Design and Optimization of a Mechanism, Suitable for Finger Rehabilitation

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Abstract. Due to demographic change and the aging of the population, diseases such as strokes are expected to increase over the years. In this situation, the medical sector is reaching its capacity limits, making any solution that takes over time-intensive treatments that can be standardised relevant for the future. In this paper, a mechanism for finger rehabilitation therapy is presented. After identifying the requirements, a detailed investigation of the current situation of hand rehabilitation devices is presented. A working prototype for fingers is designed and built to show the capabilities of the mechanism. It can be operated independently and is adaptable to different hand sizes. The prototype consists of a linear microdrive connected to the finger mechanism via Bowden cables. Additive manufacturing (AM) was mainly used as the production method. The prototype was successfully tested on four people with hands of different sizes. It allowed an actuation of 85 to 110° for all joints. Different settings of the Bowden cable allow the actuation of different sections of the finger. Different settings of the mechanism, actuator, control analysis and optimization are presented.

Keywords: Finger rehabilitation · Bowden cables · Control system

1 Introduction

The human hand is one of the most versatile limbs nature has ever created, and it plays a significant role in the evolution of the species. Strokes are one of the most common diseases affecting the neurological functions needed to control the human hand. More than 200,000 patients suffer from it every year, in Germany alone [1]. Studies show that immediate therapy involving repetitive movements of the paralyzed limb helps to regain normal function more quickly [2]. Depending on the focus of the work, different approaches can be used to classify hand rehabilitation devices. According to Yue et al. [3], devices are classified into three categories: Mechanical linkage, cable-controlled and pneumatic/hydraulic mechanisms. Mechanical linkage systems use a direct connection between an energy source such as a motor or actuator and the end effector, which is connected to the fingertip or joint. Cable-driven mechanisms for rehabilitation devices can be subdivided based on the use of cables or Bowden cables [3]. As the name suggests,

A. Cunha et al. (Eds.): MobiHealth 2022, LNICST 484, pp. 69–77, 2023.
https://doi.org/10.1007/978-3-031-32029-3_7

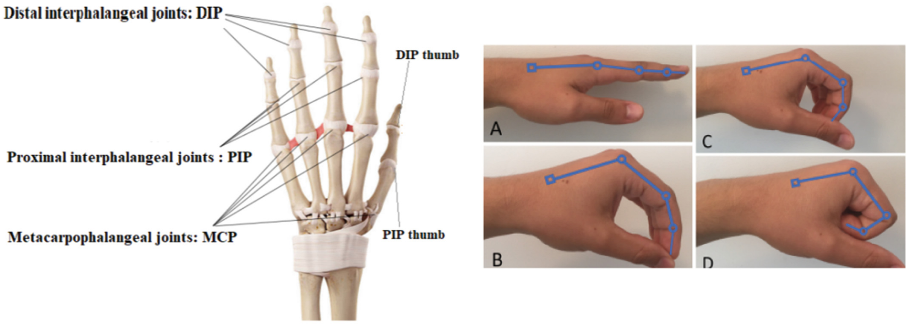
the Bowden cable relies on the pulling of the cables to generate torque for the joints. The movement of the Bowden cable is not as precise as that of the cable pull, as it is not under constant tension. For devices with a high number of degrees of freedom (DOF), Bowden cable mechanisms are used because they have a lower demand for actuators and cables. Hydraulic or pneumatic mechanisms with pneumatic power transmission are not common in rehabilitation or research applications. A disadvantage of the hydraulic approach is that handling a fluid in a medical environment can cause hygiene problems. At best it is water, at worst oil, but this always increases maintenance. Also, vibrotactile is a very useful idea for rehabilitation, but the use of different tactile systems makes the system expensive and difficult to control. So the main aim of this system is to propose a simple system that can be used alongside other vibrotactile systems [4].

2 Design of Mechanism

Some basic details of the motor functions and structures of the human hand are described here, which are needed to establish the requirements for the design process of the mechanism. Then a diagram of the functionality of the rehabilitation device, the requirements and the design steps and the derived units are explained.

2.1 Anatomy of the Hand

The fingers of the human hand have three joints: the MCP, PIP and DIP. They are all hinge joints that allow one degree of freedom. The thumb is an exception, as the MCP is positioned at the wrist and thus represents two DOF saddle joints (Fig. 1).



a. Joints of the fingers [5]

b. Different stages of flexion

Fig. 1. Schematic of finger and its flexion

Research has shown that studies that focused on a single movement of all three finger joints resulted in a very complicated and large device [6, 7]. This would clash with the requirement for a simple and cost-effective design. Therefore, this study focuses on the two proximal joints of the finger (MCP and PIP joints). Table 1 shows the different flexion angles of the individual joints according to Fig 1b.

Table 1. Joint angles in different stages of flexion

	MCP	PIP	DIP	SUM
A	0	0	0	0
B	50	40	20	110
C	45	55	40	140
D	65	95	55	215

2.2 Requirements

The first step in developing a mechanism for rehabilitating fingers is to define the requirements on which the following steps will then be based. Figure 2 shows the general structure of the desired device. All requirements in terms of weight, size, portability, operating time, harmlessness and efficiency should be evaluated. This system should weigh less than 1.5 kg and the flexion/extension angle should be between 100° and 140°.

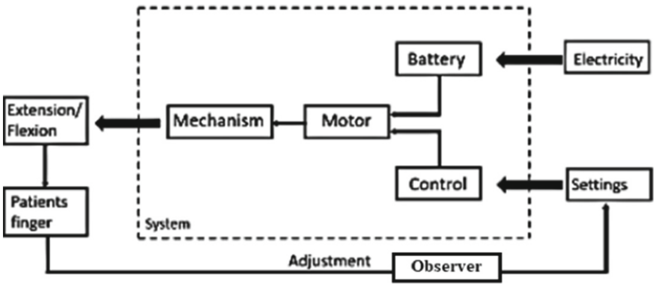


Fig. 2. Block diagram of the rehabilitation device functionality

2.3 Iterative Design

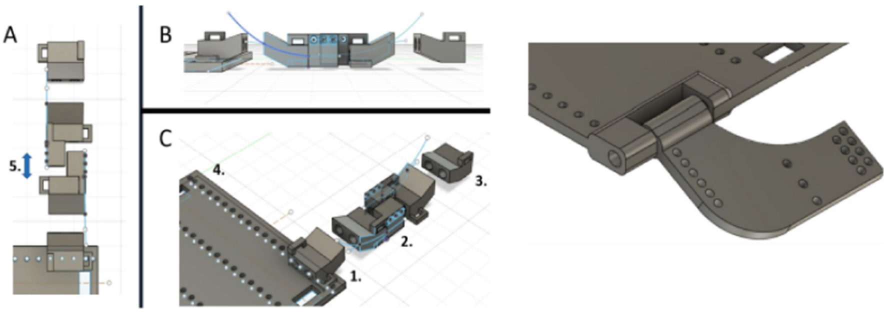
2.3.1 Approach

Based on a literature review and after weighing the advantages and disadvantages of the approaches mentioned in the introduction, the decision was made in favour of cable-controlled mechanisms. They can harness the potential of additive manufacturing (AM) for efficient design at a low cost, while the solid and durable steel cable provides the power transmission. This was preferred because the surface quality and durability of the AM parts could not be guaranteed. The Bowden cable can perform movements in both directions and requires only one drive, one fixation point and one guide for flexion and extension of the finger. This advantage over cable mechanisms leads to the decision to use the Bowden cable. Since this work develops a mechanism that can be used for all kinds of devices, a versatile applicability should be ensured.

2.3.2 Design

In this step, two different design approaches were considered and tested, the problems of the first design were analyzed and a new approach for the second design was developed. The problem of unnatural movement of the fingers was solved by moving the mechanism to the back of the finger and passing the attachments through the side space only. The two cables on each side of the finger and their guides were combined in a bridge on the top of the finger (Fig. 3). On the back of the hand, the baseboard (Fig. 3a–4) is mounted, to which the first segment (Fig. 3a–1) of the mechanism is attached. This segment is identical to the most distal segment (Fig. 3a–3). The adjustable length for different finger sizes is solved by dividing the middle part of the mechanism (Fig. 3a–2), which lies on the first finger segment (phalanx proximal). Section A in Fig. 3a shows this in the top view of the mechanism.

Looking at a prototype for different fingers shows the principles that can be adapted to form a complete hand rehabilitation device. The mechanism is designed to be modular to fit all fingers, but the connections and details to build the whole device are not addressed. Nevertheless, a possible solution for the different mechanical situations on the thumb was considered. Cheng et al. used an extension of their base plate to reach the thumb [8]. This idea was taken up and extended. To make the system suitable for different uses, a rotation axis was added to the extension plate to allow different thumb positions for maximum applicability.



a. Designed mechanism b. Thumb connection solution

Fig. 3. Designed mechanism and Thumb

The Bowden cable mechanism has already been identified as a practical way to transmit the force of the actuator and transfer the torque to the joint. Cheng et al. [8] used a 0.265 mm cable for the pulley mechanism in their development. Initially, a twisted steel cable with a diameter of 0.8 mm was chosen for the system, but it turned out that this size was too thin to transmit the force. A small resistance on the mechanism resulted in a bend before the first segment. After increasing the diameter to 1.5 mm, which could not be bent to a required radius, the perfect size of 1 mm was found. The tab at the end of the cable is connected to a pin or screw on the linear actuator and moves through the holes in the segments of the mechanism. Additive manufacturing is used as the crucial production technology. Better known as 3D printing, additive manufacturing enables new possibilities in engineering and design. As the name of the process suggests, an object is made by joining materials together.

2.4 Drive Units

To operate the stiff Bowden cable, it was decided to use a linear actuator. This allows a precise movement and defines the actuation of the cable. The Bowden cable does not bend around an axis of rotation, thus preventing frictional forces and deformation. After a complete research and a market comparison, the Actuonix L12/16 micro linear actuators (see Fig. 4) proved to be the best choice to meet the requirements.

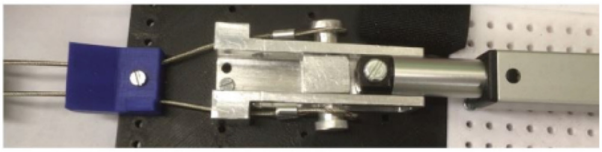
In this system, the LAC board automatically reduces the input voltage from 12 V to 3.3 V at the P+/P− terminal for the potentiometer. The control is done by a voltage adjusted with a potentiometer. A potentiometer with 10 kilo-ohm (kΩ) and a rotation angle of the rotary switch of 270° was chosen. Measurements were taken to determine the actual speed at the different angles of rotation of the switch, and the average of four measurements was taken to reduce the error due to manual data collection. It is noticeable that the actuator is slightly faster on the way back than on the way out. This should be taken into account when setting the speed manually and not via the software. Table 2 shows the stroke times for different speeds.

Table 2. Stroke times for different speeds

Speed	100%		75%		50%		25%	
Time (s): Forward/Backward	6.0	5.6	6.7	6.3	7.5	7.1	13.4	12.6
mm/s	6.7	7.1	6	6.3	5.3	5.6	3	3.2

A 12 volt (V) lithium battery with 11 ampere hours (Ah) was chosen to supply the required energy. The actuator's data sheet gives a quiescent current of 650 milliamps (mA) at 12 V voltage. The device was tested on the left hands of four different people. Care was taken to include different hand sizes in the sample. In all cases, the prototype was attached to the hand and was able to actuate the finger in the desired manner. When the device was mounted, the connection between the mechanism and the actuator made the mechanical transmission of the force difficult. This led to a high risk of this part getting jammed. After you have attached the device to your finger and switched it on, you can control the stroke of the actuator with the rotary switch on the control box. When the settings are adjusted, you can control the speed, the accuracy and the end positions of the stroke with the small screws on the board LAC. When the settings have been changed, the board LAC must be switched on before the adjustments take effect.

You can see the extension and flexion in the two cable set-ups in Fig. 5a–B. The mechanism is able to flex the finger joints by 85° to 110°. The second set-up locks the MCP and only actuates the two distal joints of the finger (PIP and DIP). This allows a combined angle of 80° to 100° for these joints. Possible factors for the variation of the determined angle are Installation position and precision, finger size, actuator, influence

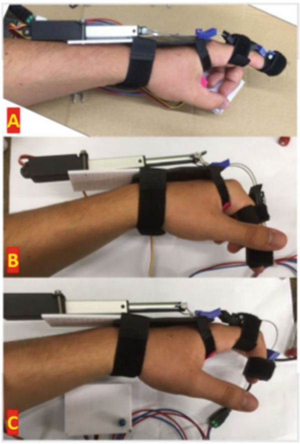


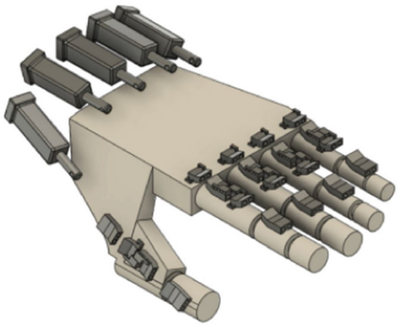
a. Assembled connector

b. Mounting of the device c. Electric components

Fig. 4. Designed and assembled mechanism

of the cable connection by the test person, hand orientation. Figure 5b shows the device for the whole hand.





a. Resulting flexion of different setups **b.** Device for the whole hand

Fig. 5. The designed mechanism, its flexibility, and 3-D geometry

2.5 Closed-Loop Controlling System

To ensure safe rehabilitation, such a positioning system needs adequate speed control. For this purpose, three control approaches were analyzed with Simulink, presented in the following section and ordered according to their complexity. In this study, three different variants of the Simulink models were analyzed in detail. The three variants are ordered according to their complexity. The first is a simple model of a unidirectional system. The second variant allows changing the direction and the type of movement. The third variant is the final, complete simulation that includes noise and disturbances. For each DoF of the system, there is a characteristic threshold angle. This angle represents the physiologically maximum permissible angle necessary to ensure patient safety [9]. This robot can be configured to allow flexion and extension of a finger. The third variant of the system is the final and most complete robot model. However, the second variant only represents an ideal situation in which the system block operates without interference or noise. To simulate a more realistic situation, noise and interference are necessary additions. To test and analyze the behaviour of the system with these external influences, one must consider the third variant of the model (Fig. 6).

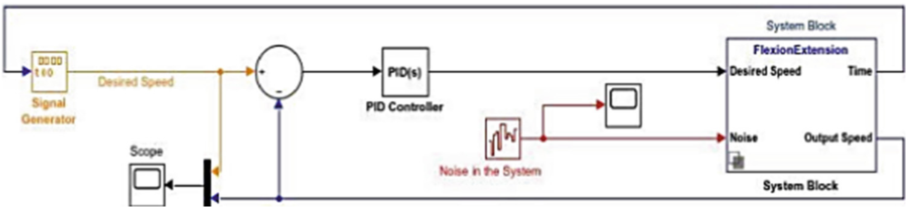


Fig. 6. The General Model of the 3rd Variant

The controller used is a PID controller. Three different tuning methods are implemented: manual tuning, MATLAB automatic tuning and Ziegler-Nichols tuning method, and after comparing the results, the manual tuning method is chosen. In manual tuning, the coefficients of the PID controller are changed manually depending on the main output. The aim of manual tuning is to design the controller in such a way that the overshoot remains close to zero, i.e. below 1%, and the rise time and settling time are significantly reduced. Ideally, the rise and settling time should be kept below 0.05 s. The results for the middle finger are shown in Table 3. From these results and the diagram shown in Fig. 7, it can be concluded that the tuned response is suitable for the system and that the system is stable.

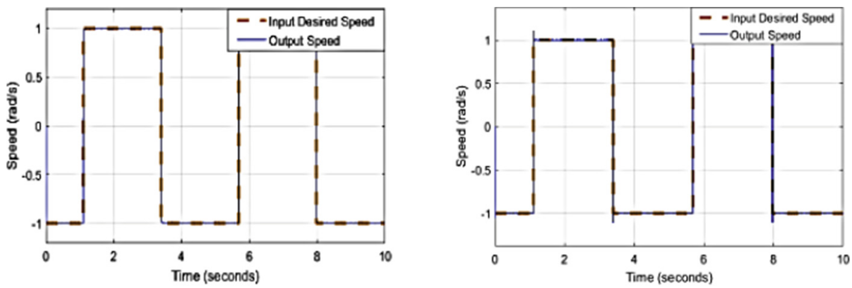
Table 3. Variant 2 and variant 3 PID Parameters and Response (Manual Tuning)

Variant 2		Variant 3	
Controller Parameters		Controller Parameters	
P	10	P	20

(*continued*)

Table 3. (*continued*)

Variant 2		Variant 3	
Controller Parameters		Controller Parameters	
I	450	I	1000
D	0.01	D	0.01
N	100	N	100
Rest time	0.000612 s	Rest time	0,000296 s
Settling time	0.00111 s	Settling time	0.000846 s
Overshoot	0	Overshoot	5.73%
Peak	0.99	Peak	1.06
Gain margin	-	Gain margin	-
Phase margin	74.8deg@ $2.61e^{+03}$ rad/s	Phase margin	63.3deg@ $4.62e^{+03}$ rad/s
Closed-loop stability	Stable	Closed-loop stability	Stable



Variant 2. Flexion/Extension Variant 3. Flexion/Extension

Fig. 7. Manually Tuned Response for variant 2 and variant 3

3 Conclusion

In this work, a mechanism was developed to allow external actuation of fingers. A prototype was made using additive manufacturing and connected to a structure that allows testing. It consists of a mechanism with two Bowden cables connected to a linear actuator Actuonix L16 with a stroke of 50 mm. This actuator is controlled by a circuit board that allows the adjustment of stroke length, speed and accuracy. A potentiometer was wired to the board to operate the actuator within the previously set end positions. The mechanism represents a way to implement hand rehabilitation into everyday life. It can actuate the paralyzed fingers and support the rehabilitation process. It can be operated in a mobile way and allows the patient to use it independently. The mechanism can support physiotherapists or provide quick and available rehabilitation when medical facilities reach their capacity limits. The mechanism is designed to fit all fingers. The variation of the middle segment by 6 mm to adjust its length allows for wide application. The segments can be assembled in different ways to suit the situation. For children or people with unusually short fingers, the mechanism may need to be adjusted to function precisely. A solution for the different mechanical situations on the thumb has also been introduced. It focuses on wide applicability in combination with the independent movement of each finger. Normally, rehabilitation devices with less functionality are in the range of 5,000 EUR. Taking into account typical margins, overheads and assembly costs, the purchased components of such a robotic system may not cost more than 1/5 of such a device, resulting in a maximum of 1,000 EUR. For the system presented, which provides a structure for all five fingers, the combined costs are well below this level, reaching 480 EUR in the bill of materials (BOM).

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