Design and Development of a Mechatronic Transradial Prosthesis

J. Fasoulas[*], M. Sfakiotakis[+], M. Petousis[*], S. Kalantzis[*] and G. Kampourakis[*]

[*]*Dept. of Mechanical Engineering, Technological Educational Institute of Crete Heraklion, Greece, E-mail: jfasoulas@staff.teicrete.gr*

[+]*Dept. of Electrical Engineering, Technological Educational Institute of Crete Heraklion, Greece, E-mail: msfak@staff.teicrete.gr*

Abstract**—This paper presents the design of an anthropomorphic transradial prosthesis that incorporates a 13 degrees of freedom robotic hand with force touch sensing capabilities. The articulated structure of the fingers and the thumb is designed as a compliant mechanism based on rigid phalanges interconnected with helical extension springs. An underactuated design has been utilized that makes use of tendon drive mechanisms, which simplifies the fabrication and the assembly of the prosthetic hand. The hand is able to actuate each finger individually, as well as rotate the thumb to create opposition or a lateral pinch grip. An artificial forearm is designed for the prosthesis to base the palm of the hand and also to be connected with the remaining limb of the patient. Finally we present early experimental results of the robotic hand in performing common gestures and grasping tasks.**

Keywords— Transradial prosthesis, prosthetic hand design, artificial forearm design, rc-servo actuators, soft fingertips, FSR sensors.

I. Introduction

The loss of a limb is one of the most psychologically, physically and financially devastating events that can happen to a person. Such an event reduces the mobility and decreases the quality of life of the amputee. In general it is difficult to distinguish the leading cause of limb loss worldwide since the main causes vary for different regions of the world. However, limb loss can be the result of trauma (mechanical, electrical, thermal or chemical) malignancy, disease or congenital anomaly. In addition, different causes of limb loss have different residual limbs which affect the type of prosthesis design and also the control interface. In this work we focus on the design and development of an transradial prosthesis which is an artificial limb that replaces an arm missing below the elbow.

Hand prosthetics can be classified into the following three main categories: (a) the Cosmetic Hand Prostheses, which are passive functional prostheses that copies the appearance of the amputated hand. However, they can only be utilized for simple tasks that include passive carrying and balancing objects but require minimum maintenance and are not heavy to use. (b) The Cable Operated Limbs that work by attaching a harness and cable around the opposite shoulder of the damaged arm. Their main advantages are the extended durability and the light weight. They are also cheaper than the other forms and will not require as much maintenance to the user. In contrast they can be used for only simple and non-intuitive grasps. Finally the last category (c) includes the Myoelectric Hand Prostheses, where instead of using a harness system, the device is controlled by utilizing electric actuators that are powered by batteries and controlled by microprocessors. These work by sensing EMG signals from the skin, when the muscles in the upper arm moves. The signals are then transmitted to a processor which control the actuators causing an artificial hand to open or close. For more positive results of this prosthetic usage, intensive training is required.

The last category is the state of the art in prosthetic limbs, but the current problem with the most advanced commercially available prosthetic hands, such as the i-limb Ultra [1], bebionic [2], and Michelangelo [3], is cost, which ranges approximately between US$ 35,000 and US$ 75,000 [4]. The development of a mechatronic transradial prosthesis is a real challenge for engineers. This is due to the effort not only to embed in a human-hand size a number of actuators sensors, batteries and control electronics but also to implement reliable control algorithms for grasping and manipulation for everyday objects.

This paper describes the design and development of a prototype low cost transradial prosthesis that weighs a little over one kilogram (1041gr). The developed prosthesis consists of a robotic hand, which includes four under-actuated fingers, a palm and an opposable thumb. Furthermore, there is an artificial forearm with its internal base, which serves as the mechanical interface between the remaining limb of the patient and the robotic hand. A direct comparison with the hand and the forearm of one of the authors is shown in Fig. 1. The prosthesis has been fabricated utilizing 3d printing, CNC, and carbon fiber technologies.

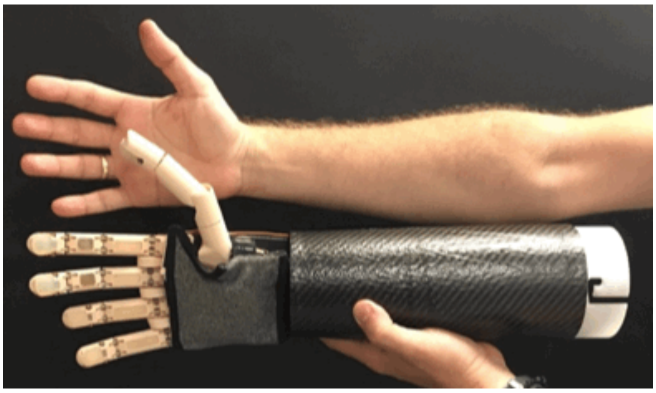

Fig. 1. The developed transradial prosthesis

II. Prosthetic Hand Design

The anthropomorphic hand of the transradial prosthesis (Fig. 2) features four fingers, a thumb and a palm. It has a total of 13 degrees-of-freedom driven by six degrees of actuation, and weighs 503gr.

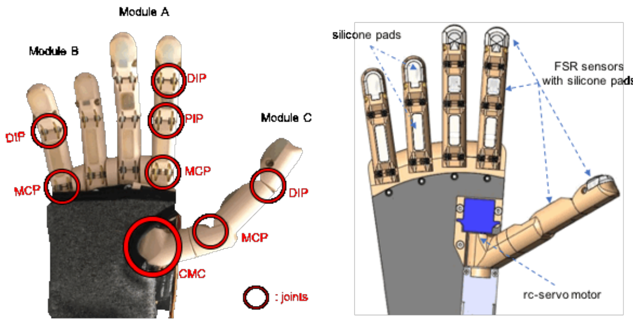

Fig. 2. CAD model of the developed prosthetic hand

The articulated structure of the hand implies 13 joints (Fig. 2) with each one corresponding to one revolute degree of freedom. The phalanges and the joints are named by adopting the corresponding terminology of the human hand anatomy. More specifically, the index and the middle finger have three degrees of freedom and identical structure (*module A*). The phalanges of the fingers are named as Proximal, Middle and Distal phalanx. The joint that connects the latter fingers with the palm is called the MetaCarpoPhalangeal (MCP) joint. The joint in the middle of the finger is called the Proximal InterPhalangeal (PIP) joint, while the one that is closest to the fingertip is called the Distal InterPhalangeal (DIP) joint as illustrated in Fig. 2. By contrast, the pinky and the ring finger have two degrees of freedom and identical structure (*module B*). They comprise of only two phalanges that are interconnected with the DIP and the MCP joints as shown in Fig 2. However, the fingers are not capable of abduction/ adduction motion.

The third module (*module C*) is the thumb, which has three degrees of freedom and a design that is kinematically different from the other two modules. The joint nearest to the palm is called the CarpoMetaCarpial (CMC) joint and allows a flexion/extension motion of the thumb, while the other two joints are called the MCP and DIP joints. All phalanges of the robot hand and the parts of the palm have been fabricated by using a 3d-printer from PLA (Polylactic acid) material.

The articulated structure of the fingers is designed as a compliant mechanism based on rigid phalanges inter-connected with two helical extension springs. Two of them are placed in parallel in order to implement a joint with one d.o.f. The springs are able to bend under the action of pulling tendons, while a limited number of coils are enough to obtain large displacements and avoid permanent deformations. It can be shown experimentally [5] that the kinematic behavior can be modelled, with good approximation, as an ideal revolute joint with a torsional stiffness.

A. *Hand fingers*

The CAD models of the finger modules A and B, along with a detailed view for the phalanges are shown in Fig. 3. The dimensions of the fingers are similar to anthropometric information available in [6]. In particular, the finger modules A, B are cylindrical in shape with a diameter of 18mm, with length of 100mm and 80mm, respectively. Silicone rubber pads are used on the anterior surface of the finger modules in order to increase the contact friction with the grasped object.

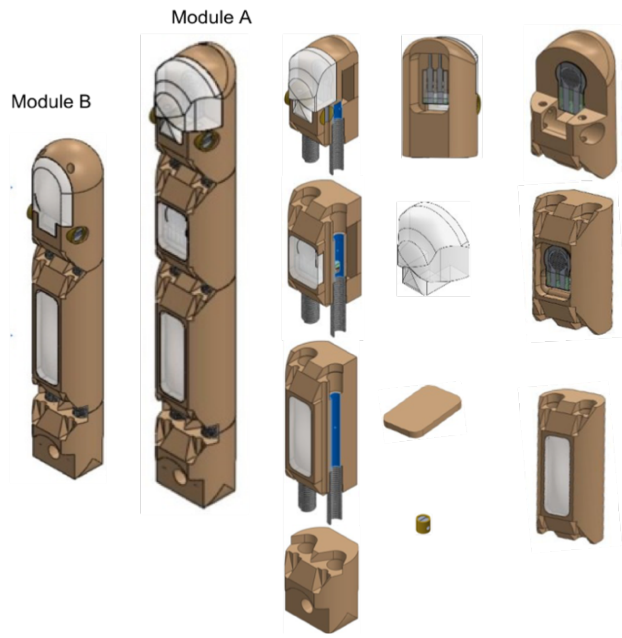

Fig. 3. CAD models of the robotic hand fingers.

A particular design feature is the two cylindrical recesses at one or both ends of the phalanges in order to place helical extension springs that form the connecting joints with the neighboring phalanges. For example in Fig. 3 the middle and the proximal phalanges have helical springs in both ends. The distal phalanx of module A has a curved silicone fingertip allowing to rolling motions that increase the manipulation abilities of the hand. Moreover, by pulling two tendons that are firmly connected on each distal phalanx the finger bends while the return is obtained by means of the flexures elasticity.

On the anterior surface of the finger module A, a low-cost force sensing resistor (FSR) is incorporated under the corresponding silicone pad of the distal and the middle phalange (Fig. 3). This allows the measurement of tactile/ pressure distribution on the phalanges during grasping tasks. The wires of the sensors are routed through the helical springs following a path with a direction from the distal phalanx into the base of the finger. Finally, all the wires are gathered inside the palm of the hand. There is no force sensing resistors for the finger module B, since these fingers play only a supporting function in most of the grasping tasks.

B. *Opposable thumb*

The thumb (module C) is the most versatile digit of the hand. It also has an underactuated design with three degrees of freedom and two actuators, one linear and one conventional rc-servo motor. Due to its kinematic structure the thumb is able to carry out rotary and abduction/adduction motions that imply the opposition of the thumb with the index or the middle finger. A detailed CAD model for the thumb along with the exploded view of the two hosted actuators is shown in Fig. 4. Force sensing resistors are also incorporated under the two silicone pads of the thumb.

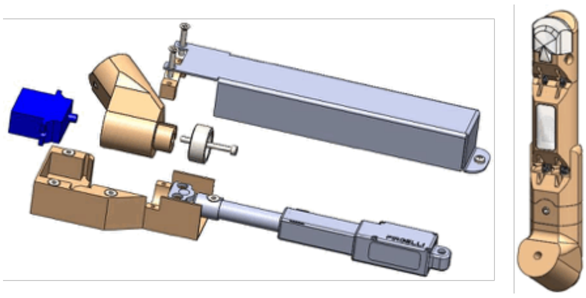

Fig. 4. The CAD model of the underactuated thumb with its actuators.

C. Palm

The palm is made of two parallel-placed thin aluminum plates, and all fingers are attached onto the edge of the palm with a slight difference in position as shown in Fig. 5. This makes the mechanism more anthropomorphic and any malfunctioning finger can be easily replaced. The actuation mechanism is hosted in the palm of the hand and allows the independent flexion/extension of the four fingers as well as their adaptation onto the grasping object. This allows a multiple contact grasp with an increasing stability. The mechanism consists of four low-cost micro linear servo-motors (L-12 Actuonix), which are connected with the tendons of the corresponding fingers with horizontal T-shaped links as shown in Fig. 5. As a result, the forces created by the pulling tendons simplify the transmission chain and evoke the independent motion of the fingers. The overall structure of the palm and the hand along with the base is shown in Fig. 1. The actuation unit has been designed to allow complete flexion (or extension) in about 2 seconds.

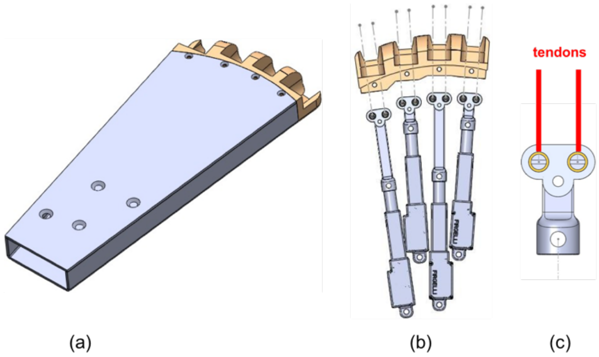

Fig. 5. (a) The CAD models of the palm, (b) the actuators of the fingers and (c) the T-shape link of the tendons.

III. FOREARM DESIGN

The forearm weighs 538gr and is designed to be part of an upper limb prosthesis in conjunction with the robotic hand. The forearm assembly (see Fig. 6) comprises the internal support plate (a), the two wedges (b), the external carbon fiber case (c) and the internal base (d). All the manufactured parts along with the prosthetic hand are shown in Fig. 7.

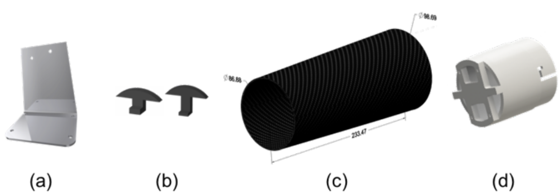

Fig. 6. The CAD models of the parts comprising the forearm: (a) the internal support plate, (b) the two wedges, (c) the external carbon fiber case and (d) the internal base as connected to the prosthetic hand.

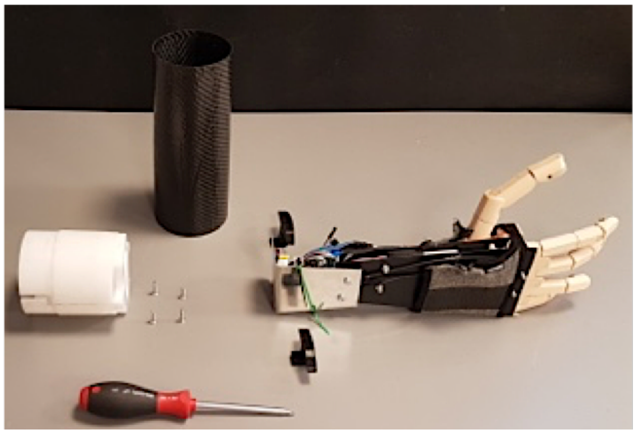

Fig. 7. The manufactured parts of the forearm and the prosthetic hand.

A. Internal support plate

The internal support plate (Fig 6a) is the main connection interface between the robotic hand and the internal base of the forearm. It is made of stainless steel 304L; its weight is 200gr and provides a firm hold for the components as well as the limitation of displacements along the plane of the palm. The hand is connected to the support plate with two M4 bolts, allowing for a simple assembly (Fig. 7). On the other side of the plate, there are four holes for the firm connection with the internal base of the prosthesis.

B. Internal Base.

The internal base (Fig. 6d) is designed to be a one-piece part with an internal cylindrical shape and an external conical surface that creates a wedging contact with the external carbon fiber case. Every stress applied to the prosthetic hand is transmitted through the internal support plate to the internal base of the forearm that weighs 230gr. Particularly, it is manufactured at a computer numerical control (CNC) milling machining center by using Ertacetal as raw material, which has good fabricating and machining properties with excellent impact strength. Finally, an external suspension system can be connected easily to the internal base through two additional channels that are designed on the rear. The idea is to have a fast and easy connection and disconnection of the prosthetic forearm to the human limb.

C. External Carbon Fiber Case.

The carbon fiber case is the external part of the prosthetic forearm (Fig. 6c). It provides protection for the internal components (actuation mechanisms, electronics, batteries, etc.) from moisture, dust or water, but also from any movements that can cause damage. The shape of the case is designed to be symmetrical with respect to the longitudinal axis, in order to have a rather easy and inexpensive construction method. The material that is used to manufacture the external case is CFRP (Carbon Fiber Reinforced Polymer) and weighs 95g.

D. Wedges

The wedges are two small parts (Fig. 6b) that are assembled between the palm and the front internal surface of the carbon fiber case. They are used to restrict lateral stress when the hand is pushing or lifting heavy objects. Wedges are made of 3d printed PLA material and they both weigh 13gr.

IV. Experimenal Results

In this section, we present experimental results demonstrating several capabilities of the prosthetic hand. An electronic prototype board was designed in order to interface the six FSR sensors and the six actuators of the digits with an Arduino Mega 2560 microcontroller. The electronic board also incorporates appropriate circuitry along with five current sensors for the linear servo motors. The control of the hand is based on an algorithm that combines data from these sensors. The basic idea is to stop the motion of the fingers when the sensors' signals reach appropriately defined thresholds. We conducted experiments for creating gesture patterns and basic stable grasps.

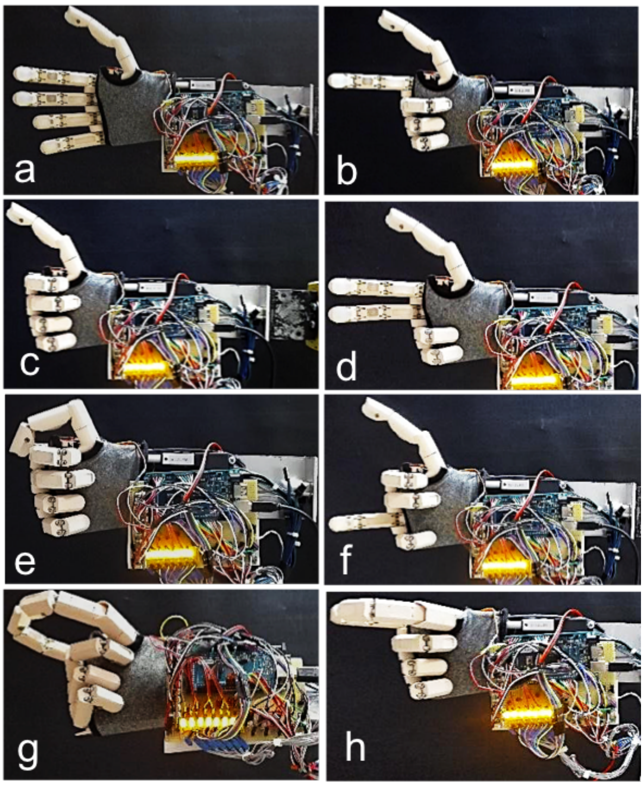

Fig. 8. Several gesture patterns made by the prosthetic hand.

A. *Gesture patterns*

In every day life, it is common for humans to use their hands for fast and simple communication with other people. Gestures can help people describe what they are talking about, e.g., point to other people, places or things in their surroundings, as well as add emphasis and give clues about their emotional state. The proposed prosthetic hand can perform gestures by activating one or more digits simultaneously. The deployment of the five digits are apriori known for each gesture and the microcontroller sends the desired position comand to the actuators. Several predescribed hand gestures are shown in Figs. 8a-f like the thumbs up, the clenched hand, the pointing gesture, or the three finger-counting gesture. Gestures involving the opposition of the thumb with the index finger are also shown (Figs. 8g,h).

B. *Grasping capabilities*

Apart from gestures, the dexterous robotic hand can grasp a number of everyday objects. Indicative examples from successful such experiments, involving objects of different shape, size and weight from 50gr to 1200gr, are shown in Fig. 9.

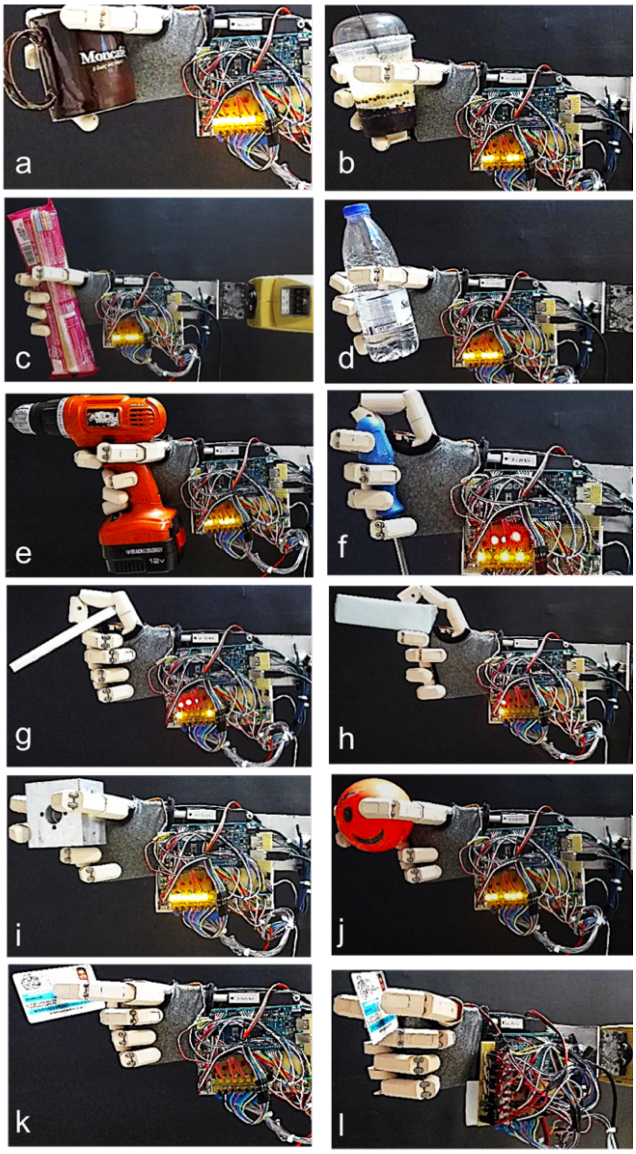

Fig. 9. The prosthetic hand grasping a variety of objects.

A *power grasp* is used for objects like a mug filled with water, a cone-shaped plastic glass with coffee, a packet of pasta, a small plastic bottle, as well as a hand-drill and a screwdriver (Figs. 9a-f). Power grips are characterized by a large contact area between the grasped object, the palm and the fingers, while there is a limited or no ability to impart motions with the fingers. The photos in Figs. 9g,h show the robotic hand utilizing *lateral prehension*, where the pad of the thumb pushes the lateral side of the index finger, for grasping a thin plastic plate and a small a paper box. Finally, Figs. 9i,j demonstrates a *three-finger grip* (thumb, index finger, and middle finger), utilized for an aluminum cube and a spherical rubber ball. In addition, for grasping thin and light objects like an ID card, a *precision grip* with the tips of the thumb and the index finger can be accomplished as well as with a passive three-finger grasp based on gravity (Fig. 9k,l). But in this case, any disturbance on the object may cause instability and lead to loss of contact. However, the envelope grasps are more stable especially when the grasped object can be slightly deformed from its nominal shape.

As a final remark, it is noted that, although each fingertip is able to exert forces up to 2N (see Fig. 10a-b), the hand is able to grasp firmly objects that are multiple times its weight, as exemplified by the grasp shown in Fig. 9e.

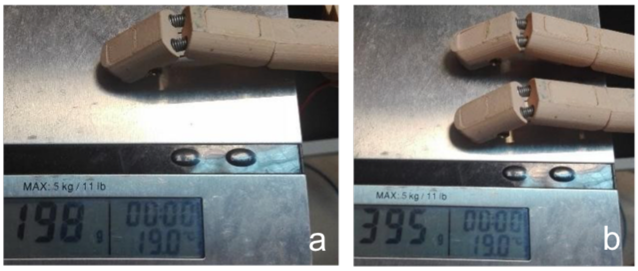

Fig. 10: Normal forces exerted by the fingertips of the prosthetic hand.

V. Conclusion

We have presented the design and development of a transradial prosthesis that incorporates a 13 d.o.f robotic hand. Motion is generated by 6 servo motors and transmitted to five underactuated fingers. Its actuation distribution allows the hand to stably perform fundamental grips and gestures useful in activities of daily life. The weight is less than the natural hand weight and comparable to commercially-available prostheses. Future work will address the incorporation of the electronics and the batteries in the internal space of the forearm, the development of an EMG interface, and the improvement of the control algorithm.

Acknowledgment

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