User Interface Design for a Low-Cost 3D Printed Electro-Mechanical Prosthetic Hand

Shunit Polinsky[1], Yair Herbst[2], and Dr. Yoav Medan[3]
[1] Department of Biomedical Engineering, Technion - IIT, Haifa, Israel
[2] Department of Mechanical Engineering, Technion - IIT, Haifa, Israel
[3] Haifa3D Founder and Chairman, Visiting Scientist, Technion - IIT, Haifa, Israel

Abstract: The loss of one's hand can lead to a drastic reduction in the quality of life by decreasing the level of independence and the capability of performing activities of daily living. Most of the advanced prosthetic hand available in the market based their design on an electromyogram (EMG) signal from the user's stump. However, this method is not suitable for all amputation cases, such as amputees who suffer from phantom pain or permanent loss of the muscular activity due to muscle atrophy. There is a need to develop an electronic prosthetic hand that resembles the movements of the real human hand using signals from the user that are not direct signals from the residual limb. The project presented here aims to design a prosthetic solution to overcome the limitations of the current commercial prosthetic hands. The main objective is to have a prosthetic hand design for specific transradial amputee user's needs that are not met by the current prosthetic solution available on the market, mainly due to the occurrence of phantom pain while using the prostheses. The solution presented here is an electronic hand that can perform a variety of user-defined hand configurations using an autonomous adaptive grip along with a variety of grip force level. For successful implementation of the device, feedback from the prospective user and feedback from healthy subjects were collected. Based on the feedback, device enhancements were implemented, and new user-inputs designs are planned for future work. Overall, our results showed that the prosthetic hand design represents a sufficient solution for several of the unmet needs of the prospective user and has the potential to give rise to a better and more suitable solution than the current commercial prosthetic hands with only minor design enhancements.

Keywords: electric prosthetic hand, current control, adaptive grip, grip force level, phantom pain

1. Introduction

1.1 Background

Humans hands play an important role not only during physical activities such as holding, grasping and lifting different objects but also in body language and social interactions. Moreover, our hands have the ability to adjust and tune our grip to different shapes and different torque grip level. Naturally, the loss of one's hand can lead to a severe reduction in life quality and in the level of independence due to decreasing in the capability of performing activities of daily living (ADLs).

Prosthetic limbs are commonly used by people with limb loss (acquired amputation) and limb absence (congenital deficiency) to restore some of the functions of an anatomical limb. Each amputation is a bit different and there are many types and levels of limb loss, and as a result, each amputee desires slightly different features.

F. Cordelle et. al 2016, have accumulated many prosthetic users' feedbacks from different publications and provided the most important needs of upper limb prosthesis users. The main need is to retrieve the ability to perform ADLs while improving performance by achieving a stable grip and controlling the grasping force.

Additional requirements gathered in this review are regarding the device weight, the reliability of battery and electrodes (for myoelectrical prosthesis), improvement of heat dissipation, reduction of the active prosthesis motor noise, improving device duration and more. Further requirements collected by S. L. Carey et. al 2015, involving – providing a sensory feedback and performing actions in an intuitive manner with less visual attention.

Unsurprisingly, due to the many different types of need from a wide range of domains, various designs of prosthetic hands are available in the market, categorized as mechanical, electrical and Myo-electric hand [5]. Most of the advanced prosthetic hand available in the market based their design on an electromyogram (EMG) signal from the user's stump [4].

However, this method is not suitable for all amputation cases, such as amputees who suffer from phantom pain when using the residual limb or people who suffer from permanent loss of muscular activity due to lack of physical activity and hence do not have a sufficient and reliable EMG signal.

In approximately 50% of persons with upper-limb amputation, a phantom pain, a painful sensation in the amputated part of the arm, can occur [5]. Besides, for some amputation cases, the residual limb is missing tendons, ligaments and total muscle volume due to atrophy from decreased use. Even if the overall muscle volume is sufficient for EMG measurements, the ability to control each of the different stump's muscles can also be reduced [3]. These phenomena can cause to an unreliable EMG signal that might cause a high error percentage. Moreover, the myoelectrical prosthetic hand controlled by analyzing surface

EMG (sEMG) is frequently unnatural, can cause fatigue and required a long training session [6].
The prospective user of this project is a below-elbow amputee who got injured during a military operation. He has experience with advanced bionic hands which based their control on sEMG signals. Unfortunately, after a usage of four to five hours a severe phantom pain prevents him to continue to use the hand, and thus he is looking for a different solution.
Consequently, there is a need to develop an electronic prosthetic hand that resembles the movements of the real human hand, performs functions like opening and closing of fingers and wrist rotation using signals from the user that are not directly acquired from the residual limb.
The project present in this paper aims to design a prosthetic solution to overcome the limitations of the current commercial prosthetic hands. The main objective of the project is to have a prosthetic hand design for specific transradial amputee user's needs that are not met by the current prosthetic solution available on the market, mainly due to the occurrence of phantom pain while using the prostheses.

1.2 Related Work

Lack of a good solution for a low cost and lightweight electric hand prosthesis that does not require a muscular activity of the amputee's hand is the trigger for this project. However, a variety of different solution can be already found in the market and in research phase. Nowadays most of the new developments in this field are focused on prostheses with a sEMG control interface.
In order to control prostheses by using a sEMG signal, a high level of skill is required and a relatively long training procedure. Nevertheless, the most advanced commercial bionic hands relay on sEMG and pattern recognition, but there is still a long way to achieve a naturally controlled prosthetic hand, according to extended market overview done by M. Atzori et. al. 2015. In this market overview, a comparison of the available advanced prosthetic hand, such as Touch Bionics i-limb Quantum, Otto Bock Michelangelo, Steeper Bebionic v3, and Vincent hand Evolution 2, was preform and exhibited the main features of each prosthesis.
A significant drawback of these prostheses is the high cost of these products and as a result, a new field was established for a development of 3D-printed hand prosthesis for people who cannot afford the commercial prosthesis.
According to a comprehensive overview of the existing 3D-printed upper limb prostheses that was done by J. Ten Kate et. al. 2017, several generic characteristics of the available 3D-printed upper limb prostheses were extracted. Most of the 3D printed externally powered prostheses are also controlled by EMG. Some of the 3D printed prostheses enable an adaptive grasp by using a force distribution over the fingers or by having fingers with an independent force, with one motor per finger.
There are different studies that tried to overcome the limitation of the sEMG control in different ways. A. Fougner et al. 2011 have shown an improvement in the pattern recognition accuracy when combining the sEMG signal with accelerometers signals. Three years later, M. Atzori et. al. 2014 has published a dataset contains EMG signals together with hand kinematics and hand force signals during different grip patterns. The goal of this database is to encourage research group to develop a more natural control hand prosthesis by using non-invasive methods.
Naturally, there is also an invasive method to control prosthetic hand, such as CyberHand design by M. C. Carrozza et al. 2006. This prosthesis is connected via a neural interface implanted in peripheral nerves and thus utilize sensorimotor mechanisms for controlling hand actions. The domain of neural prosthetic hands is still mostly under research and not available nor suitable for an average amputee user.
In this study, we present a novel hand design, intended to assist and restore hand functions of amputees during ADLs, by using methods that do not require a muscular activity of the residual limb.

2. Methods

The project present in this paper aims to design a prosthetic solution to overcome the limitations of the current commercial prosthetic hands. The main objective of the project presented here is to have a prosthetic hand design for specific transradial amputee user's needs that are not met by the current prosthetic solution.
The solution presented here is an electronic hand that can perform a variety of user-defined hand configurations and grips by actively control flexion and extension of four fingers and rotation of the wrist with two different levels of grip forces. The mechanical system design consists of four fingers with four different tendon-driven mechanisms actuated by four different micro DC motors, passive thumb with two discrete positions using two magnets and wrist rotation driven by gears and a DC motor. All five independent micro DC motors are driven by a microcontroller system which measures the motors' current and consists of four buttons that can be pressed by the user. The adaptive control mechanism allows autonomous grip adaptation to different objects' size and shape, with different torque levels.

2.1 Design consideration

Naturally, the presented design cannot fulfill the needs of all users, but several specification and functionalities were chosen to develop a solution that does not yet exist.
First, the electronic design contains only off-the-shelf components to reduce the manufacturing cost. The mechanical design was created such that the model can be manufacturable by a standard 3D printer using standard printing materials such as PLA, and the assembling of the model's component would be simple to accomplish with basic tools. In addition, the user interface design was created for quick and simple adjustments according to the users' needs and desires and does not require a long training program to understand the operating principle.

The main design considerations include :

- Electronic control that does not require a muscular activity of the residual limb;
- Lightweight;
- reliable and durable;
- intuitive and easy to use;
- rotatable;
- variable grip force pattern;
- low-cost.

2.2 Mechanical Design

The mechanical design of the prosthetic hand was done by Mr. Oded Katzman and includes three key elements – fingers actuation system, wrist actuation system and passive thumb (see Figure 1). Each actuated element of the model was tested over 53K cycles to ensure reliability and durability of the design.

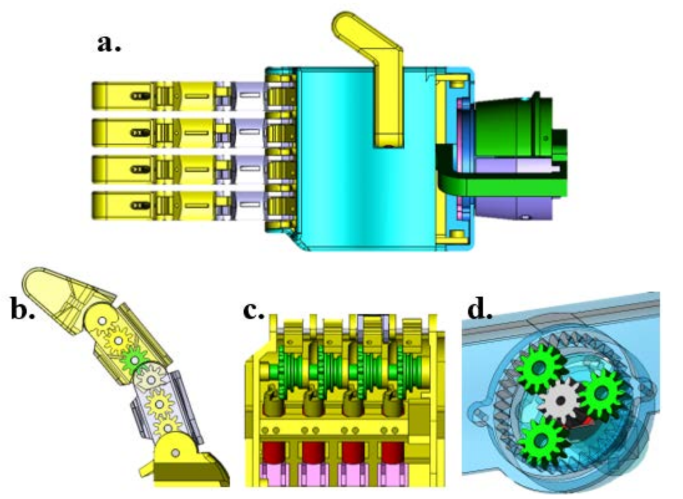

Figure 1 | Mechanical Design. (a) A general draw of the hand without the forearm where the stump can append. **(b)** The finger's structure including three joints. **(c)** Fingers actuation system including motors (red), pinions (yellow) and double pulleys (green). **(d)** Wrist actuation system including one motor (red), internal gear (blue) and spur gears (green).

Fingers actuation system. Each finger combined from 3 joints actuated by gears and cables. As the motor gets actuated, a pinion transmits the motion to a double pulley which further transfers the motion to the fingers via cables mechanism. The different diameter of each pulley is related to the different cable length needed at the internal part of the finger versus the external part of the finger during flexion and extension.

Wrist actuation system. The wrist mechanism includes internal gear meshed with spur gears coupled to one motor. The generated moments about the wrist joint are much larger than about the fingers joints, therefore the motor and the gears ratios were selected accordingly.

Passive Thumb. The thumb allows a stable grip together with the four fingers and therefore needed to be in front of them (opposed position). The thumb is passive and can be easily placed at one of two discrete positions – opposed and non-opposed position. This was done by using two magnets when their maximum magnet repulsion is at the center of the thumb motion range.

2.3 Electronic Design

The electronic circuit consists of a microcontroller, motor drivers, multiplexer, switches, LEDs, and power supply (see Figure 2).

Actuators system. The movement of the prosthetic hand is controlled by 5 Micro Metal Gearmotor Low-Powered 6V with Extended Motor Shaft. These tiny DC motors were chosen due to their size: 10X12X26 mm, and weight: 95 grams. In addition, since the required voltage is only 6 Volts, a small and lightweight power supply can meet the system requirements. The gear ratio was selected such that the motor speed would be as higher as it can while preserving enough torque to lift a maximum of a one-kilogram load. Several different gear ratios were tested, and two motors were selected by a trial and error methodology – 200 RPM of the fingers motors and 30 RPM for the wrist motor.

Microcontroller. The selected microcontroller is Arduino Nano in cooperation with the Arduino program. The Nano has 22 digital input/output pins and 8 analog pins with a clock speed of 16 MHz, 32 KB flash memory and 1KB of EEPROM (Electrically Erasable Programmable Read-Only Memory). There are many other microcontrollers available in the market including different analysis programs that are more advanced than the Arduino program. The main advantages of Arduino over other products are the relatively low price, small size, has analog inputs, and low battery consumption. However, the main drawback of Arduino microcontroller for the prosthetic hand application is that only one operation, i.e., either finger gripping, or buttons pressing detection, can be done and monitored at the same time.

Power supply. The selected power supply unit contains two lithium-ion polymer (LiPo) batteries, which provide the power to all the electronic components. LiPo batteries are rechargeable and very lightweight compared to other available batteries in the market. LiPo batteries are widespread in mobile devices and other portable small devices, hence are easy to find and purchase. Since most of the electronics component required 6 volts approximately, two LiPo batteries of 3.7 volts are serially connected. According to the required maximum current from all the electronic components, a LiPo with 1200 milliamperes per hour was chosen. For a simple and safe charging, a 3 SPDT (single-pole double-throw) switch was embedded to the circuit and is responsible to disconnect the batteries from the circuit and connect them in parallel, during charging.

Motor Driver. The requirements for this application includes driving five DC motors for both directions while measuring the current drawn by each motor during motion. The selected Texas Instruments DRV8833 device provides a dual H-bridge motor driver, therefore two DC motors can be driven for both directions using this device. As a result, three DRV883 are needed to drive the five motors .In order to measure the current drawn by the motor, the device has an option to solder a resistor to a pin called “ISENSE” that has the same current value as the motor has. Then the voltage on the soldered resistor can be measured and the motor’s current can be calculated. In addition, the device has an overcurrent protection that chops the current once the voltage across the resistor equals to a reference voltage (200 millivolts). Thus, at a given current value, a high resistance produces higher measured voltages but a lower cut-off current and vice versa. Two breakout boards for this device were tested, one of Pololu’s and one of Adafruit. The selected breakout board was Pololu breakout board for Texas Instruments DRV8833 due to its small size and versatility of the cut-off current and measured voltage, since the sense resistor is not soldered to the breakout board. In contrast, the Adafruit breakout board has a built-in sense resistor of 0.1-ohm and therefore was much simpler to solder, but the cut-off current did not provide an analog overcurrent protection (cut-off current of 1 ampere when the stall current of the motors is only 0.360 ampere).

Multiplexer. Since the Arduino microcontroller has a strict number of I/O pins, and since the circuit design requires more than this number, a multiplexer was needed. Texas Instruments CD74HC4051 multiplexer of 8 channels was selected allows decreasing the number of used pins in the Arduino (from 8 occupied pins to 4).

the force obtained at the low-force-level, and the time difference between short and long click while the user is pressing a button.

The buttons pressing stands for the user inputs; hence the next module is responsible to detect these events and forward the information to the relevant functions. The user can press on one of the four buttons in one of the following manners: no click, short click, long click and double click. The module of ‘Buttons Clicks Identification’ detects these four possible states for each button according to Table 1 and forwards the decision to the next module. There are two possible modules that can be activated due to a click detection – ‘Switch Mode’ or ‘Applying Desired Hand Movement’.

The ‘Switch Mode’ module visually indicates that a mode was changed by using LEDs with different colors. There are three active modes and one Recording mode. The active modes are split into “Grip Mode”, “Gesture Mode” and “Mobile Mode” according to the configured hand movements. The Recording mode allows the user to define new hand movements, while the hand itself signals the user what is the currently defined finger and what was the selected motion for this specific finger. Then this new user-defined movement is assigned to one of the buttons at one of the active modes. The assignment of the user-defined movement is possible even after turning off the device thanks to a small memory chip built into Arduino (i.e. EEPROM).

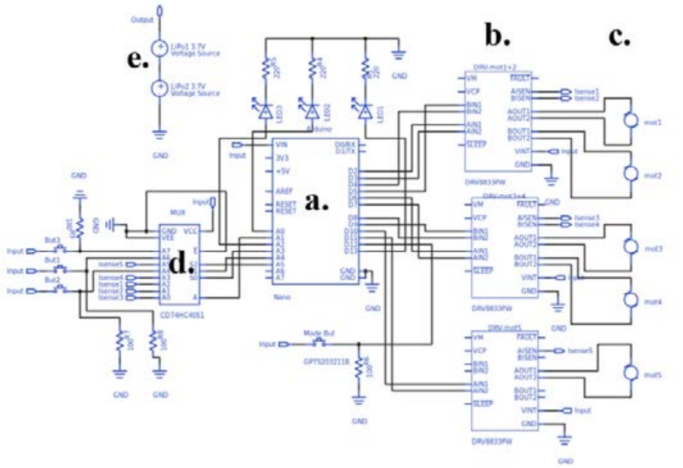

Figure 2 | Electronic Design. A schematic circuit board including **(a)** a microcontroller: Arduino Nano, **(b)** Three motors drivers: Pololu breakout board for Texas Instruments DRV8833, **(c)** Five motors: micro metal gearmotor low-powered 6V, **(d)** a multiplexer: CD74HC4051, and **(e)** two batteries: LiPo 1200mAh

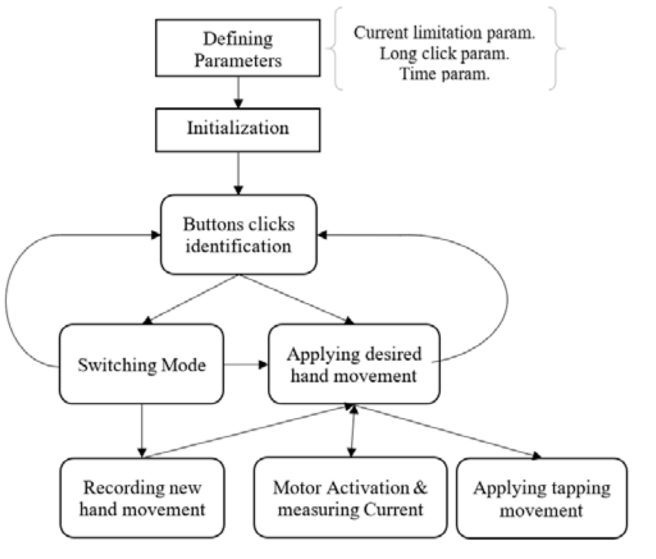

Figure 3 | The Control Modules. A general flowchart representing the different code blocks implemented in the microcontroller.

2.4 Control and User Interface Design

The flow of the program written in Arduino 1.8.5 can be seen in Figure 3. The first two modules contain initialization for all microcontroller’s inputs and outputs, and parameters setting. According to the user’s needs and desires, these parameters can be changed for better adjusting the hand functionalities, such as

The ‘Applying Desired Hand Movement’ module is the main module which translates the user inputs into the hand movements. The main functions of the module are (i) to independently activate each motor according to the defined task sent by the ‘Buttons Clicks Identification’ module, (ii) to apply an adaptive grip, (iii) and to monitor the buttons status for force grip adjustment and for the user safety (see Figure 4).

Table 1 | Buttons Click Type Decision Table:

#	Previous Button state	Current* Button State	Time / # of cycles	Meaning	Decision
0	LOW	LOW	Any	No action	**Short Click:** #2 AND (#1 OR #4) **Long Click:** #3 **Double Click:** If two successive short clicks were detected for the same button
1	LOW	HIGH	Single time	Click was started	
2	HIGH	LOW	Single time	Click was ended	
3	HIGH	HIGH	$t = t_{Thr}$	Long click was started	
4	HIGH	HIGH	$t < t_{Thr}$	Still in a short click	
5	HIGH	HIGH	$t > t_{Thr}$	Still in a long click	

** if a change was detected, a second measurement is performed after 50 milliseconds delay to overcome the bouncing phenomena when clicking a button.*

Motor Activation is done by Applying HIGH and LOW voltage to the motor driver "In1/In2" pins in order to actuate the motor clockwise or counterclockwise. The Current Measurements are done by measuring the voltage from the ISENSE pin which soldered to a 0.5-ohm resistor. Since, through this resistor passing the same current as the current drawn by the motor, a current control can be applied. The current control which produces the desired adaptive grip, is based on three parameters – the absolute current value, the current rate or the current slope and the action time, according to the below condition:

$$\left\{ \boldsymbol{I} < \boldsymbol{I}_{\text{Thr}} \cup \boldsymbol{dI} < \boldsymbol{dI}_{\text{Thr}} \cup \boldsymbol{t} < \boldsymbol{t}_{\text{start}} \right\} \cap \\ \cap \left\{ \boldsymbol{I} < \boldsymbol{I}_{\max} \cup \boldsymbol{t} < \boldsymbol{t}_{\text{start}} \right\} \cap \left\{ \boldsymbol{t} < \boldsymbol{t}_{\text{end}} \right\} \qquad \textbf{(1)}$$

Where $\boldsymbol{I}_{\text{Thr}}$, $\boldsymbol{dI}_{\text{Thr}}$ are the current threshold and the current rate threshold, respectively, according to the defined grip torque level. $\boldsymbol{t}_{\text{start}}$, $\boldsymbol{t}_{\text{end}}$ are the characteristic time of the starting current peak and the maximum time to complete a maximal closure of one finger, respectively. By combining these three parameters, an adaptive grip can be achieved while reducing the errors due to the natural high starting current and noises caused by the mechanical friction and leakage current. All the mentions variables can be defined and modified according to the user's needs at the initialization stage or during the hand motion. The monitoring of the user inputs during motion is applying by calling the 'Buttons Clicks Identification' module and checking the buttons status. Two different inputs can be obtained during the hand motion, increasing the grip torque grip via increasing the current variable values that described in equation 1 or stopping all motors. The latter option allows the user a full control to stop all movement immediately in order to prevent from unexpected and unwanted situations to risk the user safety and the user's surrounding safety.

3. Results and discussion

In this work, we presented a prosthetic hand model designated specifically for below-elbow amputees who suffer from a phantom pain during the stump's muscles activation and generally for amputees who are unsatisfied with the EMG interface. The new prosthetic hand design has a unique features combination of a lightweight, low-cost and intuitive user interface which allows a variety of ADL hand movements by using inputs from the user that are not related to the stump's muscles activation. In addition, Due to the modular device design, it can be easily customized to meet the needs of additional users.

These advantages could enable intensive use by users who reject other prosthetic hands and were looking for a better solution to their situation.

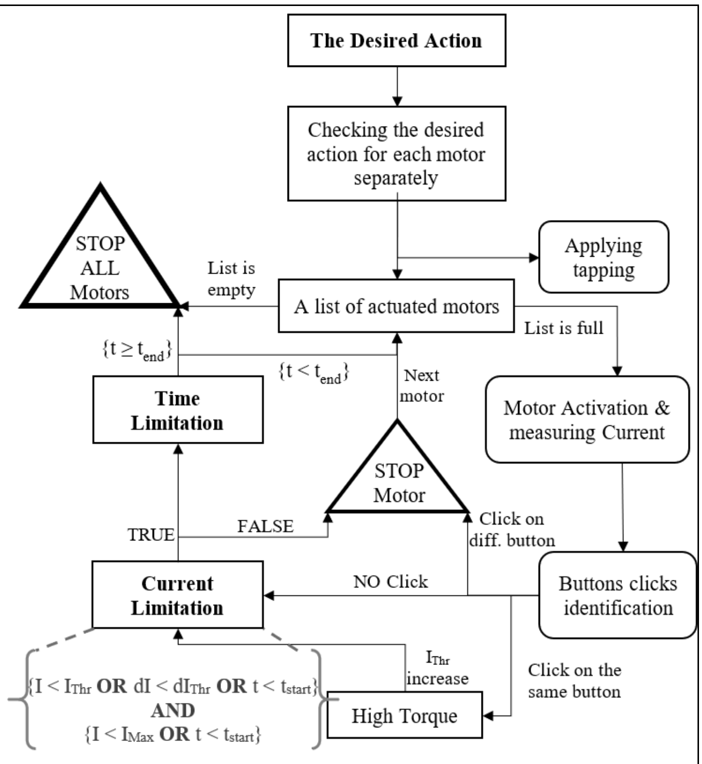

Figure 4 | User Interface Design. A flowchart describing the process used to translate the user inputs into hand movements outputs. t_{start} parameter is defined to overcome the starting current of the motors. t_{end} parameter is defined as the maximum time that takes for a full-closure of one finger. I_{Thr}, dI_{Thr} are the current and current rate thresholds.

The device was tested in common ADLs such as, holding a glass, bottle, or can; pouring liquid or particles from one container to another; gripping a ball, notebook, phone, or keys; performing gestures and writing. From all the above ADLs, only writing was not simple to accomplish, and the task could be achieved only when using a large marker pen.

3.1 Adaptive Grip Results

Our results also demonstrated that the hand has an autonomous adaptive grip. Thanks to the adaptive grip technique, capabilities like opening, closing, grasping, and lifting objects with different shapes and weight with variable grip force are available in the presented hand design like a natural hand. The adaptive grip is based on the current amplitude and rate drawn by the motors when a resistance is applied. Several tests and evaluations were done to ensure the correlation between the current control results and the grasping behavior process. Figure 5 demonstrates three examples of different objects grasping – no object, stiff object and soft object. As can be seen in Figure 5, each movement starts with a high current drawn by the motor to initiate a motion, as expected. Then, a low current is measured for each motor until the grasping has started. At this point, different current behavior can be detected. When the fingers are closing without grasping any object, the time takes for the motors to complete an action is longer and the increase in the current value is short and instantaneously. In contrast, when the fingers are holding a stiff object a steady and relatively moderate slope can be detected, and hence a different torque level can be applied to induce different grip force pattern. Also, it can be detected that each motor stops at a different time that allows the adaptive grip technique. In this example, a tennis ball represented the stiff object, and indeed a nice correlation can be detected where firstly the index finger completed the gripping task, then the middle finger, then the ring finger and lastly the pinky completed the task – same configuration as if a natural hand was holding a ball. When holding a soft object the resistance felt by the motor changes along the grasping process – at the beginning a high current is drawn by the motor due to the impact when the finger encounters the object, but then the elasticity of the soft object reduces the resistance between the object and the finger and the current drawn by the motor decreases until the object is compressed enough to increase the current again. By identifying the different current patterns related to each object type, a further work can be done in attempt to automatically adjust the grip force according to the object stiffness. Currently, by analyzing the current rate and amplitude an autonomous grip adaptive is implemented and the different force grip level can be changed upon user's selection.

Figure 5 | Adaptive grip. Three examples of the current drawn by the motors during grasping different objects – no object, stiff object, and soft object. Different current slopes can be detected at the end of the fingers motions.

3.2 Users Feedback

For successful implementation of the device, feedback from the prospective user and feedback from healthy subjects were collected. Based on the feedback, device enhancements were implemented, and new user-inputs designs are planned for future work.

One of the main topics raised by the prospective user after examining the hand is the light weight of the prosthetic hand in comparison to his current prosthetic hand. Another topic raised by him and other healthy subjects is regarding the fingers speed.

According to feedback we gathered, the speed of the fingers during movements was relatively slow. The closure time was approximal 2 seconds and the movement of the finger seems to be unsmoothed. As a result, a change in the motor gear ratio was needed. The new model comprises of 200 rpm motors instead of 100 rpm, thus the time for a full closing was shorter (1 second versus 2 seconds) but the hand torque was reduced. Although the max weight that can be grasped by the hand is only 1 kg, the balance between speed and torque of the motors was improved, since the common ADL do not require lifting heavy objects.

Furthermore, since the prospective user's left hand was also injured during the same incident and as a result, has some type of hypertonia and spasticity, he had some difficulties to press the buttons and to distinguish between short and long clicks. Hence an optimization of the buttons parameters was done while new alternatives for user inputs methodology are already in development phase.

In addition, although according to the prospective user's opinion, there are more hand configurations than what he needs, he was fond of several gestures configurations that are meant to be more for communication than for grasping and holding. This type of configuration cannot be found in most of the commercial prosthetic hand and was inspired by the natural human hand responsibilities such as communication and entertainment and not only for physical tasks.

In the previous design, the indication of which is the currently active mode was done by moving the fingers according to the number of the active motion mode (e.g. for mode 1, one finger was tapping, for mode 2, two fingers were tapping, etc.). The

previous design confused the user since he needed to remember which mode is the active one and what does each of the buttons. Thus, the buttons arrangement was changed in order to be more intuitive and simpler than the previous model and to avoid the redundant need to memorize the hand movements. Additionally, based on feedback from the users, we placed 3 LEDs to indicate which motion mode is active instead of indicating it only once when the user switches the mode.
Surprisingly, to the prospective user's knowledge, there is one important hand movement that can be done only with the classic hook prostheses and not with the current prosthetic hands available in the market nor with the presented design in this study. To pull in or out objects from one's pocket an abduction-adduction movement of the finger needs to be applied. According to the user's experience, only the hook prostheses can accomplish this type of task.

3.3 Summary

Table 2 | Specifications of the new hand design in comparison to a commercial prosthetic hand.

	New Hand Design	Steeper Bebionic v3*
Operating voltage	7.4 V, LiPo	7.4 V, Li-Ion
Current consumption	340 mA at no grip, 1240 mA at full grip	-
Wrist rotation	90°	30°-60°
Max weight that can be grasped	1 kg	45 kg
Max weight that can be rotated	400 grams	-
The average time of a full finger closure	~1 sec	0.5-1 sec
Weight	460 g without the electronics	550-598 g
Control system	by buttons	1-2 electrodes of EMG
Actuation	5 actuator – 4 fingers and one wrist	5 actuators – 5 fingers (manual thumb rotation) the wrist can be active or passive
Hand configuration	total of 12 hand config. while 6 are available at any moment	total of 14 hand config. while 11 are available at any moment
Adaptive grip method	current control	based on finger position encoders
Cost	For materials only: less than 100$ USD	25,000-30,000$ USD

** All the information about Bebionic is according to M. Atzori and H. Müller 2015 and Bebionic's datasheets.*

After enhancements and improvements were implemented, the specification of the enhanced device can be observed in Table 2. To emphasize the novel features combination of the device, Table 2 also demonstrates a comparison to the commercial prosthetic hand the prospective user currently has.
As can be seen from Table 2, there are many common features between the presented hand design and the commercial prosthetic hand that the prospective user currently has. One of the main differences is the control system where the new hand design is not based on signals from the stump's muscles in contrast to the commercial prosthetic hand. Moreover, the adaptive grip method of the commercially prosthetic hand is based on finger position encoders. Meaning the location and position of each finger in space is known to the controller of the hand while in the presented new hand design the control is based on only the current drawn by the motors, meaning the controller of the new hand has only information about the load applied on the motors. The main drawbacks of the new hand design compare to the commercial prosthetic hand presented in Table 2 are durability since the presented new hand is 3D printed from plastics materials in comparison to the commercial hand, the capability to hold heavy load (1 kg versus 45 kg) and the hand esthetic appearance. On the other hand, the main advantages of the new hand design compare to the commercial prosthetic hand are the weight, the cost (100$ versus ~25K$) and the control system the does not require activation of the stump's muscles.

4. Conclusions

Throughout the development phase, the hand was iteratively designed, tested and improved by integrating results from functional tests with feedback acquired from the prospective user, and healthy subjects with and without experience in the use of prosthetic hands. Altogether, the results of this work show that the prosthetic hand design presented here can provide a solution for resembling the movements and functionalities of a natural human hand in a unique way that cannot be found at the current prosthetic hand available in the market.
However, one of the main limitations of the current user interface design is the selected user input type. Currently, the user desires are obtained via buttons that need to be pressed with the other healthy hand. This limits the potential functionalities such as actions that require a simultaneous use of two hands.
Therefore, nowadays we are developing new user inputs that would translate movements from the user's leg into the desired hand movements. Still, future work needs to be done.
Additional future work that can be carried out includes acquiring user inputs by different methods such as leg movements, sound recognition, EEG signals and more, adding abduction-adduction movements of one finger to pull in and out objects from the user's pocket, adding feedback for the user that is not only visual.
Overall, our results showed that the prosthetic hand design represents a sufficient solution for several of the unmet needs

of the prospective user and has the potential to give rise to a better and more suitable solution than the current commercial prosthetic hands with only minor design enhancements.

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