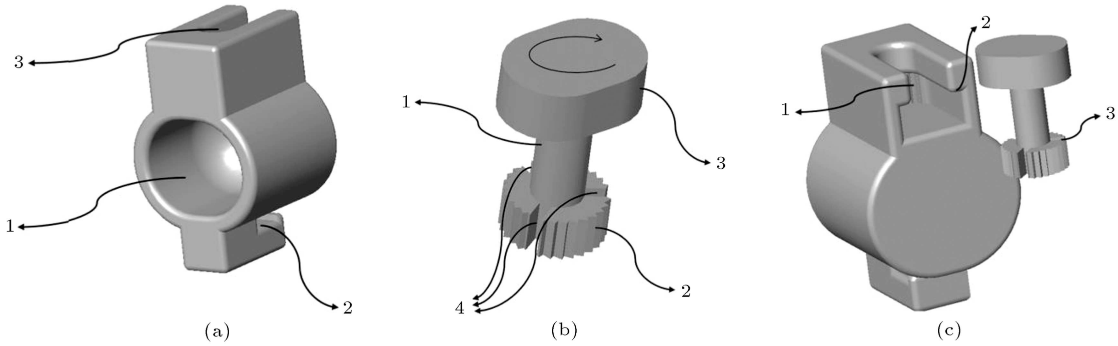

Figure 2. (a) Designed drum. (b) Cable adjusting drum. (c) The drum and its cable adjusting.

the thumb is also extended. In order to be able to adapt this robot to finger different sizes, two drums for the tip of the thumb and middle finger have been installed (9, and 10), so that the patient can initially adjust the length of the cables according to his hand. The designed drum is shown in Figure 2. In Figure 2(a), (1) is where the fingertip is placed; (2) is designed to connect the flexion cable; and (3) is the place of the cable adjusting drum.

In Figure 2(b), (1) shows the drum main body, around which the cable will be twisted; (2) shows the drum cogs used to keep the drum from rotating out of place in the ring; (3) is designed to allow the drum to be rotated with two fingers and (4) shows that shears are installed to connect the cable so that the cable passes between the two shears and is connected to the drum.

Figure 2(c) shows how the drum works and rotates in the ring cogs: (1) shows the inner cogs of the ring; step (2) was designed to engaged edge (3) and prevent the drum from moving when it is pulled.

After all the components are built by the 3D printer, we put the materials together on cloth and medical gloves that are coupled together. Figure 3 shows the assembled model.

Figure 3. The exoskeleton.

3. Results and discussion

To design and build the robot, we need to know the exact size, mass, torque, finger moment of inertia, and joint motion ranges from prior research. Holister et al. [30] discovered two axes of rotation for the thumb CMC abduction/adduction and flexion/extension after experimenting with ten bodies. He was able to locate the two axes of rotation with the help of a mechanism attached to the CMC joint's bones. In their study, Yun et al. [31] obtained the coordinates of the thumb joints while performing the opposition movement and thumb rotation. In addition to determining the characteristics of the thumb joints, they have determined the motion range of the thumb joints in each direction. The length and angle between the joints of the fingers of an ordinary person are obtained from the entropy table by gender [32]. Additionally, with the help of Digimizer software, the length of fingers' joints and the length between the fingers' joints, as well as the length and diameter of each finger's joint, have been obtained by CT scanning the author's hand [33].

Then in the precise design section, in addition to obtaining the sheath length and cable length to suit people with different finger sizes, it is very important to select the assistive finger to transmit power to the thumb to perform full opposition movement. The density of the body is 1900 kg/m^3 according to the book "Physics of the Body" [34]. In this study, because most of the finger volume is composed of bone, the total finger density is considered to be 1800 grams/ kg/m^3 Also, in the simulation part, a resistive torque is considered for each finger joint. These torques are intended to simulate joint stiffness. But in previous studies, the amount of the torque generated by muscle stiffness has not been mentioned. The torque in these equations must be reasonable. The paper [35] lists the maximum torque that MCP, PIP, and DIP joints can produce. Therefore, most of the torque produced by the joints is used as the resistive torque in the equations. Furthermore, it is designed to simulate the full flexion movement of the fingers in 7 seconds at a constant speed. In other words, this diagram incorporates the finger initial linear velocity such that it reaches a constant speed and then a negative speed after a period of time, which we set to be 5 seconds.

3.1. Obtaining the cable traction force to select the auxiliary finger

To select the assistive finger, we first obtain the cable length changes in the opposition movement in the two modes of maximum and minimum finger length after precisely designing the mechanism and calculating the cable length changes in the fingers flexion/extension motion in the two modes of maximum and minimum finger length. To calculate the cable length changes in the opposition movement, we need the joints angles of each finger in the opposite movement. For this purpose, we assume that the fingertips are in line with the MCP joint. From the following 4 equations, we obtain 4 angles of the finger joints in the opposition movement to calculate the cable length changes in the opposition movement (Figure 4(a)).

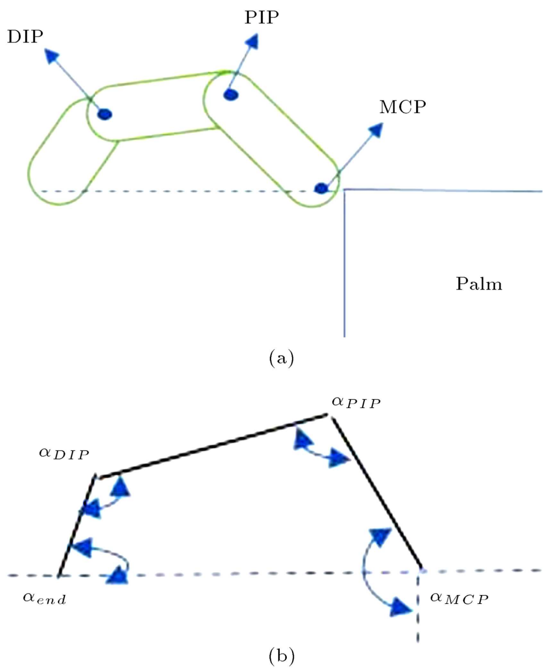

Figure 4. (a) The finger joints position in the opposition movement. (b) The joints' angles in the opposition movement.

According to the geometric relations in Figure 4(b) between joints' angle, we come to Eqs. (1)–(3) in order to calculate the amount of each angle:

$$\alpha_{MCP} + \alpha_{PIP} + \alpha_{DIP} + \alpha_{end} = 450, \tag{1}$$

$$\frac{\alpha_{MCP}}{90} = \frac{\alpha_{PIP}}{80} = \frac{\alpha_{DIP}}{100}, \tag{2}$$

$$P_1 \sin(\alpha_{MCP} - 90) = P_2 \sin(\alpha_{DIP} - \alpha_{end}) + P_3 \sin \alpha_{end}. \tag{3}$$

We calculated the cable length changes in this movement after obtaining the joint angles in the opposition movement.

According to Figure 5(a) and (b), the cable length changes are obtained by Eq. (4).

$$\Delta L = L_i + L_{i+1} - (L'_i + L'_{i+1}), \quad i = 1, 2, 3. \tag{4}$$

We obtain the L' by Eq. (5).

$$L'_i = \sqrt{(y_j^2 + y_{j+1}^2 - 2y_j y_{j+1} \cos \alpha_i)},$$

$$i = 1, 2, 3, \qquad j = 1 \cdots 6. \tag{5}$$

In Figure 6(a) and (b), P is the phalange dimension, C is the sheath length, d is the length limiter, b is the distance between the sheath and the joint, α is the angle between phalanges, a is the radios of phalanges (if we consider a cylindrical shape for fingers) and y is obtained by Eqs. (6) and (7): :

$$y = b - d, \tag{6}$$

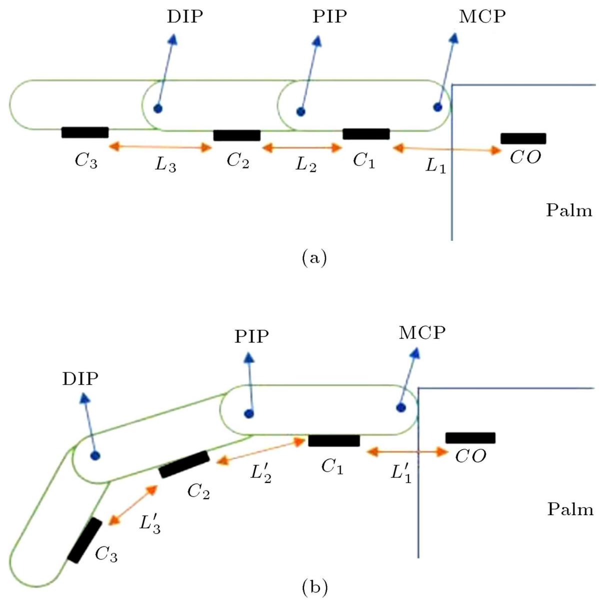

Figure 5. (a) Finger in extension mode. (b) Finger in flexion mode.

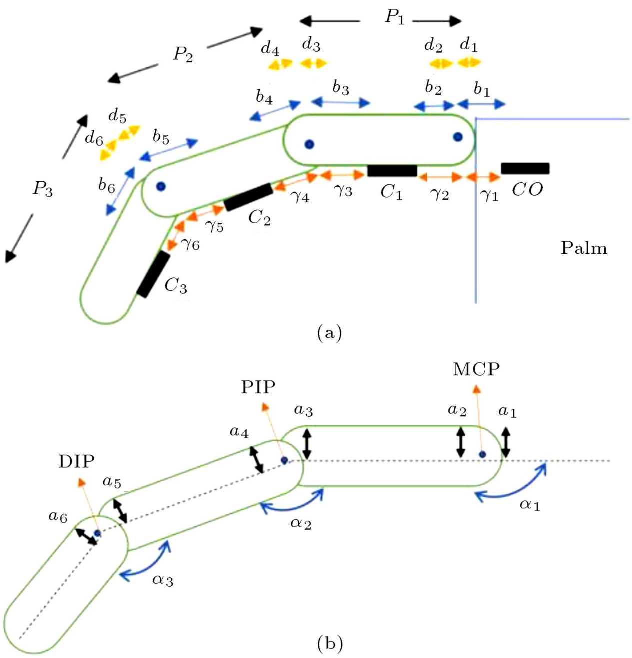

Figure 6. (a) Finger in flexion mode in detail. (b) α_i, $i = 1, 2, 3$ is the angle between phalanges and α_j, $j = 1, \cdots, 6$ is the radios of phalanges.

$$y_j = b_j - (\frac{a_{j+1}}{\sin \alpha_i} + \frac{a_{j+1}}{\tan \alpha_{i+1}}),$$

$$i = 1, 2, 3, \qquad j = 1 \cdots 6. \tag{7}$$

The length limiter is obtained by Eq. (8):

$$d_j = \frac{a_{j+1}}{\sin \alpha_i} + \frac{a_{j+1}}{\tan \alpha_{i+1}},$$

$$i = 1, 2, 3, \qquad j = 1 \cdots 6. \tag{8}$$

The cable length changes in the opposition movement for the maximum and minimum finger lengths are determined using these equations, and the results are presented in Tables 1 and 2. In these tables, the meaning of ΔL_{MCP} is the cable length change at the MCP joint and all values are in mm.

The cable traction forces of each finger are determined by calculating the static equations of the fingers free diagrams under the assumption of moving at a constant speed, with the strongest finger having the largest force.

Table 1. The cable length changes in opposition movement for minimum finger lengths.

Cable	Length changes fingers			
	ΔL_{MCP}	ΔL_{PIP}	ΔL_{DIP}	ΔL_{tot}
Index finger	7.3	4.92	6.4	18.62
Middle	12.13	8.6	9.9	30.63
Ring	9.25	6.14	7.28	22.67
Little	5.18	5.76	6.76	17.7

Table 2. The cable length changes in opposition movement for maximum finger lengths.

Cable	Length changes fingers			
	ΔL_{MCP}	ΔL_{PIP}	ΔL_{DIP}	ΔL_{tot}
Index finger	9.6	6.7	8.41	24.71
Middle	15.65	11.87	13.66	41.18
Ring	12.08	8.56	10.01	30.65
Little	7.09	7.9	9.18	24.17

Finally, we used Simulink MATLAB software finger dynamic simulation to test the right selection of the assistive finger. The static force analysis and simulation diagrams are shown in Figures 7 and 8, respectively.

In Figures 7 and 8, the greatest force occurs in the first moment. That is, the maximum amount of force is required at the beginning of the movement. Because, as seen in Figure 7, the force exerted on all five fingers is greatest at the start. Given that the amount of torque applied to each joint is assumed to be constant, and that the distance between the cable and the joint gradually increases while the movement is done, the amount of force applied during the movement is reduced. In addition, as shown in Figure 8, in dynamic simulation, to perform the motion at a constant speed,

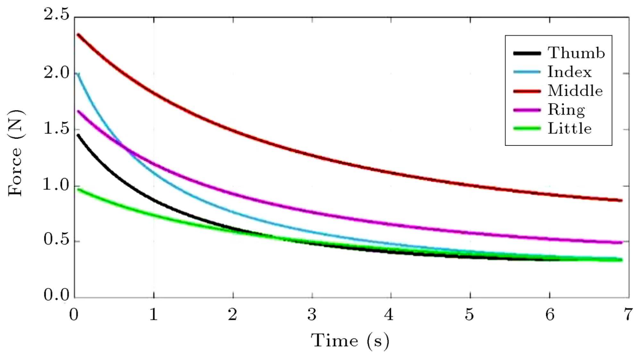

Figure 7. Static cable traction.

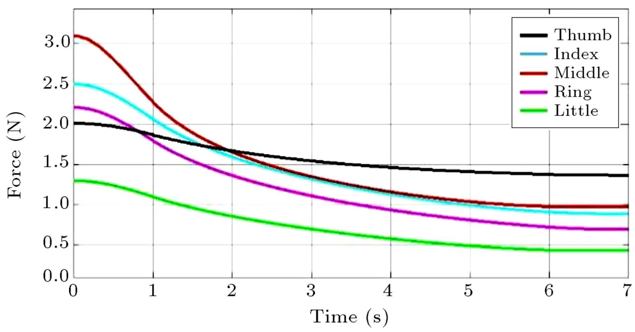

Figure 8. Cable traction in simulation.

acceleration is applied in the first second, causing an inertial force, which causes a turning point in the initial moment. By comparing the static load and dynamic simulation, we concluded that the maximum force of the cable is related to the middle finger, and thus the ability to help rehabilitate the thumb movement in performing the opposition movement. It can also be used as an assistive finger. This difference in static and dynamic forces is due to the presence of inertia.

3.2. Analyzing the force applied to the joints of each finger by simulation

The force on each finger joint, according to the resistive torque applied to each joint, has been checked in this section utilizing the Simulink MATLAB software simulation to analyze the lack of pressure on each finger joint. Figures 9–13 show the force applied to each finger MCP, PIP, and DIP joints in distinct diagrams. Qian et al. [36] have extracted the tolerance of the finger extensor tendons. The extensor tendon of the MCP finger joint can withstand an average of about 96 nm. According to the graphs, the MCP joint is where the most force is applied to the fingers. The middle finger also has the highest amount of force compared to the other fingers, which is 2.61 Newtons but based on the value of 96 Newtons, which is the average load-bearing capacity in the MCP joint of the fingers, it can be concluded that the MCP joint in the middle finger, with a safety factor of 36.78, can withstand this force, so the finger will not be harmed with this reaction force applied to the joints.

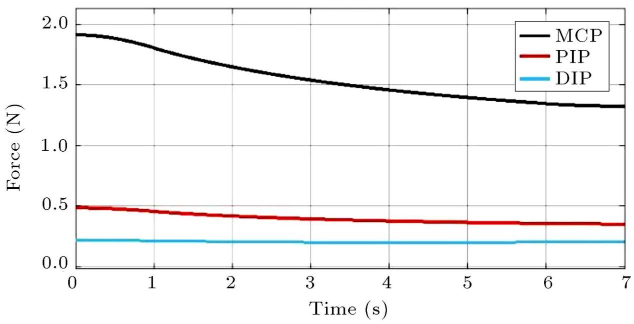

Figure 9. Force exerted diagram on the Thumb joints.

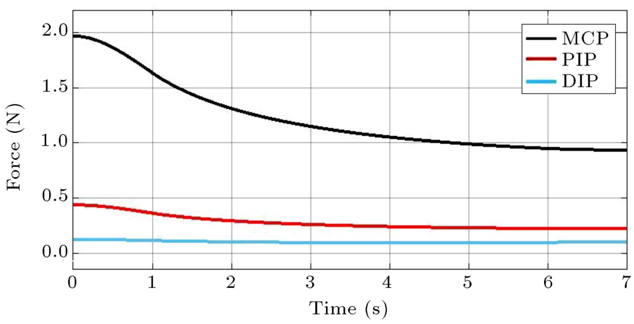

Figure 10. Force exerted diagram on the index joints.

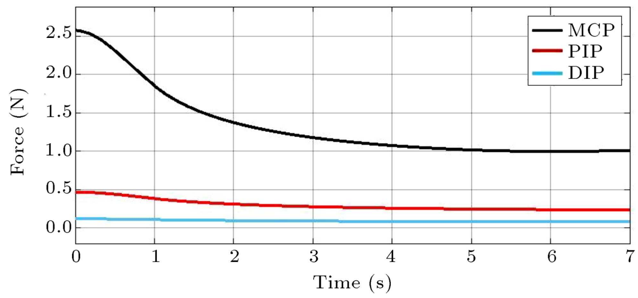

Figure 11. Force exerted diagram on the middle joints.

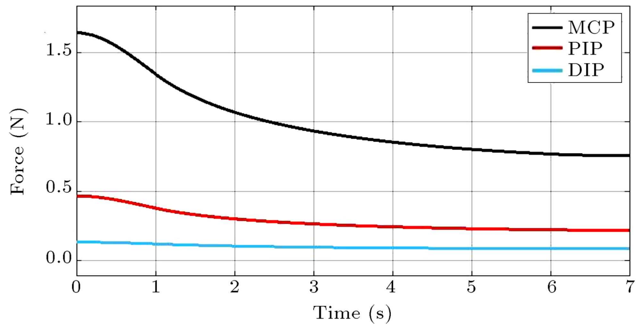

Figure 12. Force exerted diagram on the ring joints.

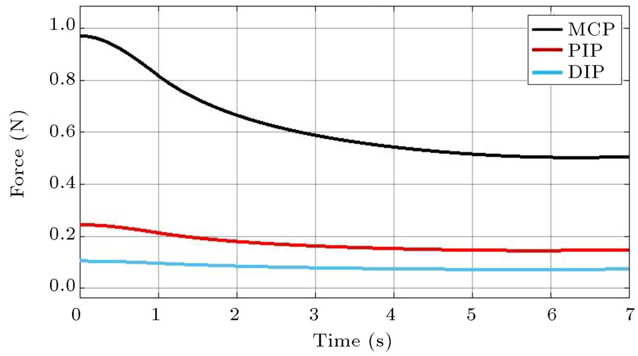

Figure 13. Force exerted diagram on the little joints.

3.3. Device performance testing

In this section, we examine the movement of the thumb in relation to the middle finger movement and how much it is delayed compared to the middle finger movement by moving the middle finger in several positions or angles; for example at angles of 170, 160, 150, and 140 degrees, in order to evaluate the device's performance. In these diagrams, the angles 170, 160, 150, and 140 degrees mean that all three middle finger joints in the first position are 170 degrees, in the second position 160, in the third position 150, and in the last position, when the complete opposition movement is performed, are 140 degrees. The results are shown in Figures 14–17.

In addition, we examined the middle finger angles and thumb in the three finger joints in Figures 18–20 as part of this experiment. The thumb angle changes

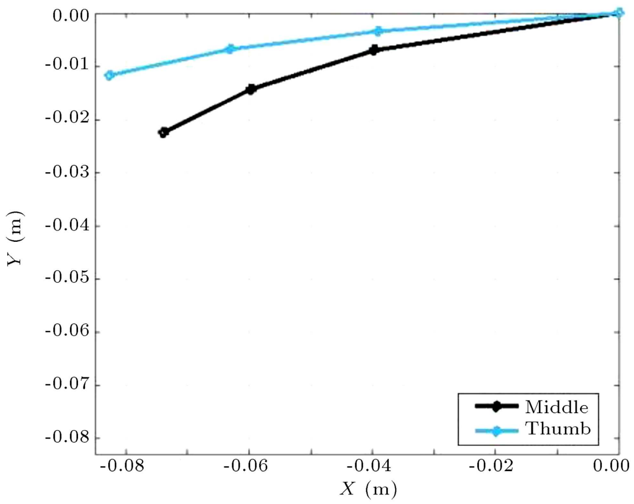

Figure 14. Comparison of the middle and thumb fingers movement at 170 degrees angle.

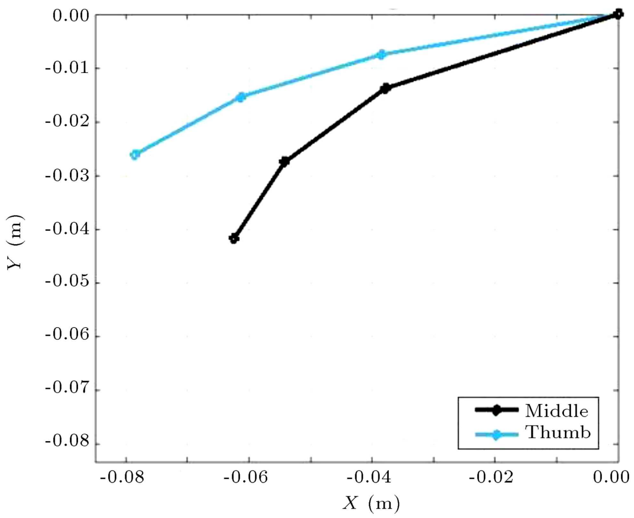

Figure 15. Comparison of the middle and thumb fingers movement at 160 degrees angle.

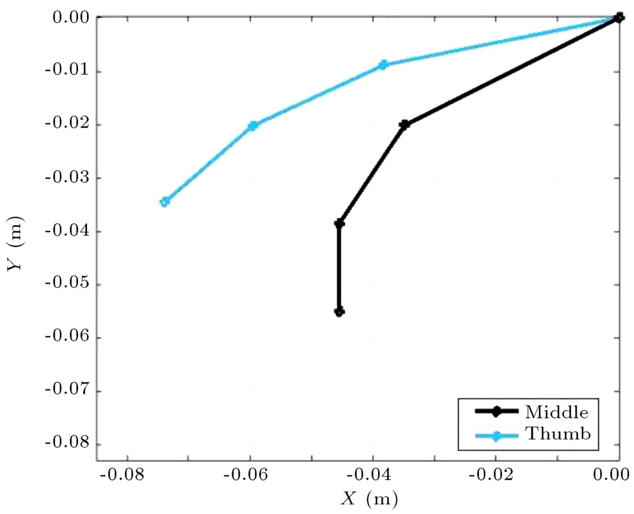

Figure 16. Comparison of the middle and thumb fingers movement at 150 degrees angle.

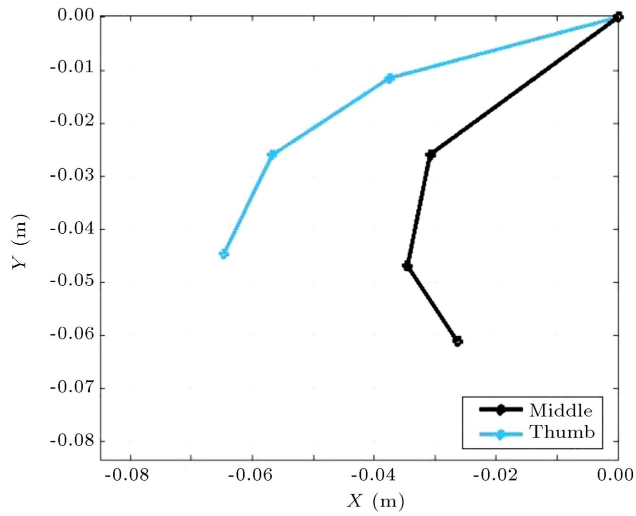

Figure 17. Comparison of the middle and thumb fingers movement at 140 degrees angle.

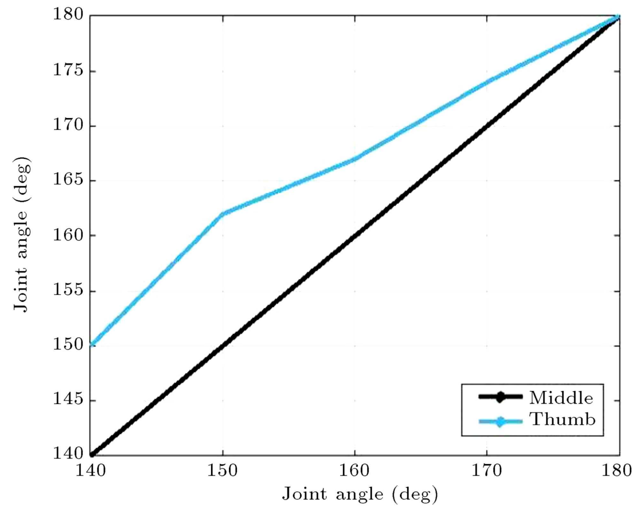

Figure 18. Comparison of the middle finger (DIP) and thumb (IP) third joint angles.

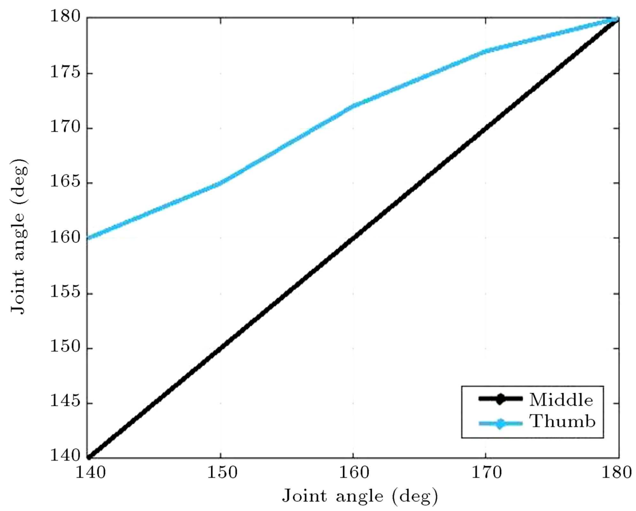

Figure 19. Comparison of the middle finger (PIP) and thumb (MCP) second joint angles.

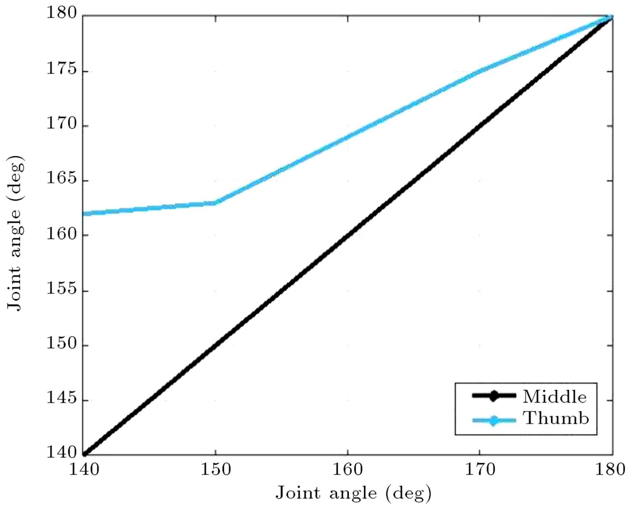

Figure 20. Comparison of the middle finger (MCP) and thumb (CMC) first joint angle.

relative to the middle finger are depicted in these graphs to see how much of a difference there is between each thumb joint angle and the middle joint angles.

The following is the conclusion drawn from Figures 14–20:

1. The average angle difference between the first and second joints of the two fingers is 10.8 degrees, 10.8 degrees for the second joint, and 6.6 degrees for the third joint, which indicates that the thumb, for example, is 10.8 degrees behind the middle finger in the first joint;
2. When performing the complete opposition movement, the highest angle difference between these two fingers is 140 degrees. The thumb's function is better in the third joint since its angle difference with the middle finger is the smallest between the first and second joints.

4. Conclusion

A one-degree-of-freedom mechanism, without the use of an external actuator, of the passive type, has a cable mechanism in which an assistive finger is utilized to move the thumb in order to rehabilitate the movement of the thumb opposition. Because the middle finger has the highest cable traction force and higher resistance than the other fingers, it was chosen as an assistive finger after solving static equations and dynamic simulations of fingers and obtaining the cable traction force.

In order to construct this robot, two drums are built at the tip of the thumb and middle finger to adjust the cable to the length of the fingers, in addition to using gloves, cables, and sheaths that are placed on the phalanges to guide the cable. A 3D printer was used to create these drums.

According to the results of the force applied to the finger joints simulation, the maximum force in the MCP joint is in the middle finger, which can withstand this force by a safety factor of 36.78, thus the finger will not be harmed by these reaction forces applied to the joints.

The average angle difference between the first joint of the middle finger and the thumb is 10.8 degrees, the second joint is 10.8 degrees, and the third joint is 6.6 degrees, indicating that the thumb motion is behind the middle finger. The largest angle difference between the two fingers is 140 degrees, indicating that the thumb function is better in the third joint because it is at a lower angle than the middle finger.

Nomenclature

$\alpha_{MCP}, \alpha_{PIP}, \alpha_{DIP}$	Joints angle
L_1, L_2, L_3	Distance between two sheaths in extension mode
L'_1, L'_2, L'_3	Distance between two sheaths in flexion mode
$b_1, b_2, b_3, b_4, b_5, b_6$	Difference between the sheath and the joint
$d_1, d_2, d_3, d_4, d_5, d_6$	Length limiter
$y_1, y_2, y_3, y_4, y_5, y_6$	$y = b - d$
p_1, p_2, p_3	Phalange length
c_0, c_1, c_2, c_3	Sheath length

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