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Development and Implementation of an Anthropomorphic Underactuated Prosthesis with Adaptive Grip

Danilo Estay [1,*,†], Alvaro Basoalto [1,†], Jorge Ardila [2], Matías Cerda [2] and Rodrigo Barraza [1]

1 Department of Mechanical Engineering, Universidad Técnica Federico Santa María, Av. Vicuña Mackenna 3939, Santiago 8320000, Chile; alvaro.basoalto@alumnos.usm.cl (A.B.); rodrigo.barraza@usm.cl (R.B.)
2 Department of Electrical Engineering, Universidad Técnica Federico Santa María, Av. Vicuña Mackenna 3939, Santiago 8320000, Chile; jorge.ardila@usm.cl (J.A.); matias.cerda@usm.cl (M.C.)
* Correspondence: danilo.estay@usm.cl
† These authors contributed equally to this work.

Abstract: This paper describes the design of a prosthetic hand for wrist amputations. The mechanism considers the use of three actuators: one each for the movement of the little finger, annular finger, and middle finger. The second actuator controls the index finger, and the third controls the thumb. The prototype is considered relevant as it is able to move the distal phalanx in all fingers; the little, annular, and middle fingers are able to adapt to the shape of the object being gripped (adaptive grip). The sequence of movements achieved with the thumb emulate the opposition/reposition and flexion/extension movements, commanded by a single actuator. The proposed design was built by additive manufacturing and effortlessly achieves a large number of grips. Additionally, the prosthesis could perform specific movements, such as holding a needle, although this grip demands higher precision in the control of the fingers. Due to the manufacturing method, the prosthesis weighs only 200 g, increasing to 450 g when the actuators are included, therefore weighing less than an average adult's hand.

Keywords: adaptive grip; prosthesis; prosthetic hand; differential motion mechanism; actuators

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1. Introduction

The quest to improve our physical, aesthetic, and functional quality of life has inspired human beings to develop innovative solutions, helping patients subject to partial or total loss of body parts [1,2]. Technological advances have played a major role in the development of prostheses. These devices are designed to replace organs and body parts, enabling the patient's partial or total replacement of the body's functionalities [3]. Prostheses can have aesthetic or functional features, where aesthetic prostheses generally provide limited or no functionality, and are designed to resemble the host's lost limb, neglecting its functionality. On the other hand, functional prostheses aim to recreate the lost limb's functional capabilities [4].

Currently with technological advances in miniaturization, prostheses have evolved from body-powered systems [5] to mechatronic devices [2,6] capable of sensing and acting on a patient's behavior [7]. These state-of-the-art devices provide enhanced functionality due to the movement of individual components [8], combined with aesthetically appealing designs based on anthropomorphic features. However, these state-of-the-art devices face commercialization challenges, as the number of suppliers are very limited, the product is costly, and in many cases, the prosthesis does not meet the user's needs. The main design issues are related to the weight of the prosthesis and difficulties in controlling it. Therefore, it is not currently possible to avoid the use of conventional body-powered devices [8].

The mechatronic control challenge lies in the complexity of obtaining the device's input signals measured in the user's body and relating the signals to a specific movement [9]. Muscle movements are initiated by electrical brain activity, which in turn are transmitted by the nerves to the muscles that execute the desired movement, for example, a muscle contraction in the forearm that generates a movement in the hand. Signals can be measured at any point in this network. Electroencephalography (EEG) is able to monitor brain activity [10], Electroneurography (ENG) can sense nerve activity [11], and Electromyography (EMG) detects muscle activity [12]. However, even when using sophisticated techniques based on machine learning, scientists have been unable to properly correlate the electrical signals with the desired movement, regardless of the method and physically where the signal is captured [9,13,14]. A different approach involves the use of signals provided by other parts of the body to enable prosthetic movement, such as the deka arm [15], which uses a device on the foot as an additional input signal to control the hand. Although the signal retrieved is clear and does not require a complex machine learning interpretation, pressing a switch located on the foot is not considered a natural method to control hand movement.

On the other hand, the weight of the prosthesis can be problematic if it exceeds the weight of a human limb; in the case of hands, a prosthesis should not exceeded 374 g for an adult left hand and 400 g for the right hand [8]. In addition, it is important to note that excess prosthesis weight can generate discomfort and fatigue in the user [9,16,17]. The weight issue is closely related to the materials used to build the devices; therefore, there is currently an increasing trend towards additive (3D printing) manufacturing. A great number of scientific publications report the use of additive manufacturing in the design of prostheses [18], where the main advantages include: the use of lightweight materials with good resistance (ABS, PLA) [19]; shorter production times [19], and lower costs when compared with commercially available devices. The Reference Mohammadi et al. [20] reported a cost of 200 USD, Saint-Elme et al. [21] indicated 350 USD, and Krausz et al. [22] quantified the cost to be around 3000 USD, mainly because of the high torque motors used. The application of 3D printing has been validated for the design of mechanisms and structures, enabling quick checks of the design's feasibility [23]. Additionally, this type of technology allows in situ adaptation of the device to meet the user's dimensions [19]. A quick methodology for the design of user-tailored 3D printed orthosis is presented by Chaparro-Rico et al. [24], where the user's hand can be scanned and digitalized, enabling prints that are a perfect fit. Design complexity can significantly influence the device's weight. The most typical actuators for prosthetic devices are rotatory electric motors; nevertheless, current research explores other options, such as a pneumatic powered device developed by Fras and Althoefer [25], where the design, manufacturing, and control system for a soft prosthetic hand is presented. This prototype allows for independent control for each finger, and the thumb is equipped with two actuators to control flexion/extension and opposition reposition movements independently. The Reference Soriano-Heras et al. [26] developed a prosthetic hand based on rapid prototyping with shape-memory-alloy actuators. This prototype is lightweight and capable of achieving 15 different positions. The Reference Triwiyanto et al. [27] designed an anthropomorphic prosthetic hand with linear actuators controlled with the aid of electromiographic signals. The Reference Belter and Dollar [28] analyzed the prostheses available on the market, concluding that a greater number of joints implies a heavier device. It is important to consider that a larger number of joints implies more actuators, although a common design practice consists of connecting several joints to a single actuator if the kinematic chain enables this. The most common example is the connection of the distal, middle, and proximal interphalangeal joints of the fingers [29]. The index and middle fingers of the MANUS hand have three joints, each commanded to a single drive; consequently, they behave as a one-degree-of-freedom system. This is referred to as underactuation [30,31].

As described above, state-of-the-art prosthetics are not able to meet user needs when considering factors such as weight and device control problems. Therefore, these two aspects must be considered when designing a prosthesis, as well as the gains in functionality of the limb, and an aesthetically pleasing appearance. One of the best known among classic prostheses is the hook grasper prosthesis, which allows the user to grasp objects [32]. Recent technological advances are being used to develop equipment capable of fulfilling both functions, that is, prostheses must provide both anthropomorphic characteristics and allow the grasping of objects.

This paper describes the design and development of an anthropomorphic prosthetic hand with adaptive grasping characteristics. The objective of the design is focused on minimizing the main causes of user discomfort, that is, reducing the weight of the prosthesis and minimizing the number of signals required to control it. The problem is addressed by the design and manufacture of an adaptive grip mechanism. Three actuators are used to generate the hook grip, allowing for opening and closing of the five fingers by means of cables that act as tendons. Each finger was designed to close in a proximal-middle-distal sequence of the phalanges through the tension of a single cable. Opening occurs in an inverse order, but by retracting a cable acting opposite to the closing cable. The action of the five fingers is performed through a system that deferentially connects the movement of the middle, annular, and little fingers, moved by a single motor, while the remaining two actuators are used to activate the index finger and thumb. These design considerations reduce the number of actuators required to perform various movements and grips. Finally, a prototype of the design is constructed and tested through a variety of human grasping techniques.

2. Available Adaptive Hand Prostheses with Adaptive Gripping System

This section presents the main mechanical characteristics of hand prostheses with adaptive gripping systems which include the number of actuators, type of actuator, weight, time for the execution of the movement, feasible movements, and manufacturing complexity. These characteristics are explained in detail for commercial and research prostheses.

2.1. Commercial Devices

Commercial devices are scarce, and the following section describes the most outstanding devices in terms of their mechanical characteristics. I-limb [33] and Bebionic [34] are among the best-known prostheses. Both devices are very similar; they both have five electric motors [28]. Regarding their weights, the i-limb varies between 450–615 g, and the bebionic is in the 495–539 g range. Regarding the activation time, both are similar, ranging from 0.5 to 1 s for movement execution. Both designs consider a single motor to control the thumbs' movements and must be rotated manually to achieve different positions. The movement of the other fingers is similar, and both designs use a single motor for flexion/extension movements.

On the other hand, the smallest version of the Vincent Evolution 3 device [8] weighs 378 g and has six electric motors. The execution time for a single movement is less than 1 s. The movement of the thumb is controlled by two motors, and therefore, no manual intervention is required by the user for its adjustment. The remaining fingers are controlled individually and allow for flexion/extension movement. It is important to note that the manufacturing process of commercial prostheses is complex. In order to reduce weight and increase durability, the prostheses are manufactured using a wide variety of materials, including metals and composite materials.

2.2. Research Devices

A large number of devices are designed for research purposes. Table 1 presents a summary of the main devices reported in the literature. The TBM Hand prosthesis is designed for children from 7 to 11 years of age. It weighs 280 g and uses an electric motor to control the five fingers, which are able to close by adapting to the shape of the object being held. This adaptive mechanism is based on compression springs, whose design is considered simple, and does not require sensors or electronic processing for its control [35]. However, the reaction speed for the grip to closure is between 4–5 s, one of its major limitations. Additionally, the manufacturing of the device is considered complex as it requires metal machining. The RTR II weighs 350 g and features only three fingers controlled by an adaptive underactuated mechanism. It uses two motors to perform the movements, where one motor controls the abduction-adduction movement of the thumb and the other controls the flexion-extension of the thumb, index, and middle fingers [31]. Movement execution time is less than one second. However, as it has only three fingers, it cannot be considered an anthropomorphic hand, therefore losing its aesthetic appeal. The Fluid Hand III weighs 400 g and is distinguished by an actuation system based on a hydraulic pump and five valves to control the movement of each individual finger.

Table 1. Summary of research hand prostheses and their main characteristics.

Name	Weight (gr)	Actuation Time (s)	Number of Actuators	Actuator Type	Movements	Manufacturing
TBM Hand (1999) [35]	280	4–5	1	DC Motor	Adaptive grip coupled movement of the five fingers.	Complex, made of T6 aluminum.
RTR II (2002) [31]	350	1	2	DC Motor	Thumb abduction and adduction, can perform flexion in two of the ramaining fingers.	*
FluidHand III [36]	400	*	6	One pump and five valves	The movement of each finger is not described, only five achievable positions are indicated	Complex, mainly due to the pump
Smarthand [37]	520	1.5	4	DC motor	Thumb controlled by two motors with flexion/extension and opposition movements. The index finger is controlled by another motor and the rest of the fingers (middle, annular and little finger) are differentially controlled by the fourth motor.	Complex, requires machining for non-back-drivable actuation unit
Keio Hand [38]	730	1	1	Ultrasonic motor	The thumb can only perform a grasping movement (flexion), the remaining fingers can be flexed and extended.	manufacture requires complex aluminum machining.
Vanderbilt Hand [39]	580	0.5–1	5	DC motor mounted in the forearm	Opposition and flexion of the thumb and independent flexion of fingers.	Simple, additive manufacturing
SoftHand ProH [3]	520	*	1	1 motor and 1 manually operated lever	flexion/extension of the fingers	*

* This information was not published by the authors.

The time needed to perform a movement is under one second. Its major disadvantage is its manufacturing complexity, as the hydraulic components are not commercially available [36]. The SmartHand weighs 520 g, and is a human-sized experimental prosthesis, with 16° of freedom driven by four motors, allowing the movement of its five fingers. Two motors are used for the flexion/extension and opposition movements of the thumb, another motor controls the flexion/extension of the index finger, and the remaining motor is used to move the remaining fingers. Movements can be executed in under one second [37]. The manufacturing of the device is considered complex as it requires metal machining. The prosthetic hand in Kamikawa and Maeno [38] weighs 730 g and moves all five fingers with a single ultrasonic-type motor. Their design is based on a series of tendons that connect to the actuator through lever mechanisms. Movements can be performed in under one second. The thumb movement is limited to closure, and it can only be used in opposition to the other four fingers, reducing the number of attainable postures, but which results in an unnatural appearance while open. Additionally, its manufacturing is complex as it requires the machining of mechanical parts. The Vanderbilt hand weighs 580 g, and its 16 joints are driven by five motors located in the forearm, allowing movements to be performed in less than one second. Its main disadvantage is that the motors are mounted externally, making its design more applicable to transradial amputations. Moreover, its manufacturing is considered simple, as it is designed through additive manufacturing (3D printing). The SoftHand ProH weighs 520 g, and its design is based on the Pisa/IIT SoftHand, an industrial-type gripper inspired by the human hand. It has 19 joints controlled by a single motor. Control of the device requires the actuation of a lever that activates the hand. No information related to response time or manufacturing can be found in the literature.

Typically, for each of these prototypes, the number of actuators varies depending on the degrees of freedom the prototype can achieve. The analyzed designs use a maximum of six actuators, which can control the closure of each finger independently. As the number of actuators decreases, the motors are typically required to move more than one finger. As for the actuation time, most of the prototypes are able to perform movements in under 1 s, which is considered suitable for daily use activities (ADLs) [40]. It is important to note that, if the prosthesis is not carefully designed, an increase in the number of actuators results in an increase in the weight of the device. On the other hand, individual movements of each finger are considered an advantage only if control signals can be measured to allow the correct interpretation of the desired action. Finally, it should be noted that most of the devices analyzed are heavier than an adult's hand (370–400 g), and they are therefore prone to generate fatigue in the user.

3. Overview of the Main Mechanisms Used in Prosthetics

3.1. Underactuated Mechanisms for a Single Finger

The index finger has three joints referred to as distal, proximal, and metacarpophalangeal. It is complex to use three actuators to control a finger's movement, when considering the weight and volume restrictions of a prosthesis. Therefore, the operation of the joints is performed in an under-actuated system. Traditionally, there are two methods to achieve this:

- A cable-driven finger: A cable is used to connect the kinematics of the three phalanges (see Figure 1).
- Rigid Linkage System: Movement is achieved through a mechanism composed of rigid bodies (see Figure 2).

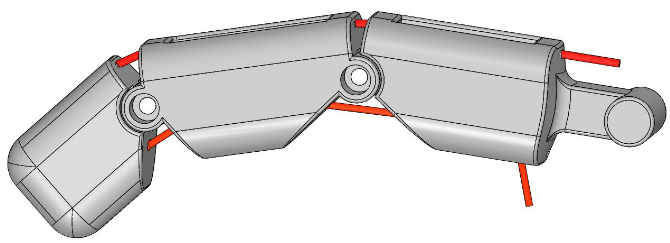


Figure 1. Finger movement mechanism using a top wire for extension and bottom wire for flexion of the finger.

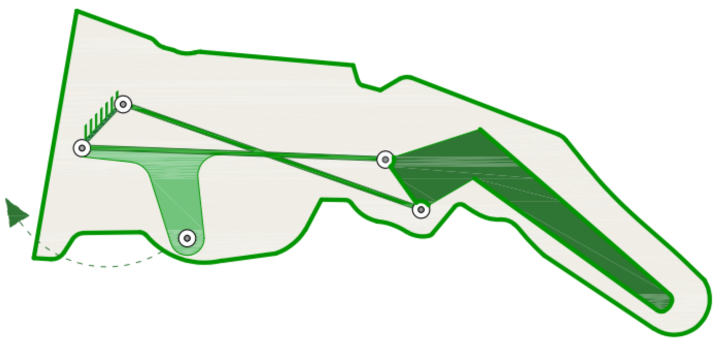
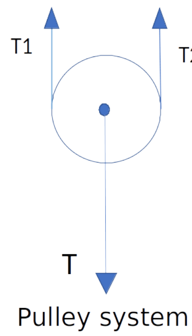
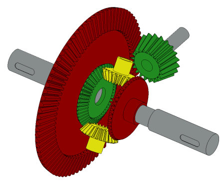
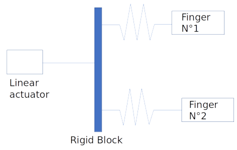
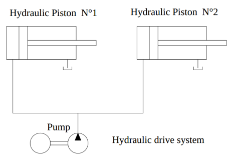
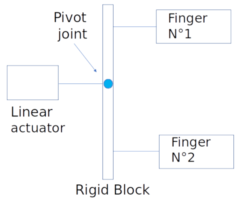


Figure 2. Finger movement mechanism through rigid connections. Distal and middle phalanges do not allow for relative motion.

3.2. *Underactuated Mechanisms for Multiple Fingers*

When considering multiple fingers, the basis for an underactuated drive is a differential type of mechanism. Table 2 summarizes the typical manners to achieve this motion. The Reference Cheng et al. [41] presented a design of an underactuated anthropomorphic finger with a self-adaptive motion. When the finger contacts an object, the movement is controlled by a coupled adaptive linkage mechanism.

Table 2. Differential motion mechanisms used in prosthetics.

Mechanism	Description	Figure
Mobile Pulleys [31,42]	When tension (T) is applied on the lower cable, the force at T1 and T2 have the same magnitude, and both upper ends move simultaneously. Once the finger connected to cable T1 touches an object, tension T1 increases and the movement is fully transmitted to T2.	
Mechanical Differential [31]	This mechanism has traditionally been used in vehicles to allow wheels on the same axle to rotate at different speeds while turning a corner. The differential mechanism allows the rotation to be transmitted to the output axle that has a lower load.	
Springs [35]	On this system, the actuator moves a rigid block which is connected to the fingers through springs. Once a finger D1 encounters an object, the rigid block, and thus the finger (D2), can move further due to the spring's compression.	
Oleohydraulics [36]	In an oil hydraulic system, the pump is responsible for generating the movement of the fluid, in turn the fluid moves through the lowest resistance path, therefore when the actuator (1) collides with an object, the fluid will flow towards the second actuator (2).	
Levers [38]	This system contains a lever capable of moving and pivoting at the point where the actuator contacts the rigid block. When the finger D1 strikes an object, the lever pivots and transmits the movement to finger D2. The relative distances from the pivot to the finger create different gripping forces for each finger.	

4. Proposed Adaptive Grip Prototype Design

4.1. *Dimensions and Range of Motion*

The prototype was designed by means of a 3D model of the bones of a hand [43] and the information acquired from [44]. The lengths of the phalanges are defined in Table 3. The palm and the back of the hand was designed to support the fingers and pulley systems required for the adaptive gripping system. In addition, the range of motion for each finger of the prosthesis is presented on Table 4 based on the functionality of the human hand [45]. It should be noted that the index, middle, annular, and little fingers of human hands are triphalangeal, and possess flexion/extension and abduction/adduction movements. Furthermore, the human thumb can perform opposition-reposition, flexion-extension, and adduction-abduction movements.

Table 3. Distal, middle, and proximal phalange measurements in millimeters for each finger of the prosthetic left hand of a man in the age range of 25–29 years. Source: Elaborated by the authors based on [44].

	Thumb [mm]	Index Finger [mm]	Middle Finger [mm]	Annular Finger [mm]	Little Finger [mm]
Distal phalanx	42	51	55	45	37
Middle phalanx	-	31	36	32	23
Proximal phalanx	34	25	27	23	20

Table 4. Movements and amplitude for the prosthetic fingers. Source: Elaborated by the authors based on [46].

	Thumb	Index Finger	Middle Finger	Annular Finger	Little Finger
Relaxed extension	60°	0°	0°	0°	0°
Distal phalanx flexion amplitude	90°	70°	70°	70°	70°
Middle phalanx flexion amplitude	-	110°	110°	110°	110°
Proximal phalanx flexion amplitude	60°	90°	90°	90°	90°
Opposition-reposition amplitude	90°	-	-	-	-

4.2. Number of Actuators

As presented in [46], one-handed grips can be classified into static, gravity, and dynamic grips, which in turn are further categorized, as shown schematically in Figure 3.

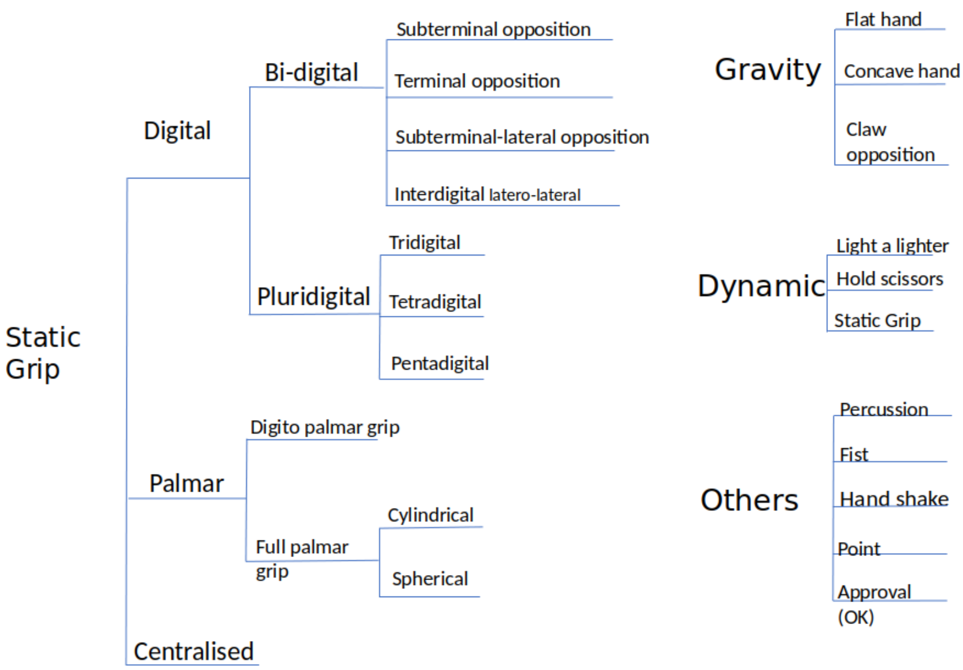


Figure 3. Human hand grip types [46].

The number of achievable grips is analyzed to select the quantity of motors required. These results are summarized in Table 5. This work considers sub-actuated movements with an adaptive grip system, varying the number of fingers moved by each motor.

- One motor is connected to five fingers.
- Two motors: one controls the thumb flexion, the other controls the remaining fingers.
- Three motors: one motor for the thumb, one for the index finger, and one for the remaining fingers.

- Four motors: two motors for the thumb, one for the index finger, and one for the remaining fingers. As this type of configuration is similar to the three-motor arrangement, it is not considered in this study.
- Five motors: one for each finger.
- Six motors: two for the thumb and one for each remaining finger.

Table 5. Feasible grips based on the number of actuators in a hand prosthesis.

			Number of Actuators					
			1	2	3	4	5	6
		Terminal opposition term-pulpezoid	Si *	Si *	Si *	Si *	Si *	Si *
		Subterminal or thumb opposition	Si *	Si *	Si *	Si *	Si *	Si *
		By subterminolateral opposition or lateral pulpex	No	No	No	Si	No	Si
	Bidigital grips	Interdigital latero-lateral	No	No	No	No	No	No
		Tridigital	Si **	Si **	Si	Si	Si	Si
		Tetradigital	Si **	Si **	Si	Si	Si	Si
Digital grips	Pluridigital grips	Pentadigital	Si **	Si **	Si	Si	Si	Si
	Digitopalmar grips		Si **	Si **	Si	Si	Si	Si
		Cylindrical	Si **	Si **	Si	Si	Si	Si
palm grips	Full palmar grip	Spherical	Si **	Si **	Si	Si	Si	Si
Centered or directional grips			No	No	Si	Si	Si	Si

* A highly coordinated finger movement or a specifically designed actuation system is required for this grip, therefore the phrothesis would be unable to achieve other holds. ** An adaptive grip system is required for some of the holds in the group.

Single and dual motor prostheses require a system that allows for complex coordination of the required movements. Generally speaking, for this type of prosthesis, a specific grip configuration is required, and this specific configuration would exclude the remaining grips mentioned in Table 5. An additional issue to be considered is that when more than three motors are used, only one grip is gained. Thus, the authors consider that the three-motor device provides a good compromise between possible grips and the complexity of the prosthesis. The technical information of the actuators is presented in Table 6. To ensure optimal control of pulley rotation, servomotors were selected.

Table 6. Actuators selected to implement the drive pulley motion.

Finger	Little, Middle, and Annular	Index and Thumb
Quantity	1	2
Servomotor model	LH2018M	MG996R
Stall torque kgf · cm at 6V	20	11
Running current A	-	0.9
Stall Current A	-	2.5
Speed at 6V degrees/seg	315	430

4.3. Design of Index, Middle, Annular, and Little Fingers

The design developed for the index, middle, annular, and little fingers is presented in Figure 4, where it can be seen that all these fingers are triphalangeal, presenting solely geometric differences. The two joints that connect the phalanges (distal and proximal), as well as the joint that connects the finger to the hand (metacarpophalangeal), allow only a flexion/extension movement.

The flexion/extension movement is controlled by the top and bottom cables, respectively, each one tied to the pulley as depicted in Figure 4. The pulley diameter allows to perform the complete movement with a rotation angle under 180°. A 0.5 mm diameter fishing line is used as a tendon, and the maximum supported force is 140 N. The finger extension movement is controlled by rotating the pulley in a clockwise direction, where the bottom cable is pulled and the top cable is released, presenting no opposition to the movement. As this grip does not require a specific phalange coordination sequence, no additional considerations were taken. When the pulley rotates counter-clockwise, the bottom cable is pulled by flexing the finger, and the top cable is simultaneously released so the motion is executed with no opposition.

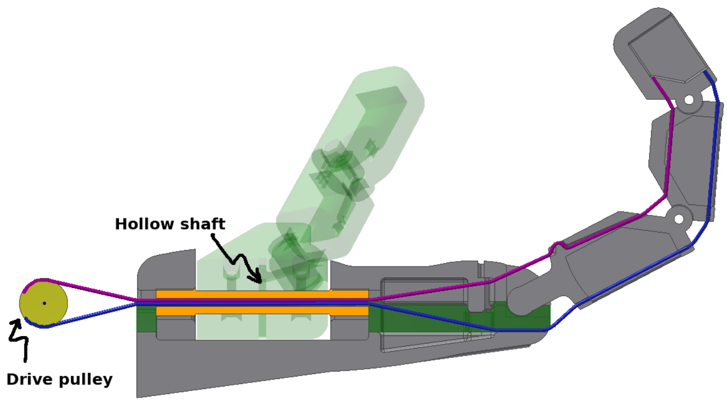


Figure 4. Lateral cross-sectional view of the index finger. The top tendon generates the flexion, and the bottom tendon, the extension movement. The connection to the pulley allows to pull only one of them while releasing the other.

To allow the fingers to wrap around the objects when grasping, the finger performs a sequential closure movement where the proximal phalange is the first to move, followed by the middle phalange, and finally by the distal phalange. This movement was achieved by varying (a) the distance between the proximal and middle phalanges, and (b) the distance between the middle and distal phalange, as shown in Figure 4. The greater this distance is, the lower the tension required to generate the movement, that is, as a > b, the middle phalange moves before the distal phalange. Figure 5 illustrates the closing sequence of the finger as the tension in the flexion cable increases. The movement starts with the proximal phalange moving 90° towards the palm (Figure 5a), followed by bending the middle and distal phalanges (Figure 5b), and finally, reaching a fully flexed finger (Figure 5e).

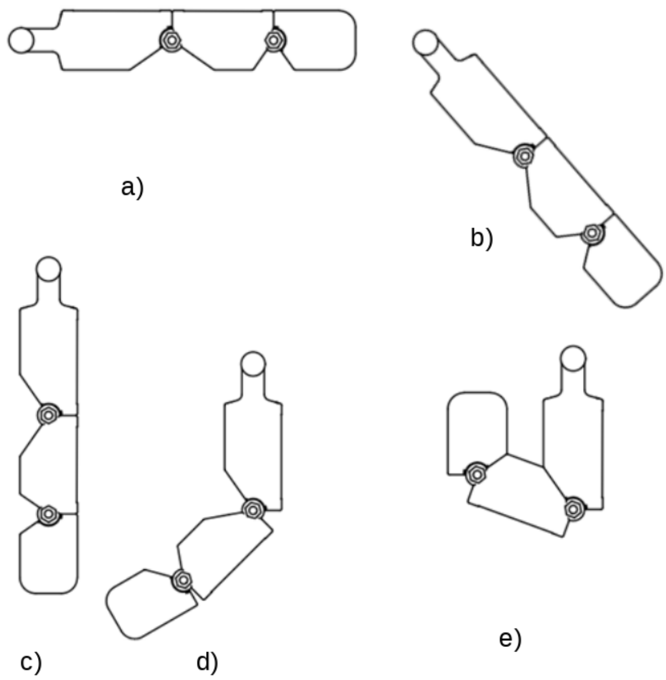


Figure 5. Coordinated flexion of the finger relative to the rotation axis of the hand in an extended position. (**a**–**c**) Flexion of the proximal phalange from a resting position. (**c**,**d**) Flexion of the middle and distal phalanges. (**d**,**e**) Completely flexed finger.

4.4. Design of the Thumb

The thumb design can perform flexion/extension and opposition/reposition movements commanded by a single cable. The execution of these movements must be performed sequentially, as shown in Figure 6. The movement starts with the opposition (Figure 6a), performing a 90° rotation relative to the red axis, followed by the flexion movement represented in Figure 6b, reaching the final position in Figure 6c. This sequence of movements is achieved in the same manner as in triphalangeal fingers, that is, by adjusting the distance between the axis of rotation and the tendon. To open the thumb, it is not necessary to follow a specific sequence as it is not used for any of the hand grasp described in Figure 3. The movement is controlled by the opposite cable, as in the other fingers. Two external cables are used to operate the thumb movements, one for flexion and the other for extension, as shown in Figure 7. Both tendons are connected to a drive pulley, as shown in Figure 4.

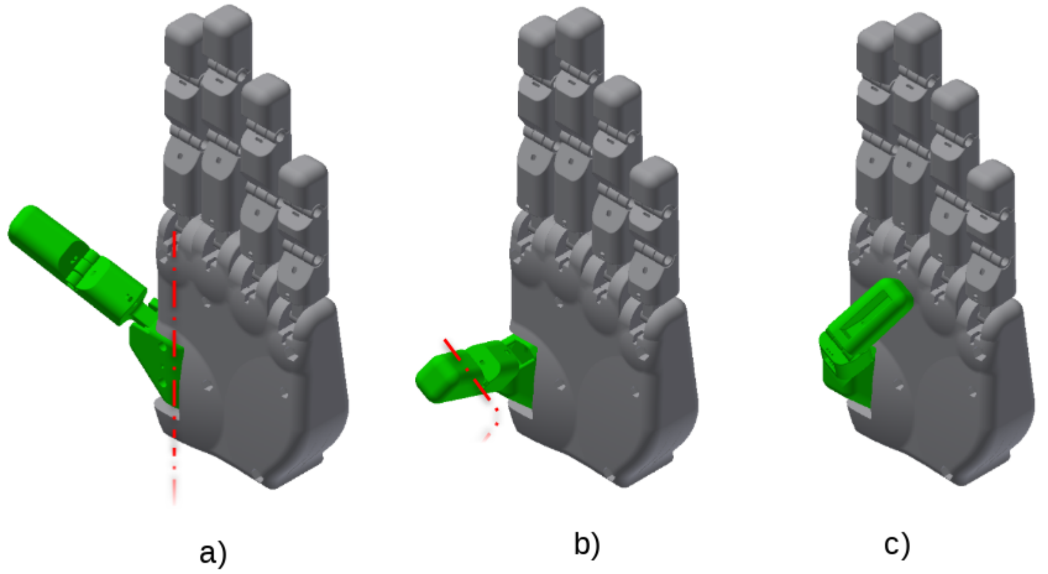


Figure 6. Coordinated flexion of the thumb relative to an axis of rotation parallel to the hand. (**a**,**b**) Oppositional movement of the thumb. (**b**,**c**) Flexion of the thumb.

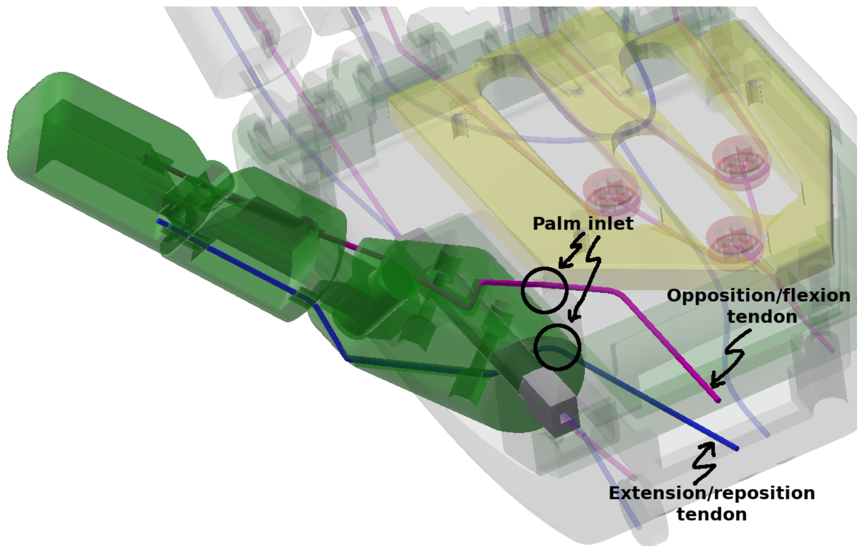


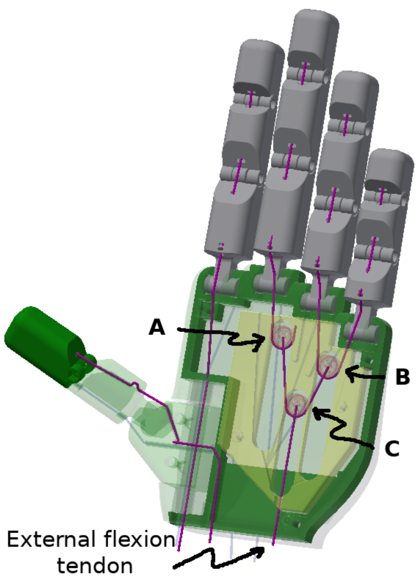
Figure 7. Diagram of the internal tendons for opposition/flexion and extension/reposition movements of the thumb.

4.5. Adaptive Grip Mechanism Design

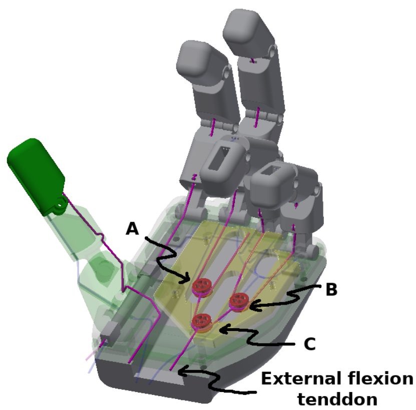
The adaptive grip gives the prosthesis the ability to adapt to the shape of the object being gripped. The index finger and thumb are moved independently by two motors, therefore their arrest is caused by direct contact with the object. The middle, annular, and little fingers are moved collectively by a single motor, a differential mechanism such as the mechanisms previously discussed in Section 3.2 is required to ensure that the movement continues when one of the fingers touches the object.

The system used to achieve the adaptive grip originally proposed by [47] is based on pulleys located inside the palm. Figure 8 shows the prosthesis in two different positions. The flexion movements are generated by the differential mechanism conformed by the purple tendons connected to the pulleys A, B, and C. The pulleys are highlighted in Figure 8a,b at fully extended and partially flexed positions. Figure 8a shows pulleys A, B, and C at the upper end of their stroke, which corresponds to the extended middle annular and little fingers. Figure 8b shows the middle, annular, and little fingers in an intermediate position achieved by the traction of the external flexion cable connected to pulley C, which in turn moves the pulleys A, B, and C through the guide. When one of the fingers touches an object, it stops and the pulley system can transmit the movement to the remaining fingers.

The extension movement is accomplished by the blue tendon highlighted in the Figure 8c,d, at fully extended and partially flexed positions. The external extension cable is tied to the three intermediate cables, and when pulled, the extension movement is performed by the middle, annular, and little fingers, as depicted in Figure 8c. The external flexion and extension tendons cannot be pulled at the same time as they perform opposite movements, and to solve this, they are connected to a single drive pulley, as seen in Figure 4. When the external flexion cable is pulled, no tension is applied to the external extension cable, enabling movements as depicted in Figure 8d.

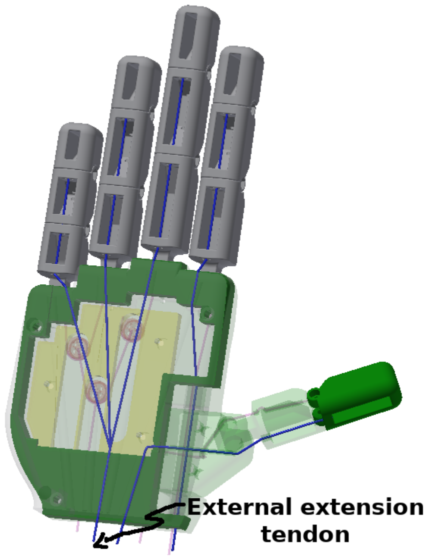


(**a**) Palmar view, adaptive grip system pulley locations for the flexion movement, with fully extended fingers.

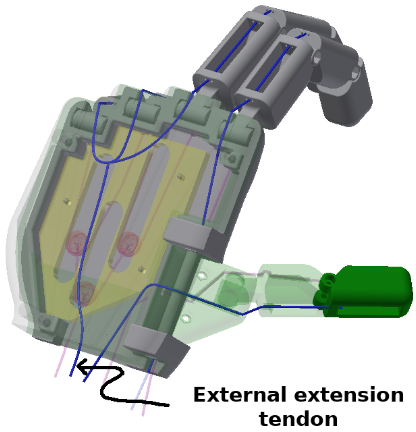


(**b**) Palmar view, adaptive grip system pulley locations for the flexion movement, with partially flexed fingers.

Figure 8. *Cont.*



(**c**) Dorsal view, cables for the extension movement with fully extended fingers.



(**d**) Dorsal view, cables for the extension movement with partially flexed fingers, note that the cable does not have any tension.

Figure 8. Diagram of the internal tendons and pulleys during flexion and extension movements of the middle, annular and little fingers.

4.6. Actuators

Usually, actuators can be placed within the prosthesis or externally. When they are placed inside the prosthesis, the palm is the preferred location, as this section has more available space. The palm space is largely occupied by the pulley system to provide the adaptive grip, therefore the actuators are placed in an external location of the prosthesis.

A final design was achieved and the prototype was constructed through additive manufacturing using a poly-lactic acid (PLA) polymer. The design is simple, requiring bolts for assembly and tendons composed of nylon yarns. The prosthetic hand weighs 200 g, which is significantly lighter than an average adult hand. When considering the external components, that is, the motors and electronics, the weight increases to 480 g.

5. Results: Performance Tests, Gripping of Various Objects

The prototype was designed to imitate a maximum number of movements of the human hand. Tests were conducted for each of the hand grips previously mentioned in Figure 3, thus testing the capabilities of the prosthesis.

5.1. Digital Grips

5.1.1. Bi-Digital Grips

Terminal Opposition

Terminal opposition is the most precise grip as it allows for the grasping of small objects. This grip is generated using the index finger and thumb, by joining them at the fingertip. Figure 9 shows the execution of the grip while holding a needle.

Figure 9. Prosthesis holding a needle through a bidigital opposition grip (terminal/terminal-thumbscrew dam).

Subterminal Opposition

This grip is similar to the terminal opposition, except that it is used to hold slightly larger objects. It is generated by using the index finger and thumb and joining them at the fingertips. This grip was not possible to achieve, as the mechanical design of the prosthesis is not compatible with terminal opposition.

Subterminal Lateral-Opposition

Achieving this grip requires abduction/adduction of the thumb, a movement that cannot be achieved by the prosthesis.

Subterminal Interdigital Latero-Lateral

Achieving this grip requires abduction/adduction of the index and middle fingers, a movement that cannot be achieved by the prosthesis.

5.1.2. Multidigital Grips

Tridigital Grip

This grip is one of the most frequently used grip techniques and involves the use of the thumb, index, and middle fingers. Figure 10 shows how this grip is executed by the prosthesis when holding a sphere.

Figure 10. Prosthesis holding a sphere through a tridigital hold.

Tetradigital Grip

This frequently used grip involves the use of the thumb, index, middle, and annular fingers. Figure 11 shows the execution of this grip by holding a ball and a screwdriver.

(**a**) Tetradigital thumb grip for holding a sphere.

(**b**) Tetradigital thumb grip for holding a screwdriver.

Figure 11. Prosthesis holding objects by tetradigital grips.

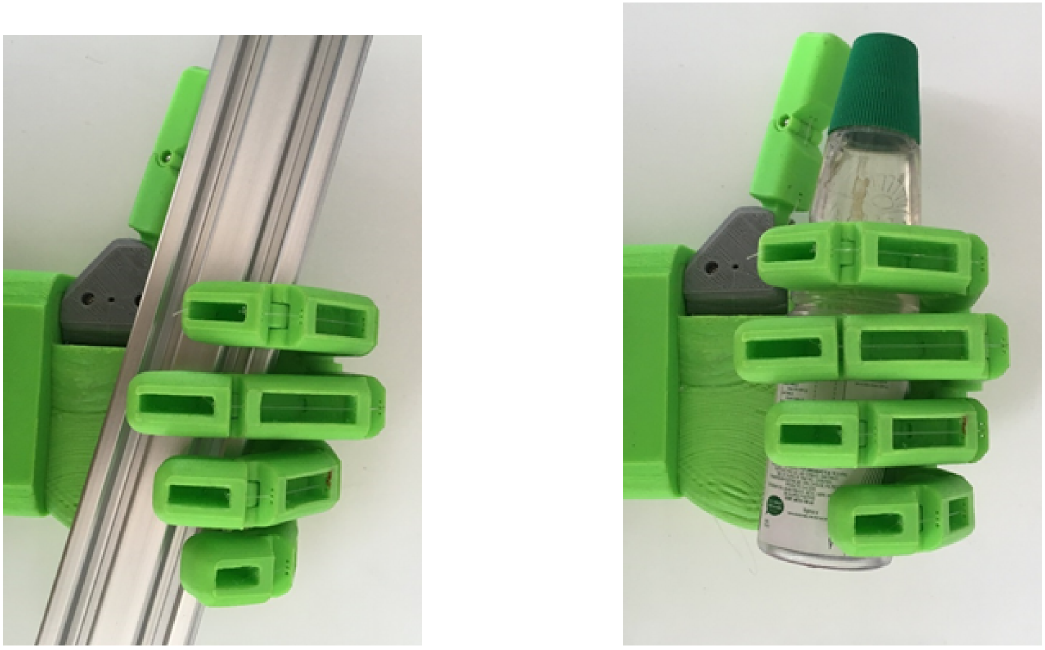
Pentadigital Grip

The prothesis has no difficulty in achieving the lateral-thumb pentadigital grip, whereas the pentadigital grip of the thumb cannot be accomplished, due to the fact that for very small objects, the adduction of the little finger is required. Thus, in these situations, the grip would become tetradigital due to the lack of contact of the object with the little finger.

5.2. Palmar Grip

5.2.1. Digito-Palmar Grip

Digito-palmar holds involve grasping by using the palm, index, middle, annular, and little finger. Figure 12 illustrates the execution of this grip when grasping a rectangular profile and an irregular cylindrical container.



(**a**) Holding a rectangular object. (**b**) Holding an irregular cylindrical object.

Figure 12. Prosthesis holding objects by a palmar digit grip.

5.2.2. Full Palmar Grip

The full palm grip uses the entire palm and all five fingers. This grip is used when strongly gripping an object or when grasping bulky objects. Figure 13 illustrates the execution of this grip when grasping a rectangular profile and an irregular cylindrical container.

Figure 13. Full palmar grip while holding a conical object.

5.3. Central Grips

This type of grip is performed in such a way that the object being held causes a distal extension of the hand. Figure 14 illustrates this grip when the prosthesis holds a feather. Here, the grip is supported by a passive abduction/adduction created by play between the parts; thus, this grip could not be performed if the object had a larger diameter.

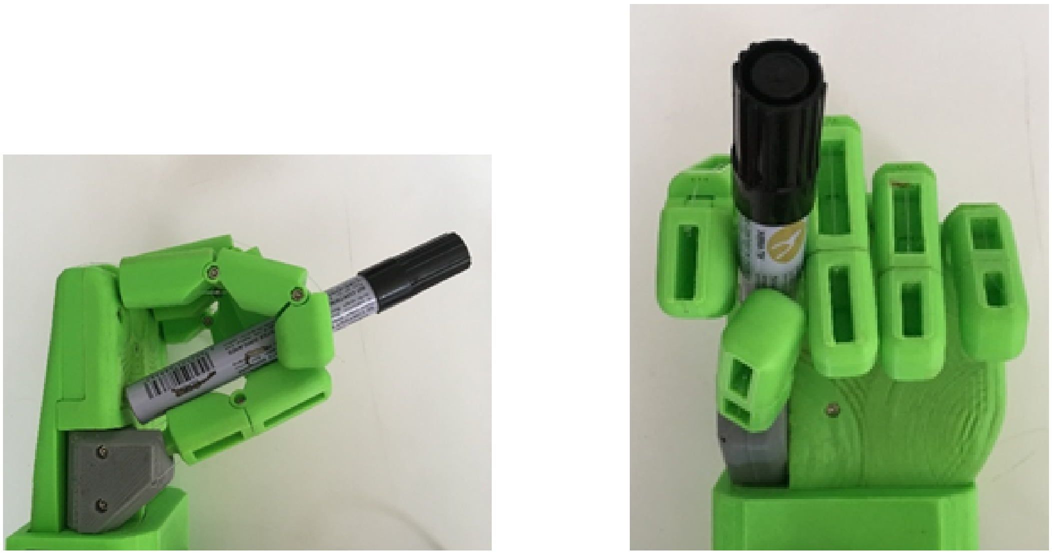
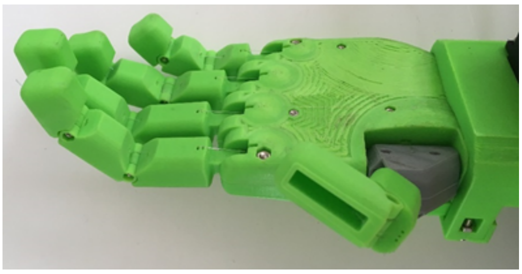


Figure 14. Centralized grip of the prosthesis while holding a pencil.

5.4. Gravity Grip

As shown in Figure 15, gravity grips help to hold the object using the hand as a support device. Figure 15 shows the execution of these holds in two different variations, flat and concave. These grips are easily achieved by the prosthesis, as well as the hook grip.



(**a**) Position of the prosthesis in a flat/concave gravity grip.

(**b**) Holding an irregular cylindrical object.

Figure 15. Hook gravity grip holding a backpack.

5.5. Dynamic or Active Grips

Active grips are complex holds in which the hand interacts through movement with another object, such as igniting a lighter, cutting with scissors, or tying a knot, among other actions. These tasks are difficult to perform and could not be achieved with the prosthesis.

5.6. Other Grips

It is difficult to categorize all movements that could be performed by a human hand. The following section presents additional postures that can be performed by the prosthesis that are not included in the previous classification, yet these grips are relevant to ADLs. Figure 16a shows the hand adopting a position for knocking on a door, and Figure 16b the position for pressing keys. Figure 16c shows a handshake used for greeting. Figure 16d shows how the prosthesis can adopt a shape to indicate a signal, and finally, Figure 16e demonstrates how the hand adopts an approval gesture.

(**a**) A hand held for knocking on a door.

(**b**) Percussion: typing on a computer.

(**c**) Greeting with a handshake.

(**d**) Signal or expression to point or direct to a specific direction.

Figure 16. *Cont*.

(**e**) Expression to indicate approval.

Figure 16. Additional positions.

6. Results and Analysis

The previous section discussed how the prosthesis is able to adopt different positions to execute grips, including several previously unclassified grips which are important for ADLs. Figure 17 displays a summary of the prosthesis grasping test results, displaying the achieved and unachieved grips. The analysis performed indicates that the prosthesis has the ability to accomplish most of the static holds tested.

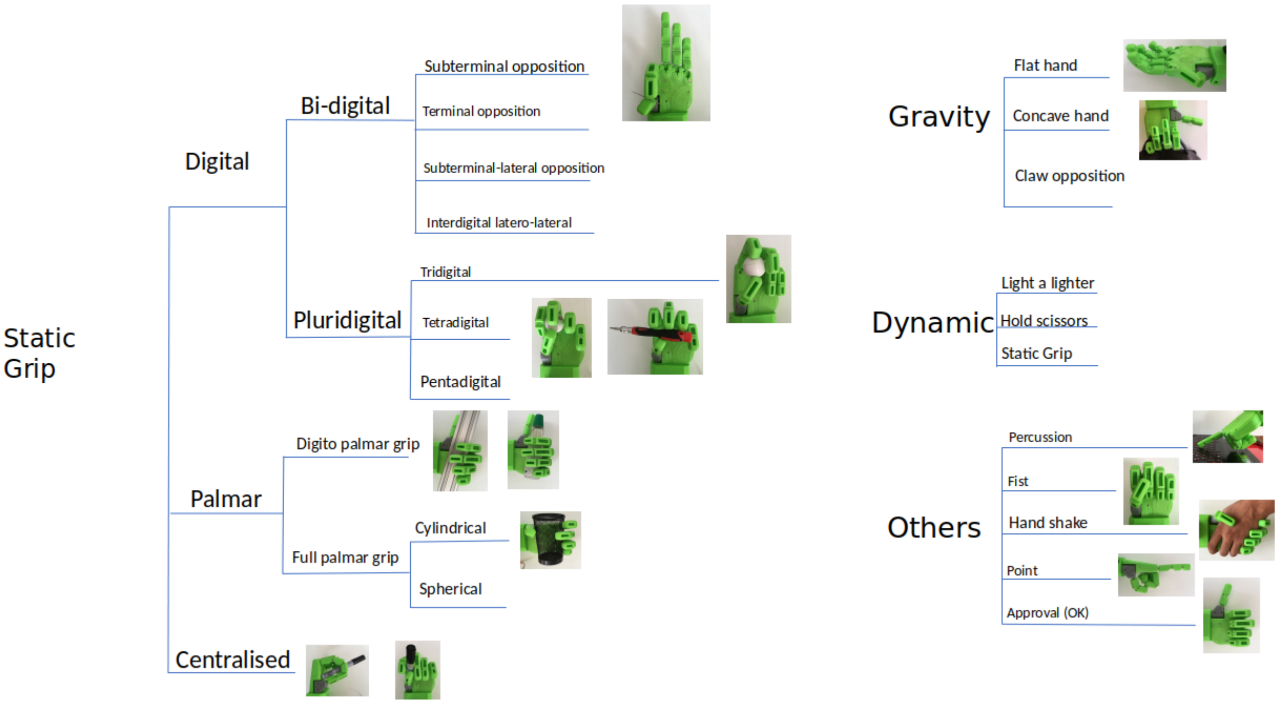


Figure 17. Summary of the attainable and unattainable grips of the prosthesis.

7. Conclusions

This paper presented an anthropomorphic-style prosthesis with three degrees of freedom. Two degrees of freedom are associated with the movement of the thumb and index finger, while the remaining degree of freedom controls the annular, middle, and little fingers in a sub-actuated manner. The featured design is characterized by:

- Having distal articulation in the index, middle, annular, and little fingers. Articulation is only found in research-related prostheses, and not in commercial models.
- Sequential closure of the phalanges through a single tendon.
- Ability to conduct opposition/restitution movements, in addition to flexion/extension movements of the thumb, controlled by a single tendon.
- Opening and closing movements are performed by the same actuator.

Furthermore, the proposed design is light (200 g), weighing less than an average adult's hand, this feature is mainly the result of its PLA construction, and the external location of the actuators and electronics. Therefore, this design has major advantages over traditional prostheses which enclose the entire device inside the palm. Some of these advantages are:

- The lightweight design enables the construction of smaller prostheses, thereby allowing the construction of devices to be used by children.
- When worn by a child who eventually outgrows the prosthesis, it is possible to replace the prosthesis (hand) and preserve the actuation system, thus reducing replacement costs.

On the other hand, external actuators have the disadvantage of requiring motion transmission devices (such as wires), that may be uncomfortable for users.

In terms of the mechanism, the prosthesis is capable of performing multiple grips, providing the prosthesis with a high degree of versatility, a fact that has been confirmed by the tests performed. From a control perspective, the prosthesis can easily achieve some of the tested grips, such as a full palmar grip. Other positions, like picking up a needle (terminal opposition), are difficult to achieve due to complex control requirements.

The authors are currently working on the control mechanism of the prosthesis, which is a major development challenge, and the strategy under development will allow the user to be able to hold objects without the need of a complex interaction with the device, which is complemented by the prosthesis presented. Other important challenges remain, from a mechanical point of view, where the following points must be considered:

- Placing the motors at a distance from the hand and determining a simple way to transmit the movement to the prosthesis. This will help in the manufacturing of smaller prostheses for children, without the need to alter the design or diminish the performance due to weight restrictions.
- Although the device is easily fabricated using a 3D printer, the assembly process is laborious. Therefore, a reduction in the number of required parts is necessary in order to simplify the device's manufacturing process.
- Verification through laboratory tests of the kinematic and dynamic capabilities, such as grip force, and speed of the prosthesis.

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