Research on Biomedical Engineering (2021) 37:867–879
https://doi.org/10.1007/s42600-021-00185-w

TECHNICAL COMMUNICATION

Design of a lightweight hydraulic myoelectric prosthetic hand

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Received: 15 March 2021 / Accepted: 22 September 2021 / Published online: 23 November 2021

Abstract

Purpose There are several hand prostheses available in the market, each with its advantages and disadvantages. Some modern commercial prostheses have weights close or higher than the human hand weight causing discomfort and stress to the patient that decides to use this technology. On the other hand, high-tech hand prostheses are expensive and, therefore, inaccessible to the majority of the population. This paper aims to present the design and prototype of a low-cost, hydraulic, lightweight, and myoelectric prosthetic hand.

Methods The parametric mechanical design of the hand prostheses was done using the software Inventor and Adams in order to permit its customization and to optimize the pressure in the hydraulic system. Also, the stress analysis was performed using the Finite Element Method, and from the results, the appropriate materials were chosen to support the loads. Most of the components were manufactured using Acrylonitrile Butadiene Styrene (ABS) polymer through of Fused Deposition Modeling (FDM) process, in a 3D printer. The Arduino platform was adopted for the electronic design, and the shields for electromyographic signals acquisition and motor control resulted in a compact, flexible and reliable architecture.

Results A prototype of a low-cost, hydraulic, lightweight, and myoelectric prosthetic hand was designed and built. The prototype has 225 g and 10 degrees of freedom, letting it be 43% lighter than the natural hand weight, and to do several types of grips with force and velocity control. Also, for the manufacturing process, US$ 1250.00 was spent which is lower than the price of similar commercial prostheses.

Conclusion The prototype presented is an attractive economic and technical alternative to accomplish most of the day-to-day activities of the prosthetic user in comparison with several modern commercial prostheses.

Keywords Hand prosthesis · Hydraulic prosthesis · Myoelectric prosthesis

Introduction

The human hand is a complex system capable of performing a wide range of functions, including holding and handling objects, ranging from precision grasp to powerful grips (Segil et al. 2017).

The lost of a limb is perceived as a damage that has a strong impact on the life of the amputee, limiting his ability to work, his day-to-day activities, and his social relations (Fonseca et al. 2006). The effects of an amputation, whether on the job or psychological side, can be mitigated by providing prosthetics, which can restore some functionalities to the limb of the amputee.

However, the mere fact of offering a prosthesis to the amputated patient, if it is not functional, comfortable, light and aesthetic, does not solve the problem, leading to the abandonment of its use by the patient (Biddiss and Chau 2007).

The properties most valued by users of myoelectric control prosthesis are, in order of importance: mass, comfort, functionality, appearance, durability and cost (Cordella et al. 2016). Therefore, replacing the missing limb is a great challenge, which requires the application of multidisciplinary technologies, which involve everything from its design, through the acquisition and treatment of biomedical signals, through the control system, to medical rehabilitation procedures, among others (Segil et al. 2017).

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The success in the rehabilitation process of amputees is in the balance between the user needs and the prosthesis capabilities. For example, if the patient uses a prosthetic hand with many degrees of freedom (DoF), the probability of rejection is high due to the prosthesis weight. There is a directly proportional relationship between the DoF and the weight of the prosthetic device. On the other hand, if the patient uses a cosmetic prosthetic hand, it can be rejected due to its low functionality.

The prosthetic device must be designed to support the typical loads that the natural hand could support, this means, for example, that the prosthetic must be resistant enough to do the Activities of Daily Living (ADL). However, if the strength of the prosthesis is increased then the weight and energy consumption increases too. Furthermore, functional commercial prosthetic devices with many DoF are expensive and, for this reason, are not widely used by the population. So, the functionality and price of prosthetics are important aspects that should be taken into account in its design.

Another aspect that must be considered is the mechanism to drive the prosthesis. Generally, if the number of DoF increases, electrical control is commonly used. On the contrary, if the prosthesis has low DoF, it is usually driven mechanically and it has not anthropometric shape. Then, the appropriate choice of a prosthetic hand is an interplay between functionality, weight and price (Biddiss and Chau 2007; Carey et al. 2015; Weir and Sensinger 2003).

In order to find the balance between these variables, here in this paper, the development of a lightweight, hydraulic and myoelectric prosthetic hand is presented. The prosthetic device was developed at the University of Pernambuco and is called as UPE - Hand.

Methods

Mechanical design

The mechanical design of a prosthetic hand includes different variables such as weight, size, actuation method, among others. In order to quantify the design variables, different modern commercial prosthetics devices, such as the iLimb, iLimb Pulse, Vincent Hand, Bebionic, Bebionic v2 and Michelangelo, and prosthesis developed in research centers, such as Remedi Hand, Keio Hand, FluidHand III, Smarthand, Vanderbilt Hand and UNB Hand were studied (Belter et al. 2013). All these prostheses have anatomical shape, it means that these devices have four fingers and a thumb, as a natural hand, as shown in Figs. 1 and 2. The comparisons between the principal design variables of commercial hands and prosthetics hands developed in research centers are given in Tables 1 and 2, respectively. With this information, the design parameters will be discussed in the next sections.

Mass

The human hand has, on average, 400 g of mass (considering disarticulation in the wrist and excluding the extrinsic muscles of the forearm) (Chandler et al. 1975). It is observed that modern prosthetic hands have masses that approximate that of the natural limb. However, the natural limb has its weight evenly distributed over the musculoskeletal structure, while the artificial limb is supported by the stump, which generates reactive forces and moments. These efforts act, practically, in a localized way, since the prosthesis works as a cantilever beam, causing discomfort, due to the sensation of high weight, which has been mentioned previously as one of the main problems reported by users of prosthetic equipment. So, the weight of the prosthetic hand is very important for the amputee, because it can cause discomfort and fatigue (Cordella et al. 2016). Also, it is a critical design factor because it depends on the DoF (Tavakoli et al. 2015).

The weight of commercial prostheses is between 420 and 615 g and of the research center projects is between 400 and 730 g. Then the main challenge is to develop a prosthetic hand with a weight of less than 400 g. Commonly, if the DoF increases, the mass increases too as can be seen in Tables 1 and 2.

Size

The hand dimensions vary with the gender, age, population groups and also with the professional activities. Also,

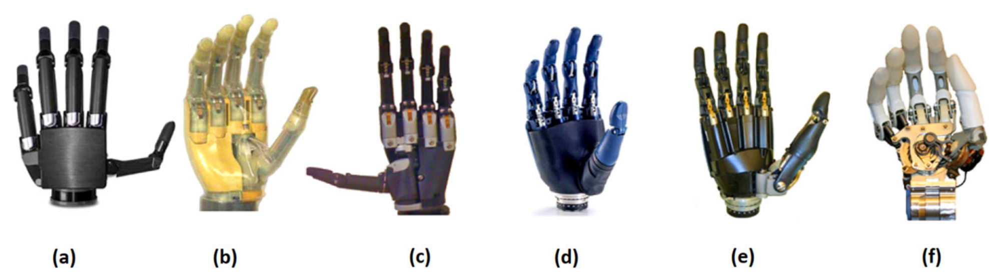

Fig. 1 Commercial hands: **a** Vincent hand, **b** iLimb hand, **c** iLimb Pulse, (**d**) Bebionic hand, **e** Bebionic hand v2 and **f** Michelangelo hand. Adapted from Belter et al. (2013)

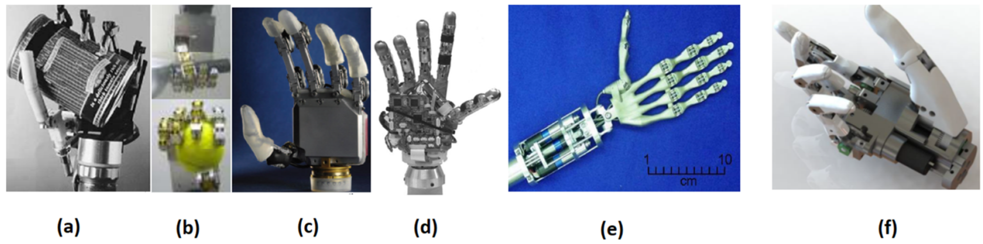

Fig. 2 Research centers hands: **a** Remedi Hand (Light and Chappell 2000), **b** Keio Hand (Kamikawa and Maeno 2008), **c** FluidHand III (Gaiser et al. 2009), **d** Smarthand (Cipriani et al. 2010), **e** Vanderbilt Hand (Dalley et al. 2009) and **f** UNB Hand (Losier et al. 2011)

Table 1 General characteristics of commercial prosthetic hands

	iLimb	iLimb Pulse	Vincent Hand	Bebionic	Bebionic v2	Michelangelo
Mass (g)	450–615	460–465	—	495–539	495–539	420
Number of Actuators	5	5	6	5	5	2
Degrees of Freedom	6	6	6	6	6	2
Adaptive Grip?	Yes	Yes	Yes	Yes	Yes	No
Precision Grasp (N)	10.8	—	—	34	34	70
Power Grasp (N)	—	136	—	75	75	NA
Lateral Pinch (N)	17–19.6	—	—	15	15	60
MCP joint motion (°)	0–90*	0–90*	0–90*	0–90	0–90*	0–35*
PIP joint motion (°)	0–90*	0–90*	0–100*	10–90	0–90*	NA
DIP joint motion (°)	20	20	NA	20	20	NA
Thumb Circunduction (°)	0–95*	0–95*	—	0–68	0–68	—
Average Speed* (°/s)	95.3	60.5	—	45.8	96.4	86.9

*On the MCP joint. ***NA*, not applicable. Adapted from Belter et al. (2013)

Table 2 General characteristics of research centers prosthetic hands

	Remedi Hand	Keio Hand	FluidHand III	Smarthand	Vanderbilt Hand	UNB Hand
Mass (g)	400	730	400	520	580	—
Number of Actuators	6	—	5	4	5	3
Degrees of Freedom	6	15	8	16	16	5
Adaptative Grip?	No	Yes	Yes	Yes	Yes	Yes
Precision Grasp (N)	9.2	—	45	—	20	—
Power Grasp (N)	—	37	—	—	80	—
MCP Joint Motion (°)	0–81	—	0–90*	0–90	0–90	0–90
PIP Joint Motion (°)	—	—	0–80*	—	0–90	0–90
DIP Joint Motion (°)	0–90	—	35	—	0–90	—
Thumb Circunduction (°)	—	90	0–90*	0–120	− 10 to +80	0–120
Grasp Speed	2.5 s*	0.8 s**	1.0 s**	1.4 s*	0.4 s**	—

*Time to open or close the hand. **To achieve a power grasp. Adapted from Belter et al. (2013)

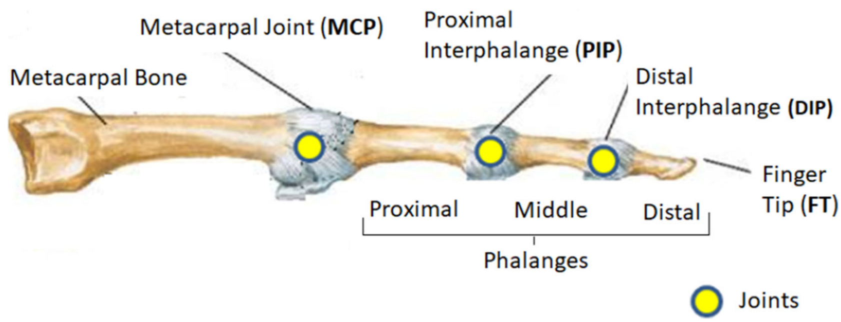

Fig. 3 Finger model. Adapted from Netter (2008)

differences are observed between the right and left hand. It is also known that the dimensions of the hand are closely correlated with the gripping forces developed by it (Paschoarelli et al. 2010; Yu et al. 2013; Fernandes et al. 2011). For an anthropometric design, the prosthetic fingers must have the same geometry as a human finger. Then the project of a prosthetic hand must be parameterized in order to include these variables and to permit its customization.

Actuation method

The actuation method involves the kinematic finger, thumb kinematics, type of actuator and driven mechanism, grip force, grasp speed and achievable grasps.

The most common actuator used in electric prosthetic devices is the DC motor coupled to drive reductions to increase the torque and reduce the rotation speed, but this increases the weight of the prosthesis (Weir and Sensinger 2003). Another alternative is the hydraulic actuator, which can achieve the typical forces for prosthetic hands and reduce the hand weight because all the power system can be installed outside of the hand (Smit 2013).

Requirement analysis

The force that a prosthetic hand must apply to execute the ADLs depends on many factors, such as the object geometry and mass, contact points and friction between the object and the hand.

Commercial hands like iLimb and Bebionic fulfill these requirements. These prostheses have individual finger holding force, at the fingertip, that lies between 3.0 and 14.5 N depending on the prosthesis size and configuration (Belter et al. 2013).

The time that the amputee has to actuate the prosthesis is essential to control it. If it is very fast, maybe the user cannot stop the finger in the right position. For this reason, finger flexion/extension speed is an important factor in the design of the prosthetic hand.

As the suggested closing time of 0.8 s is enough for prosthetic hands and between 1.0 and 1.5 s to accomplish the ADLs, the flexion/extension speed may be ranged from 60 to $112.5°/s$. Commercial myoelectric prosthetic hands have flexion/extension speed between 36.6 and $110.6°/s$ (Belter et al. 2013).

A most comprehensive study found 33 main different grasps for the human hand (Feix et al. 2008). The grasp patterns for typical ADLs includes power (35%), precision (30%), lateral (20%), hook, tripod and finger point (15%). From these grasps, the top 10 are responsible for 71% of the total usage frequency. Hand gestures such as handshaking, waving, pointing/clicking, like (thumb up)/dislike (thumb down), and also tap/hold/slide/flick and pinch/spread on a smartphone/tablet were considered as an important functionality of the prosthetic hand (Tavakoli et al. 2015; Vergara et al. 2014). Most of the movements described above can be reached by the Vincent, iLimb and Bebionic prosthetic hands that have at least 5 actuators (Belter et al. 2013).

To model the UPE-Hand was used the anthropometric dimensions for the Brazilian male (Klein 2008). Specifically, for the determination of forces and velocities, was

Table 3 Segments of the middle finger

Segment	Length (mm)
Proximal Phalange	40
Middle Phalange	35
Distal Phalange	16

Table 4 Basic requirements for the UPE - Hand

Variable	Design requirements
Weight	< 400 g
Size	Similar to human hand
Finger Actuation Method	Hydraulic
Thumb Actuation Method	Electro mechanic
Force (on the FT of each finger)	6 N
Speed (on the MCP joint)	$110°/s$

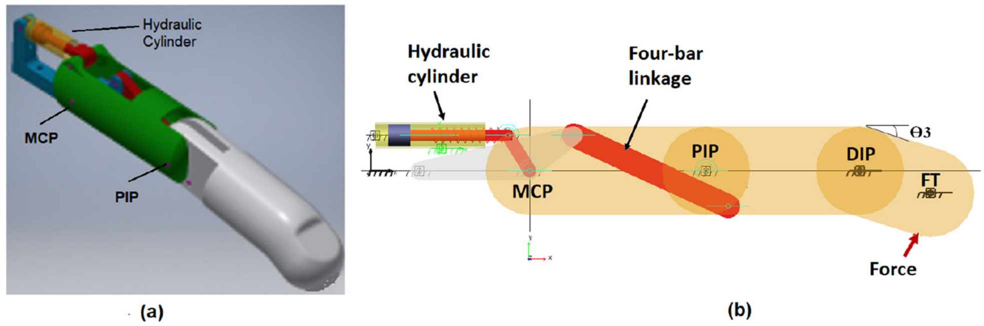

Fig. 4 **a** 3D CAD model and **b** ADAMS/View finger model

chosen the finger number 3 (middle finger) because it presents the largest lever arm and, therefore, it is the critical finger. The finger model is represented in Fig. 3 and the length of each segment is specified in Table 3.

For the human hand, the motion ratio of the MCP to PIP joints depends on object size that should be grasped. For the commercial hands, the motion of the PIP and the MCP joints are usually given by the four-bar linkage. The thumb has only two phalanges and its kinematics is given by the motion of the MCP and PIP joints, and by the rotation of the circumduction axis which can be parallel to the wrist axis or angled to achieve a more anthropomorphic motion and also lets the hand switch between the lateral grasp and a power or precision grasp (Weir and Sensinger 2003).

Although the human hand is able to develop speeds above 40 rad/s ($2290°/s$) and forces above 400 N, the requirements for most daily activities require only speeds in the range of 3 to 4 rad/s (172 to $230°/s$) and forces in the range of 0 to 67 N (Heckathorne and Childress 1981). Considering that, and the technical restrictions, the requirements for the UPE - Hand are in Table 4.

Electronic and control design

The electronic and control design discusses the strategies to drive the actuators from the myoelectric signals. The electronic system must be able to control the DC motor coupled to the hydraulic system and the DC thumb motor. It can be done using an H - Bridge. Besides, the DC motors are powered by rechargeable batteries. On the other hand, the surface myoelectric signal is collected by electrodes on the skin over the muscle. Then, the signals must be collected, amplified and smoothed to be processed in a microprocessor that will enable the outputs for the drive motors.

The myoelectric control has been studied during the last years. Basically, the control of prosthesis can be done through the pattern-recognition-based and non-pattern recognition-based methods. In the first case, the signals pass through the modules for data segmentation, feature extraction, and classification. After that, the digital controller generates output commands. In the second case, the control is based on threshold control and/or finite state machines where the output is limited by the sequence of input signal patterns (Stegeman and Hermens 2007; Delsys 2003; Kutz 2009; Adewuyi et al. 2016).

Modeling

In order to fulfill the requirement list, a 3D CAD model and a virtual model of the finger were built, as shown in Fig. 4, using the MSC ADAMS/View software, and then the kinetic characteristics of the movement were determined.

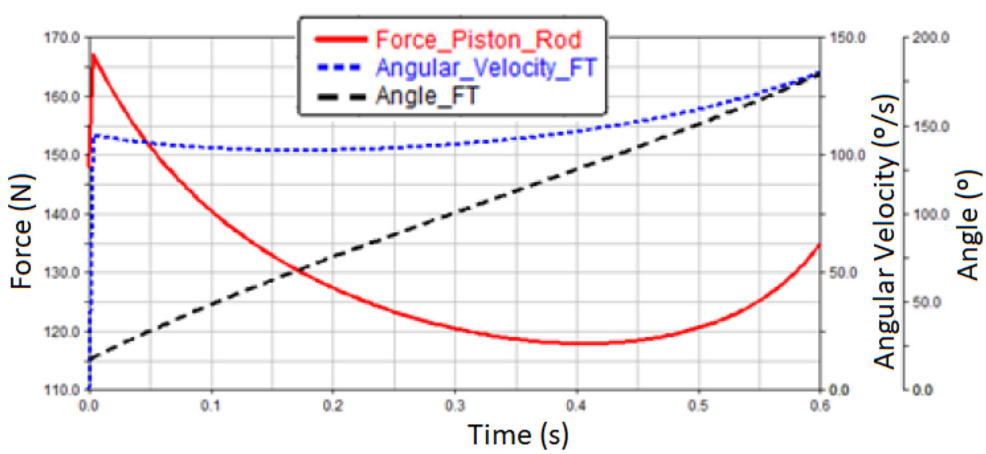

Fig. 5 Kinetic characteristics

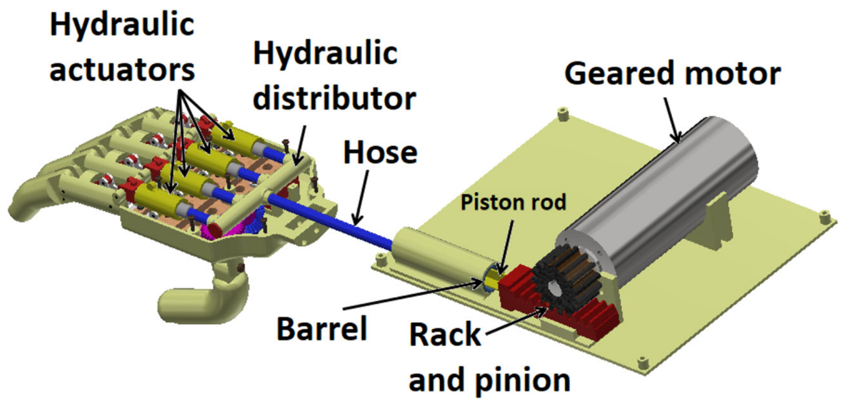

Fig. 6 Hydraulic power system

This software is a Multibody dynamics software that is used to study the dynamics of moving parts, and to determine how loads and forces are distributed throughout mechanical systems. The software checks the model and automatically formulates and solves the equations of motion for kinematic, static, quasi-static, or dynamic simulations.

The proposed finger was simulated and the dimensions were optimized to minimize the force on the actuator. The main results of the simulation are shown in Fig. 5, which shows the force at the piston rod, the flexion speed, measured at the MCP joint, and the fingertip (FT) turning angle. The data indicated are for a constant gripping force of 6 N, applied at the FT.

In the proposed device, each finger, which was modeled using the Autodesk Inventor software, is actuated by a hydraulic cylinder, which is connected to a manifold, coupled to a hydraulic power system, by a hose, as shown in Fig. 6, and a four-bar linkage.

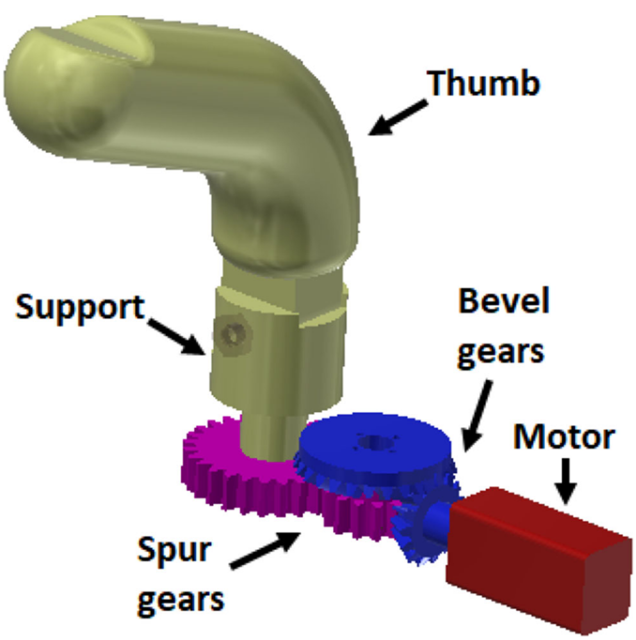

Fig. 7 Thumb drive schematic

The UPE - Hand has its hydraulic power generation and control system located in a remote unit, which can be wrapped in a backpack or bag, which is connected to the prosthesis by means of a hose and an electric wire, which transmit the energy required to activate it. The hydraulic system is driven by a DC motor that provides a torque of 7.7 $N.m$ at 21.2 rpm and the thumb is driven by a DC motor with a torque of 11.5×10^{-2} $N.m$ at 26.1 rpm.

The thumb was modeled considering that it is joined to a gear reduction and a motor as shown in Fig. 7. In this case, the PIP joint is kept in a fixed angle whereas the MCP joint does the flexion/extension movement of the thumb through a DC motor coupled to a double reduction (one with spur gears and the other with bevel gears). Furthermore, the abduction/adduction movement is done manually, by rotating the MCP joint onto a support, in order to obtain a lateral grasping and precision or power grasping.

Finite Element Analysis (FEA) was applied to all parts of the proposed model to determine the maximum values of stress and strain. The maximum values of stress and strain were determined using the Stress Analysis software based on the Finite Element Method (FEM), which is an add-in of the Autodesk Inventor software. In Fig. 8 is shown an example of the main results for the PIP/DIP segment. From the results, the Acrylonitrile Butadiene Styrene (ABS) polymer and Aluminum Alloy 6061 - T6 were chosen to build the prosthetic device. The mechanical components, of ABS and aluminum, were made using the Fused Deposition Modeling (FDM) considering 99% infill density and CNC machining, respectively.

On the other hand, the proposed hydraulic power system is composed of a motor coupled to a rack-and-pinion gear mechanism, as shown in Fig. 6, where the displacement of the rack is the same for the hydraulic cylinder rod. This movement is responsible for the fluid pressure to the actuators on the hand.

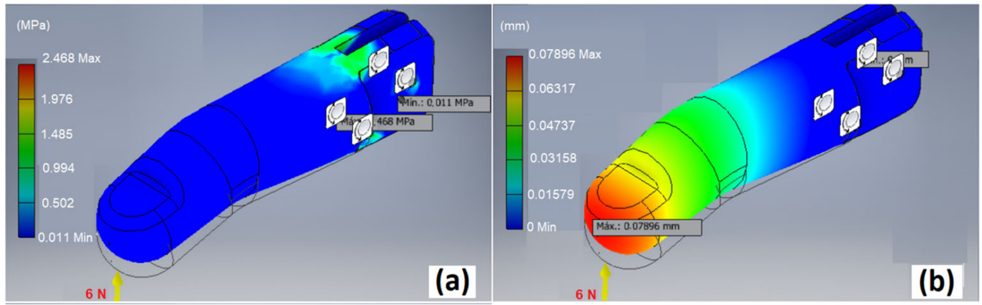

Fig. 8 Sample of the main finite element analysis results applied to the middle finger, where the maximum stress occurs in the region of the holes and the maximum deflection occurs at the tip of the finger: **a** stress and **b** deflection

Electronic

The electronic hardware consists of a Muscle Sensor v3, which has three electrodes positioned in the amputated limb, to collect the MES (Myoelectric Signals) to drive two motors. The position of the electrodes is defined by a previous analysis of the electrical response of the amputated limb. From this analysis, a map of the best points to glue the electrodes is obtained. Once the position of the electrodes is defined, a training process of the muscle is initialized to establish a relation between the excitation of the muscle and the movement of the prosthesis. Once the position of the electrodes is defined, a training process of the muscle is initialized to establish a relation between the excitation of the muscle and the movement of the prosthesis. The MES is obtained when the muscle is excited and the signal amplitude depends on the user. Once the MES is collected, it is sent to an ARDUINO board to read and process these signals. A threshold is identified and included in the Arduino program. Then, the information is sent to an L298N H bridge to control the speed and direction of rotation of the motors.. The electronic sketch for UPE - Hand is shown in Fig. 9.

The Arduino code is designed to work simply and safely. When initializing the board, for safety, none of the motors can be driven. The user must intentionally produce electromyographic pulses to make the choice of the motor and its direction of rotation. The force and the velocity of grip are proportional to the MES emitted, which gives wide control to the user on the operation of the prosthesis. Figure 10 shows the logic diagram of the code developed for the prosthesis control.

As an example, after auto-calibration of the sensor (a process that consists of the calculation of the mean of the signal captured by the sensor, in a certain time interval, and used as a parameter to release the drive of the motors), the user must emit three pulses, which activates the thumb motor and then emits two more pulses to activate the direction of rotation of the motor (finger flexion). This order of three or two pulses can be reversed without interfering with the operation of the system. At this time the system is enabled for use. If two more pulses are emitted, the

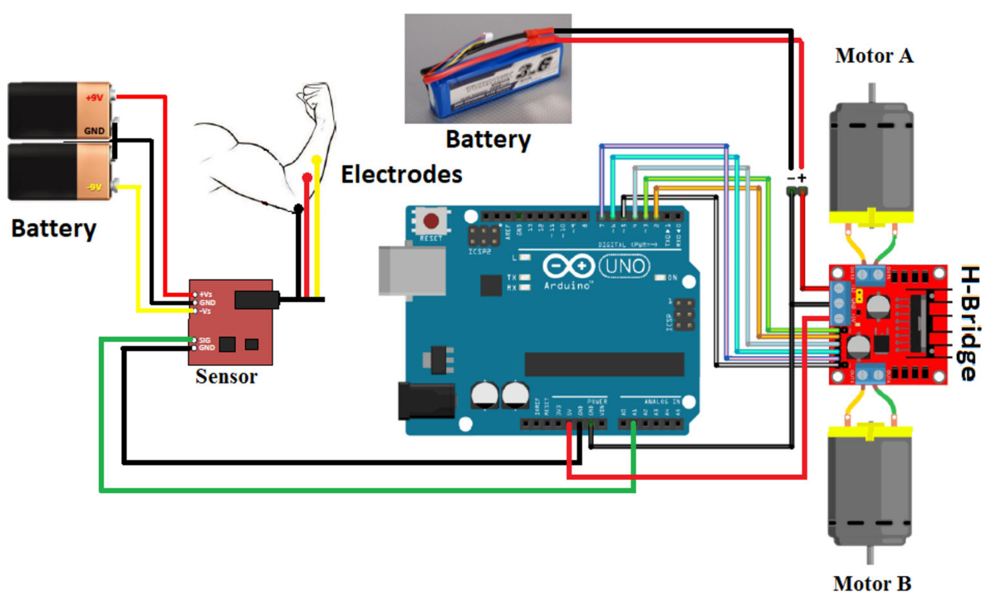

Fig. 9 Electronic sketch for the UPE - Hand

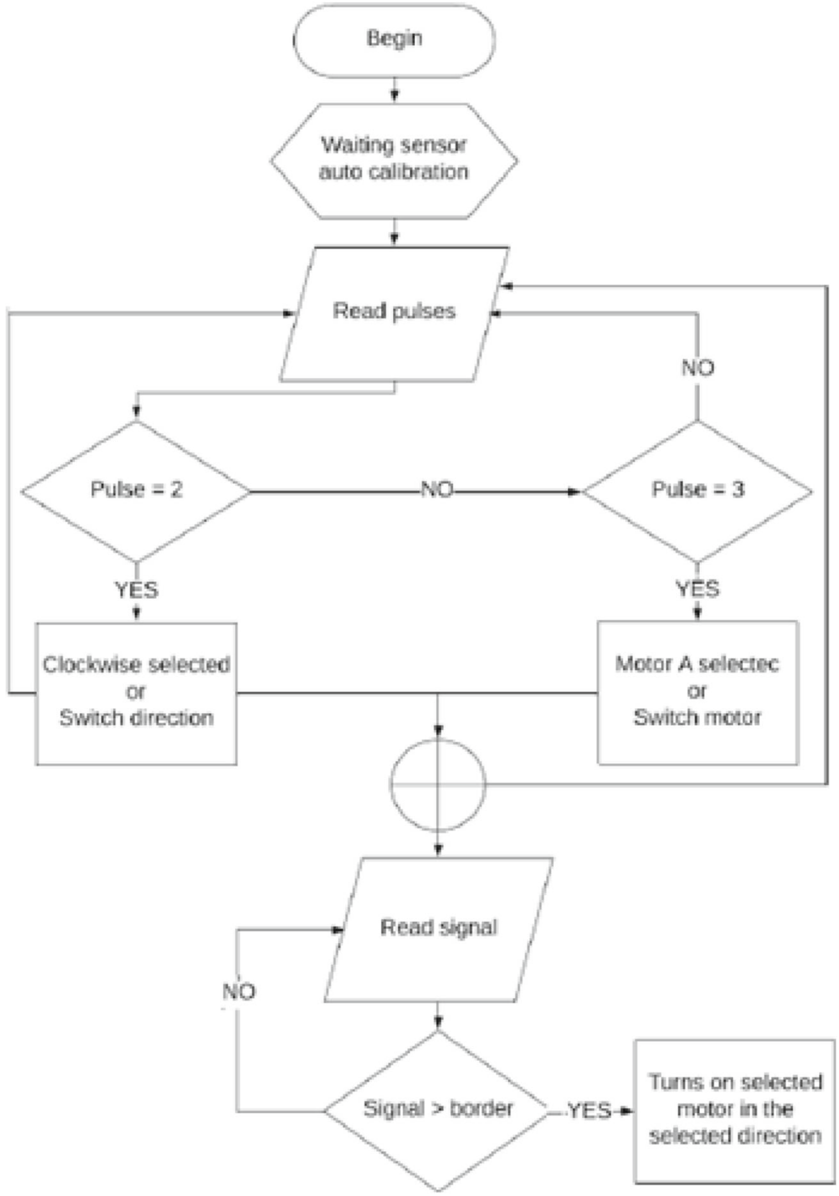

Fig. 10 Logic diagram

Fig. 11 UPE-Hand: **a** system overview and **b** use concept

Fig. 12 The UPE-Hand

direction of rotation of the motor will reverse and three more pulses will switch the motor, and so on. The motor and direction of rotation can be changed at will. The effective movement will occur when a continuous MES is emitted and the motor speed will be a function of the intensity of this signal. The threshold of the MES to generate pulses must be adjusted to each user. The control of grip strength is done visually.

Results

In Fig. 11 is shown an overview of the system and a concept of use, with its remote unit wrapped in a backpack. It means that in the proposed design, the user can use a customized back bag to support, not only the power source of the prosthetic device but also any other kinds of stuff. The weight of the prosthesis is 225 g and its control unit weights 1592 g. It means that the hand is remotely actuated and, as the unit of energy and control is external, the mass felt by the user in the stump of the amputated limb is only the weight of the prosthesis.

In Fig. 12 is shown the UPE-Hand over a precision scale, where details of the MCP support can be seen in aluminum and the others parts in ABS.

The mechanisms of fingers 2–5 are actuated by a hydraulic system that allows them an adaptative grasp. It means that the final position of each finger is given by the position constraints of each finger. At these positions, the maximum hydraulic pressure allowed by the user is achieved in all fingers. Then, the hydraulic actuator cannot be used to describe the position of all joints, because they depend on the contact of each connection with the object, so this is an adaptative mechanism with 8 DoF's, (2 DoF's for each MCP and PIP joints of 4 fingers) (Birglen et al. 2007; Dollar and Howe 2010). About the thumb, the PIP joint is fixed, the MCP joint does the flexion/extension movement through a DC motor and the abduction/adduction movement is done manually, by rotating the MCP joint. In this way, another 2 DoF's are on the thumb, totaling 10 DoF's in the UPE hand.

Discussion

The analysis of the human hand reveals 33 grasping possibilities (Tavakoli et al. 2015). According with the methodology adopted in this study, 29 grasping possibilities are achievable for the UPE-Hand, as shown in Fig. 13.

It should be noted that some grasping were made with the prosthesis bare and others with it dressed with a latex glove in order to increase the friction between the hand and the object. It is worth noting that the imitation concept attributed to the quality of the grasp, indicated in Fig. 13, represents only the author's feeling in the tests performed in a laboratory, by himself, with the prosthesis. It is important to note that the imitation concept attributed to the quality of the grasping is associated with stability to grasp the object. Also, all grasp possibilities, indicated in Fig. 13, were obtained using the MES. However, in some cases, a poor imitation concept was given for a grasping possibility that needed external help to accomplish the desired grasping.

Although the noise emitted by the mechanical system was not measured, it was estimated to be around 50–60 dB. However, the noise coming from the power source can be adjusted using an external foam. It is important to note that auditory feedback can be used in upper limb prosthetics to control the prosthetic device (Antfolk et al. 2013; Gonzalez et al. 2012) but it requires training for effective use (Schofield et al. 2014).

A comparison of the weight and DoF of the UPE - Hand and commercial hands (the research Delft Cylinder Hand and Fluid Hand III were here included by having hydraulic actuators) was done. For the comparison, prosthesis activated by body movements and the most modern, electrical, controlled by myoelectric signals, were used, as shown in Fig. 14. It is important to note that only the Delft Cylinder hand and the UPE hand have an external power

Fig. 13 UPE - HAND grasping possibilities


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Nº Name	Picture	UPE Hand	Imitation	Nº - Name	Picture	UPE Hand	Imitation
1 - Large Diameter			VG	18 - Extension Type			G
2 - Small Diameter			VG	19 - Distal Type		Not Possible	-
3 - Medium Wrap			VG	20 - Wrinting Tripod			P
4 - Adducted Thumb			G	21 - Tripod Variation		Not Possible	-
5 - Light Tool			G	22 - Parallel Extension			G
6 - Prismatic 4 Figer			G	23 - Adduction Grip		Not Possible	-
7 - Prismatic 3 Figer			G	24 - Tip Pinch			G
8 - Prismatic 2 Figer			G	25 - Lateral Tripod			P
9 - Palmar Pinch			G	26 - Sphere 4 Finger			VG
10 - Power Disk			G	27 - Quadpod			VG
11 - Power Sphere			VG	28 - Sphere 3 Finger			G
12 - Precision Disk			G	29 - Stick			P
13 - Precision Sphere			VG	30 - Palmar			VG
14 - Tripod			VG	31 - Ring			G
15 - Fixed Hook			G	32 - Ventral			P
16 - Lateral			VG	33 - Inferior Pinch			VG
17 - Index Finger Extension		Not Possible	-				

Imitation concept: VG = Very Good; G = Good; P = Poor.

source. Results, shown in Fig. 15, reveal that the UPE-Hand weight was 225 g, which is lower than the prosthetic hand available in the market.

It shows that the UPE - Hand is a candidate to mitigate the problems about weight described by prosthetic users. Furthermore, the proposed hand prosthesis manufacturing cost is about US$ 1,250.00, which is similar to another 3D printed prosthesis that is sold as a commercial product (Ten Kate et al. 2017). The end user price must include, e.g., distribution and marketing costs. For comparison, the cost of commercial prostheses ranges from the US$ 25,000.00 to the US$ 75,000.00 for myoelectrics, and from US$ 4,000.00 to 10,000,00 for a body-powered prosthesis (prices based in New York, USA) (Resnik et al. 2012).

Conclusion

The UPE - Hand was built according to the requirement list for the commercial hand prostheses. The optimization

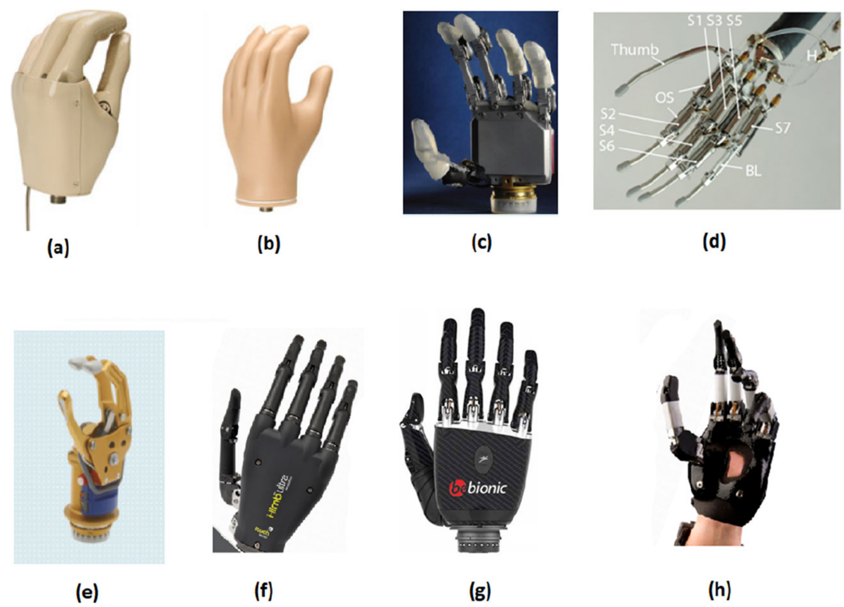

Fig. 14 **a** Hosmer APL Hand (Hosmer 2016), **b** Hosmer Soft Hand (Hosmer 2016), **c** Fluid Hand III (Gaiser et al. 2009), **d** Delft Cylinder Hand (Smit 2013) **e** Otto Bock DMC Plus 7 1/4 (Otto 2014), **f** i-Limb Ultra Small (Bionics T 2015), **g** Bebionic v3 Medium (Steeper 2014) and **h** Michelangelo (Otto 2012)

process for the actuation force on the hydraulic system was performed using the MSC Adams/View software and the 3D model, using the Autodesk Inventor Professional. According to the results, the CAD project, with the optimized dimensions, was analyzed, in order to verify collision and interference. The finite element analysis was applied to determine the stress and strain, and from the results, the appropriate materials were chosen. The main manufacturing process was the rapid prototyping or 3D printing, and the power system was located remotely, which allowed a lightweight and low-cost prosthesis.

The UPE-Hand performance meets the requirements imposed. It has 10 DoF and most of the day-to-day activities of the amputee can be carried out. In addition, the prosthesis has an anthropometric size, low weight (225 g) and it is able to provide a force of 6 N at the end of each of the fingers, including the thumb. Can reach an average flexion speed of $157°/s$ on the thumb and $110°/s$ on the others fingers. Its cost, of about US$ 1,250.00, is well below the cost of the simplest commercial prostheses available today, making it an option accessible to the majority of the population.

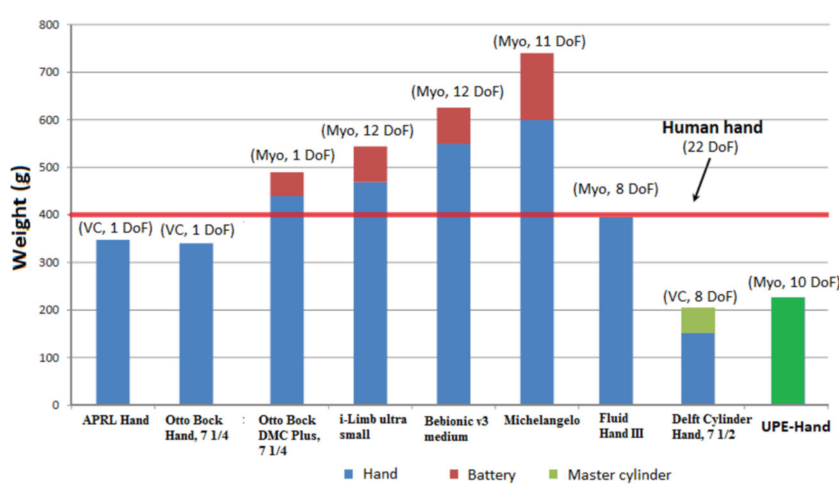

Fig. 15 Comparative of weight. Legend: VC, body-powered voluntary closing; Myo, myoelectric control; DoF, degrees of freedom. Adapted from Smit (2013)

Declarations

Ethics approval Not required

Conflict of interest The authors declare no competing interests.

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