Article

Human hand anatomy based prosthetic hand

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Abstract: The present paper describes the development of a prosthetic hand based on the human hand anatomy. The hand phalanges are printed by using 3D printed with Polylactic Acid material. One of the main contributions is the investigation on the prosthetic hand joins; the proposed design enables to create personalized joins that allow the prosthetic hand a high level of movement by increasing the degrees of freedom of the fingers. Moreover, the driven wire tendons show a progressive grasping movement, being the friction of the tendons with the phalanges very low. Another important point is the use of force sensitive resistors for simulating the hand touch pressure. These are used for the grasping stop simulating touch pressure of the fingers. Surface Electromyogram (EMG) sensors allow the user to control the prosthetic hand grasping start. Their use may provide the prosthetic hand the possibility of classification of the hand movements. The practical results included in the paper prove the importance of the soft joins for the object manipulation and to get adapted to the object surface. Finally, the force sensitive sensors allow the prosthesis to actuate with more naturalness by adding conditions and classifications to the Electromyogram sensor.

Keywords: prosthetic hand; MyWare sensor; force sensing resistors, human hand anatomy

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1. Introduction

More than 3 million of people suffer from hand amputations or loss due to health disorders caused by infections, congenital absence, diabetes, cancer or others [1,8]. Over 75% of the amputations are partial [2]. The hand loss has an important impact on the person functional aspect. Many of the people with loss of hand have the possibility of using a prosthetic hand. The development of prosthetic hands has been less based on their functionality, relying more on the human hand aesthetic aspects[3, 4, 5, 6,7]. With the technological advances in biotechnology, the innovation reached the area of robotics and prosthetic hands development. Consequently, current commercial prosthetic hands have become more sophisticated. They are fitted with sensors and actuators, so that the fingers are motorized and can realize grasping movements. Nevertheless, the automatized prosthetic hands are expensive and not accessible to all social strata. Usually, the most common prosthetic hands are passive, and their goal is to substitute the human hand more esthetically than functionally. The powered prosthetic hands are classified in body powered and external powered prosthetic hands [9]. Body powered prosthetic hands mechanism is actuated by the human body movement through wires or cables. Usually, these types of devices are simple devices with grasping movement and are relatively lightweight. Moreover, body powered prosthetic hands require harnessing. External powered prosthetic hands are based on external power and actuators. Some of this type of prosthetic hands are controlled by Electromyogram (EMG) [10, 11] for grasping. The most common EMG controlled prosthetic hands use surface EMG [12] while other fewer use intramuscular EMG [13], [14]. EMG prosthetic hands are amplitude-based measurement devices and usually the control is slow. Because most of the prosthetic hands are controlled by a single input, the control of individual fingers or joins is not allowed. Usually, the prosthetic hands based on EMG use electrical signals of two antagonist muscle contractions. They allow two directions of movement: flexion and extension;

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one is for start grasping and another to start extension. As the EMG based prosthetic hands do not have external cables, these devices are more esthetical. To obtain more than two movements for the prosthetic hand, it is required to introduce more conditions, such as triggering or artificial intelligence (pattern recognition and classification). Prosthetic hands that are aimed to perform movements for all fingers operate in a sequential order with time delay. In some prosthetic hands the movements of the different fingers are performed by using several contractions of the same muscle (quick contractions of the same muscle) or by alternating both muscle contractions to control different joint movements. Another control system is based on force-sensing resistors, pull or push switches or Inertial Measurement Unit (IMU) [15].

Prosthetic hands also include hybrid prostheses. Hybrid prostheses are body powered and externally powered devices. Often, these devices are used in cases of upper limb amputations including transhumeral and shoulder. Regarding external powered prosthesis devices, these can be classified in those with one degree of freedom and those with multiple degrees of freedom. Devices with one degree of freedom perform only the extension and flexion movements. Usually these devices are robust [16, 17]. The ones with multiple degrees of freedom, also known as multi-articulated prostheses, are fitted with several actuators for different fingers and/or interphalangeal joins [17, 18]. They use small actuators that perform the required movement. Despite the high accuracy of the EMG signals, the researchers are still looking for the best methods of prosthetic hand control by combining EMG with artificial vision [19], microphone [20], tongue control system [21], etc.

The present study introduces a novel prosthetic hand development based on a combined control system that uses EMG, buttons, and force sensing resistors. The device design is totally based on the human hand anatomy. All phalanges are human hand scanned phalanges. The ligaments and joins are strictly developed as real ones. The device has 15 DOF (Degree of Freedom) and have different speed and forces. The soft material joins provide prosthetic hand a high level of adaptation to the object surface. They increase DOF of each join, enabling the small abduction/adduction. The use of force sensitive resistors allows the prosthetic hand to simulate the touch pressure sensing that stops grasping movement.

The paper is structured as follows: Section 2 describes the materials and methods of the prosthetic hand development. The Section 3 presents the experimental results and, finally, in the Section 4, the conclusions are provided.

2. Materials and Methods

2.1. Prototype design

The prototype is built using a human hand anatomy-based design. All the elements of the prosthetic hand are based on real human hand measurements that include the dimensions, proportions and human hand functionality. The idea of the proposed prosthesis relies on the reproduction of the human fingers' motions. For the prosthetic phalanges design, the real human hand phalanges have been 3D scanned and then designed by using a 3D drawing technology: the Autodesk Inventor Professional 2019. The whole prosthetic hand structure for actuators and processing supports was modelled with the same 3D drawing tool. Before proceeding to the prosthetic hand design and assembly, the main design specifications based on the human hand behavior as joins and movement capabilities were analyzed. All hard elements were constructed by using 3D printing technology with Polylactic Acid (PLA) filament that have good functional and structural characteristics and that are suitable for 3D printing. One of the main novelties of this prototype relies on the employed materials, which are ideal to reproduce human tendons, ligaments, fibrous sheaths, joins, etc.

The human hand consists of Carpal bones, Metacarpal bones, Proximal, Middle and Distal Phalanges. All fingers are based on four bones: Metacarpal bone, Proximal, Middle and Distal Phalanges (see Figure 1). The thumb finger is different and has one phalange less that rest of the fingers: Metacarpal bone and the Proximal and Distal phalanges. The joins are located between the

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phalanges and the bones. There are fourteen joins for the whole hand. The join between Carpal and Metacarpal bones does not have any Degree of Freedom (DOF). The Thumb is the only having a Metacarpal join with abduction/adduction movement with respect to the sagittal plane. The rest of joins have one DOF, flexion and extension movement with respect to the frontal plane.

Taking into consideration the number of ligaments and their characteristics, the artificial ligaments are chosen from rubber materials with different hardness and elasticity characteristics.

It is known that the bones dimensions are important for the prosthetic hand design and development. The phalanges and Metacarpal bone lengths considered for the prosthetic hand are the ones corresponding to an adult female.

The average lengths of the human hand is presented in the Table 1. The lengths of the phalanges significantly affect the object manipulation and hand movement. As the prosthetic phalanges are based on the human hand anatomy, the length of the fingers is 99% of the real hand; the 1% remaining depends on the joins. As the joins are reproductions of the human hand joins, the abduction/adduction and rotation for each join is possible.

Table 1. Anatomic human hand dimensions

Bone	Thumb	Index	Middle	Ring	Little
Metacarpal Bone	1.3567	2.049	1.906	1.719	1.578
Proximal Phalange	1.134	1.489	1.683	1.563	1.254
Intermediate phalanges		0.864	1	0.994	0.719
Distal Phalange	0.74	0.757	0.798	0.778	0.698

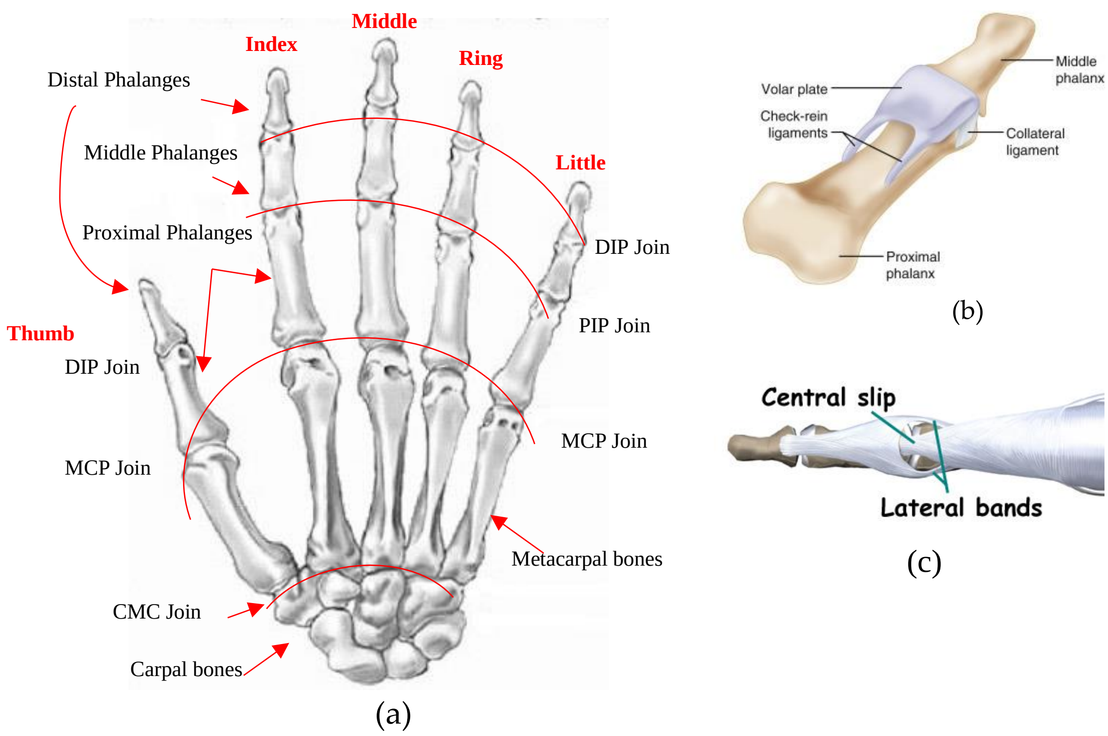

Figure 1. Human Hand anatomy. (a) Human hand bones and joins; (b) Volar plate and collateral ligaments; (c) Extensor hooks.

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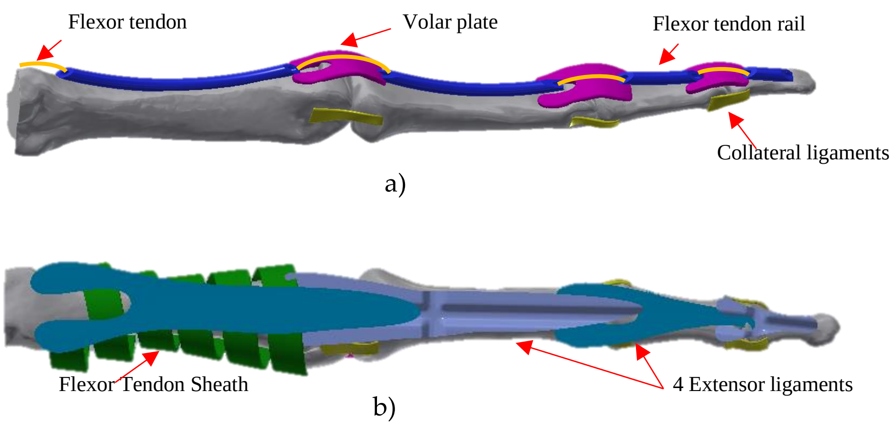

Figure 3. a) Finger flexor tendon route and joins (two side collateral ligaments and volar plate). B) Finger extensor tendons. 3D model of the prosthetic index finger assembly.

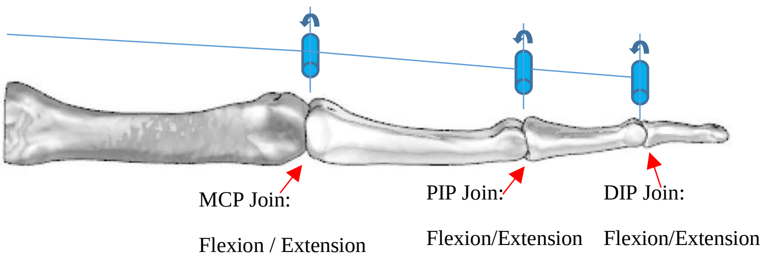

Figure 2. 3D model of the prosthetic hand assembly and its kinematics.

The abduction/adduction as well as the flexion/extension of the thumb are independently controlled by the control system. The kinematics of the Index finger is represented in Figure 2. The five fingers are driven by six actuators; each finger is controlled by one actuator, except on the Thumb, which is actuated by two. The purpose of this architecture, relying on using at least one actuator per finger, is to allow the prosthetic hand to perform finger movements independently.

As it can be seen in Figure 2, the prosthetic hand kinematics is based on the real human hand anatomy. The solution for the joins is to design the volar plate, collateral ligaments, and extensor ligaments as shown in Figure 1 b) and c) using rubber materials with different hardness. The developed joins elements are presented in Figure 3. The joins can perform 2-DOF at each join that allow to increase their functionality. Nevertheless, the abduction/adduction movement of the phalanges is so small that it does not have sense to introduce it in the prosthetic hand. The only existing abduction/adduction and flexion/extension movement in the four fingers is between the Metacarpal bone and Proximal Phalange, in the MCP join.

To reduce the movement range, the role of the stopper plays the tendon rail. All fingers are actuated through wires (tendons), which substitute flexor and extensor tendon connected to the actuators pulley. The mechanism for fingers movement is based on the endless routing tendons, in which the flexor and extensor tendons are connected to the same actuator pulley (see Figure 4). This architecture enables driving the pulley in both directions at the same time. The assembly of the prosthetic hand is presented in Figure 5. The difference versus another devices is that in this prosthetic model the inter phalanges driven pulley is not used. The tendon passes through tendons rails of each phalanges and ends on the distal phalange. To avoid tendons tearing, an additional 15% of tendon is added to each finger.

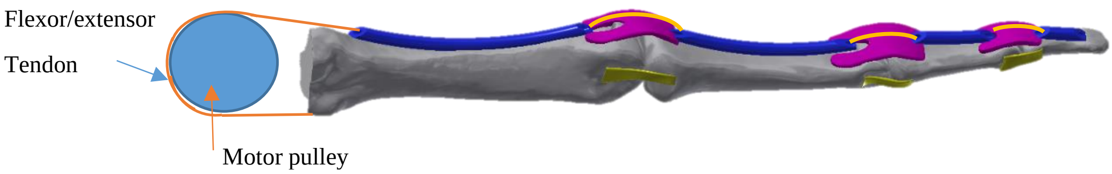

Figure 4. Mechanical architecture of the tendon transmission.

For the hand control, five force sensing resistors are used. The sensors are placed on the Distal Phalange muscle and are built using soft flex material. The Artificial Abductor Muscle is fabricated with rubber and prevents the movement more than it is necessary. It also enables to complete the palm of the prosthesis. As the thumb join with the trapezoidal carpal bone is made by tendons and collateral ligaments, it allows the join to perform 3DOF (flexion/extension, abduction/adduction and turn).

The maximum motion angle of the thumb abduction is 80 degrees. For the other four fingers (the Index, Middle, Ring and the Little finger) the motion flexion/extension angle is from 0 degrees to 90 degrees. Each join of the phalanges is dotted with artificial cartilages to avoid phalanges friction. The tendon sheath covers and holds the flexor and extensor tendons rails.

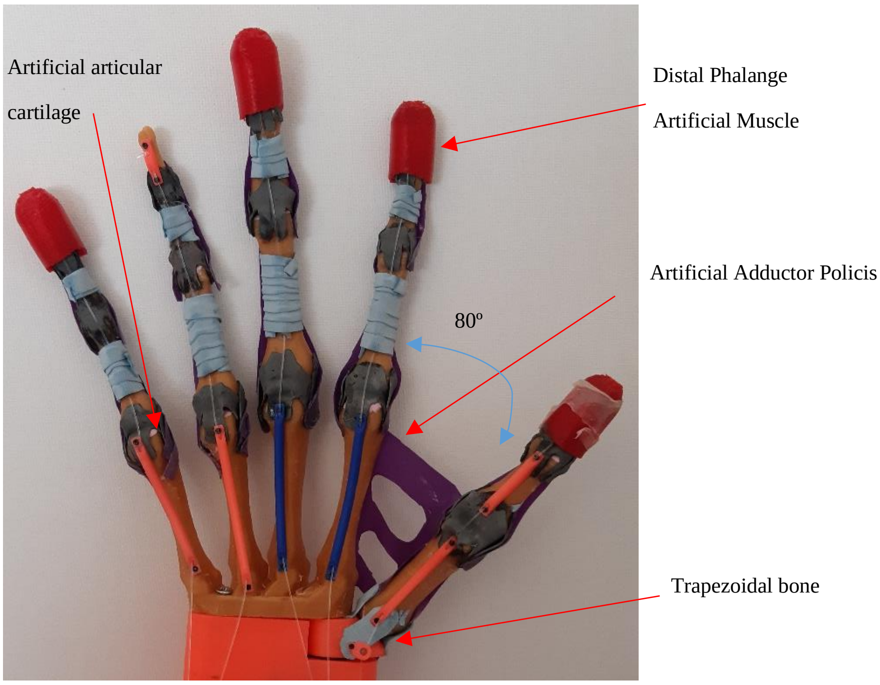

Figure 5. Mechanical assembly of the prosthetic hand.

The actuators and EMG are placed in the prosthesis forearm, while the servo motor for abduction/adduction movement of the thumb is located in the carpal bones of the prosthesis.

2.2. Control system

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The electronic system of the prosthetic hand is based on: a Myware EMG sensor, five step motors, five drivers, a servo motor, an Arduino AtMega 2560, two pushbuttons, a shield and five force sensing resistors. The characteristics of the electronic components are presented in the Table 2.

Table 2. Electronic components

Components	**Specifications**
Arduino AtMega 2560	Imput Voltage 7-12 V Analog Input Pins 16 DC Current per I/O Pin 40 mA DC Current for 3.3V Pin 50 mA Clock speed 16 MHz EEPROM 4KB SRAM 8KB Flash memory 256 KB Analog imputs Pins 16 Digital Imputs 54
Myware EMG	Operating voltage 2,9V - 5,7 V Operating Current 9Ma – 14 mA Outut RAW and filtered signal
force sensing resistors	Measuring range 0-2 kg Thickness <0.25mm Precission +/- 2.5% Initial resistance >10Mohm Voltage DC 3,3V Response time 1ms
Servo motor	Operating Voltage 4.8 V Operating current 50mA Speed 0,12 at 4.8V Torque 1.8kg/cm Degree 180º
Step motor	Operating Voltage 5V - 12V Operating current 2.5A Speed 0,1 Torque 0.34kg/cm
DRV8825 driver	Operating Voltage 8.2V - 45V Operating current 2.5A
Pushbutton Switch	12mm button square

The main control unit of the prosthetic hand is the Arduino AtMega 2560. The prosthetic hand movement activation is controlled by a surface Myoware muscle sensor. The sensor electrodes are placed on the human hand skin above the flexor muscle and the reference electrode is installed in a neutral place (over the join bones), as shown in the Figure 6. Figure 7 shows the prosthetic hand control flow.

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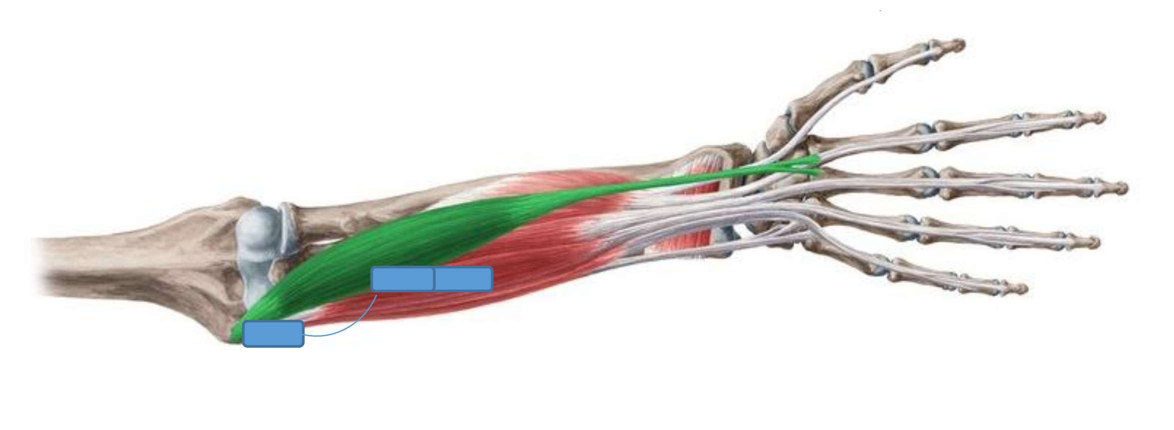


Figure 6. Positioning of the EMG sensors of the human hand hand.

Once the extension is required, the user presses the button for the extension and the hand automatically passes to the initial position and waits for the new command.

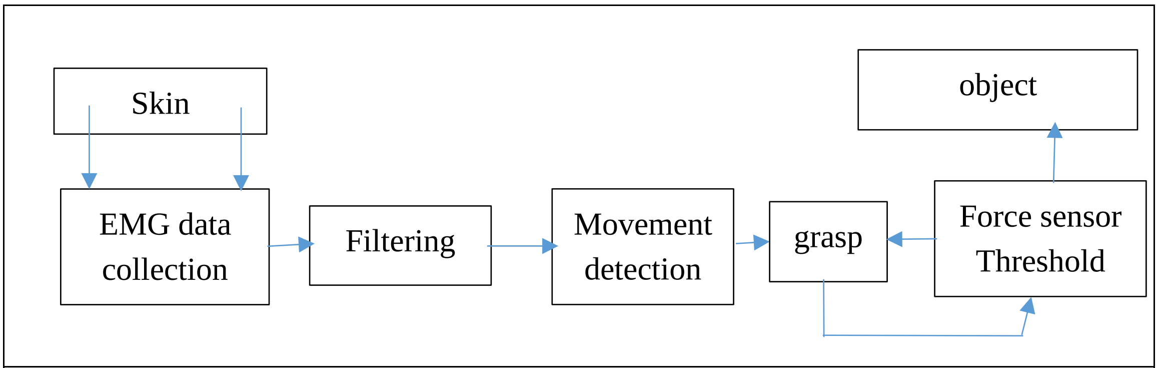
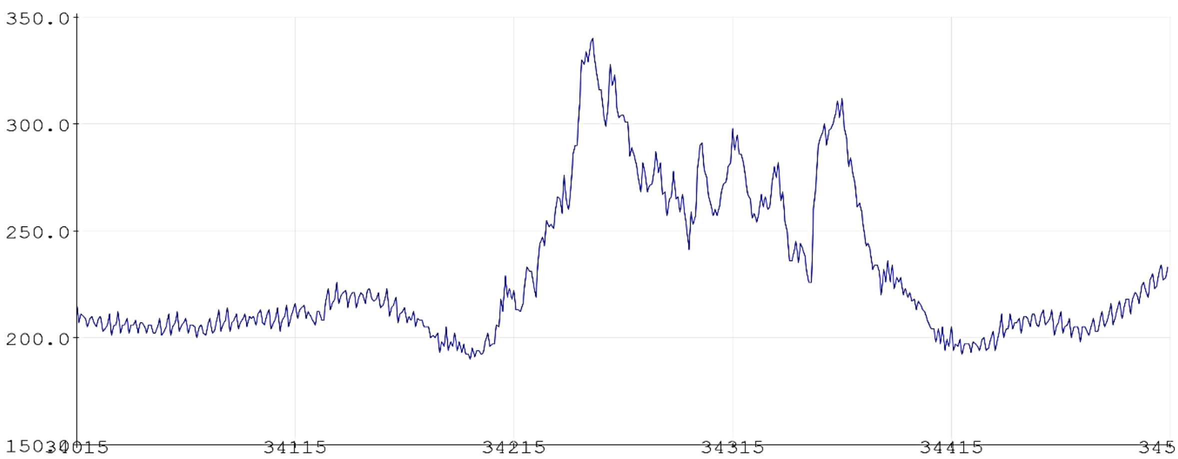


Figure 7. Motion sensing block diagram of the prosthetic hand.

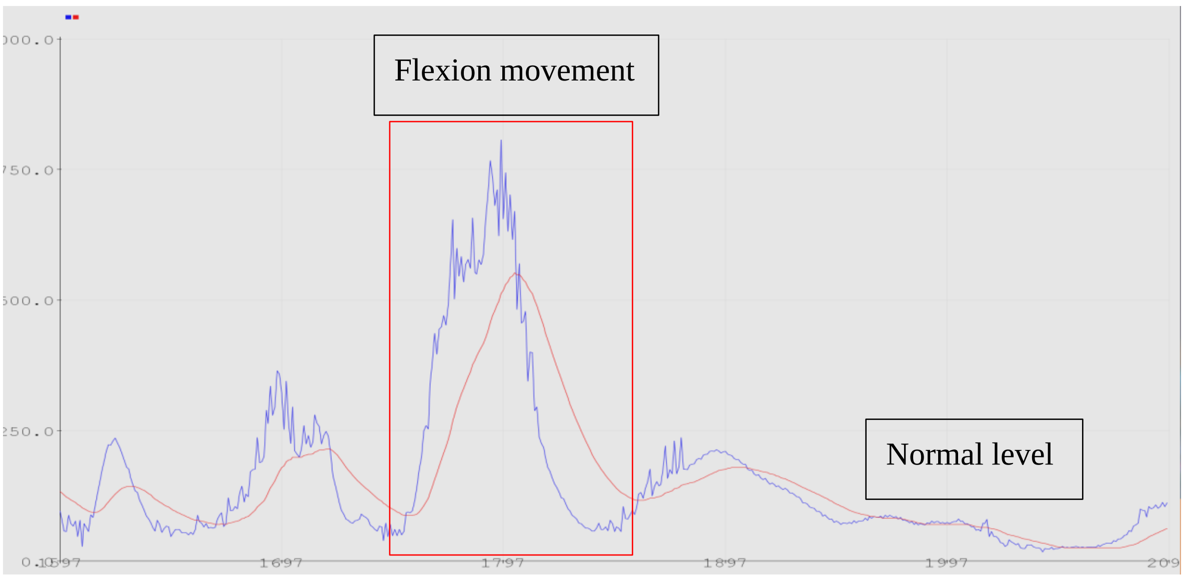
The signals received by EMG sensors are amplified and rectified. Figure 8 a) illustrates the EMG signal and in b) the filtered signal. The input amplitude signal of the EMG is in millivolts. Once the EMG signal is received, it should be filtered with a band-pass filter or by using a low-pass filter and a high-pass filter. Firstly, the signal is filtered with a digital Low-Pass Filter based on the Kirchoff's Law in order to reduce signal noises. The amplification is calculated by:

$$x[n] = \alpha * y[n] + (1 - \alpha) * y[n-1] \qquad 1)$$

Where α is the smoothing factor that varies from 0 to 1, x[n] is the resulting filtered discrete signal, y[n] is the discrete signal received by EMG. Example of an EMG filtered signal is presented in Figure 6 b). In that figure, the EMG signal was filtered at α=0.05. The EMG signal was tested for different α values from 0,05 to 1. For the α=0,05 value, the filter is slower and clear. In Figure 8 b) can be perceived the filtered signal with red color.



a) EMG signal



b) Low Pass Filtered EMG signal for α=0,05

Figure 8. Example of EMG signal.

The filtered signal is then classified and analyzed for Finger flexion and extension. The features are extracted and discriminated from the EMG signal. The power for grasp movement is considered in the present study. The posture of the fingers is not considered.

In order to quickly calculate the EMG signal, the features are extracted in time domain. Furthermore, the grasping function starts with the condition of EMG signal amplitude. It starts grasping when the EMG signal amplitude exceeds the predefined threshold.

$$f(x) = \begin{cases} 1 \; if \; x > threshold \\ 0 \; otherwise \end{cases} \qquad 2)$$

Where f(x) is the EMG input signal. The threshold is defined in accordance with the EMG signal voltage for each type of grasping.

Figure 8 presents, in the red rectangle, the grasping movement. The signal below the amplitude threshold is not considered.

The grasping end depends on many factors as contact points, force closure, grasp control, external force, friction, etc. it means that there is necessary to realize object surface exploration.

Let us consider that external force is defined as f and depends on the external wrench w, at a moment m, the contact force p and the torque τ.

The torque can be defined as:

$$\tau = p * J^T \qquad 3)$$

Where J^T is the Jacobian matrix for manipulation.

The force balance f= -G*w can be calculated by taking into consideration that the applied contact force must balance the external force applied to the object, where G is the grasp matrix.

The grasping force is also proportional to the actuators current f=k*I. If considering that the force sensitive resistance sensor voltage v, then the contact force p=k*v.

The grasping stop function then is calculated as:

$$v = \begin{cases} 1 \; if \; p > threshold \\ 0 \; otherwise \end{cases} \qquad 4)$$

3. Results

The experiments that were carried out with the prosthetic hand are aimed to verify the correct functionality of the device. Moreover, in these experiments, the evaluation of the device structure is also performed. To this end, the joins equilibrium is studied. As the joins are made of rubber, it is important to analyze the correct fingers flexion/extension trajectory, as well as the limits of the possible deviations of the phalanges under pressure. During the experiments, the prosthetic hand is placed in vertical position. The grasp experiments are conducted with three different size objects; the objects employed in the experiments are: a ball, a pencil, and a note block, as shown in Figure 9. The ball diameter is 64mm, the note block width is 4mm and the pencil diameter is 10 mm. The hand is able to grasp the ball without any glove, but the use of a glove is also tested. The glove used in the experiments was a standard glove made of latex. Because the glove has a dry surface, it was impossible to grasp the tennis ball since it slipped from the hand. Also, the glove design influences the prosthetic hand grasping experiments. Afterwards, the ball grasping is tested without the latex glove, and the prosthetic hand is able to grasp the ball, as observed in Figure 9.

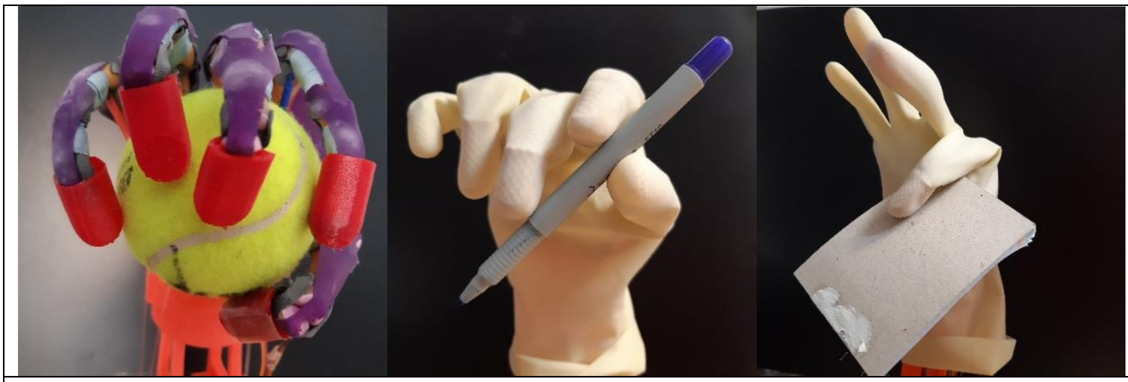


Figure 9. Grasp with a tennis ball without glove, pencil and notebook.

Grasping time is different and its depends on the objects thickness or diameter. The basic grasping time was 1,3 seconds from the open hand position.

With regards to the design of the prosthetic hand, the rubber materials resistance is studied. The joins and the rubber made extensor tendon, as well as the artificial adductor policis (muscle), are analyzed. The hand is evaluated and tested during 6 months. During this period, multiple grasping movement experiments are performed. Some wear in the extensor tendon and artificial adductor muscle is observed after this period. The rubber starts cracking and changes the color in the joins zone as well as where other rubber material is, as it can be seen in the Figure 10. Also, after 6 months,

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the artificial adductor muscle, made by the same material, breaks when big objects are tested, such as the tennis ball. The rubber extensor tendon generates resistance when the grasping is performed, and this resistance requires high powered actuators. Small servomotors with the torque of 1,8kg/cm are not enough. Due to this problem the usage of the stepper motors is adopted in the current prosthetic hand. The weight, size and power supply of the prosthetic hand depends on the electronics and the prosthetic hand functionality. Taking into consideration that the fingers load is correlated with the rate torque of the actuators, the whole load is based on the actuators axis.

Figure 10. Rubber materials.

One of the objectives of the presented prototype has been to improve prosthetic hand functions with its design. The conventional prosthetic hands with robotic joins can realize just 1 DOF per join [22, 23]. Nevertheless, the proposed design has flexible joins, so that the small abduction/adduction on the joins will allow the fingers to easily adapt to the object forms. Basically, this improvement of the joins can provide multiple additional features to the prosthetic hand, such as hook, spherical grasp, cylindrical grasp, tip, etc... The proposed design also avoids abduction/adduction limitations and permits a better prosthesis function increasing the range of motion. The use of the force sensitive resistor placed on the distal phalange of the thumb allows to define a better pressing over objects and stop grasping of the prosthetic.

The sensory controlled prosthetic hand allows the user to actively enable the desired task. The sensor feedback gives to the user a more adequate control over the prosthetic hand and the external objects. The experimental results with the force sensitive resistors shows good results on the grasping end as well as implies minimum computational costs. When the pressure threshold is detected, then the grasping is stopped. Therefore, the grasping stop generate a new grasping order (flexion or extension) waiting for the new EMG signal and force sensitive resistor. When the new flexion (grasping) order is generated, the cycle is repeated agin.

The integration of 5 force sensing resistors will allow the actuators to work autonomously, i.e., with independent movement of the fingers. In this case, it will not be necessary to introduce muscle movement classifications for all types of grasping. This will decrease the EMG classification processing time that will reduce memory space required for the signal processing. All these improvements will facilitate a real time functionality of the prosthetic hand avoiding time delays. The sensor feedback allow user to control the prosthetic hand and take decisions on the prosthetic hand activity. Vision, also help the user to define the prosthetic hand activity.

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4. Conclusions

In the present work, the design and development of a prosthetic hand that emulates the human hand motion is presented. The proposed mechanical architecture of the prosthetic is based on the human hand anatomy and offers a broad range of movements. The articulation joins increase the degrees of freedom of the fingers and improve the hand flexibility. The prosthetic hand can perform fine movements and grasp different size objects. The work shows that the employed materials must have enough flexibility and hardness to enable a correct use of the hand. The wire driven tendons methodology that is employed in the proposed prosthetic hand solution shows a good grasping performance. The friction of the tendons is very low, which is another advantage of the prototype. The friction generated by the extensor tendons with respect to the tendon sheath, makes that actuators with higher power are required.

On the other hand, the use of the EMG to control the prosthetic hand enables to increase its ability when using human muscle actuation. It is also remarkable the use of an advanced signal processing (signal acquisition, filtering, classification, and training) to enable a reliable realization of the different hand movements. Finally, the usage of force resistive sensors to end the grasping movement allows the prosthetic hand to simulate the touch pressure of the real hand.

In conclusion, the proposed solution shows interesting advantages versus available alternatives, enhancing the functionality and ergonomic nature of the device and not only relying on esthetic aspects.

Author Contributions: Larisa Dunai Dunai realized the prosthetic hand design, structural analysis of the components, prototyping, designed the experiments and wrote the paper; Martin Novak developed the software of the prosthetic hand and performed the experiments and revised the paper; Carmen García Espert contributed with the human hand anatomy content and revised the paper;

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