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A Sustainable & Biologically Inspired Prosthetic Hand for Healthcare

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Abstract

There are many persons in the world affected by amputation. Upper limb amputations require high cost prosthetic devices in order to provide significant motor recovery. We propose a sustainable design and control of a new anthropomorphic prosthetic hand: all components are modular and exchangeable and they can be assembled by non-expert users. Phalanges & articulations of the fingers and the palm are manufactured via a 3D printing process in Acrylonitrile Butadiene Styrene (ABS) or Polyactic Acid (PLA) materials.

The design is optimized in order to provide human-like motion and grasping taxonomy through linear actuators and flexion tendon mechanisms, which are embedded within the palm. HardWare (HW) and Software (SW) open sourced units for ElectroMyography (EMG) input and control can be combined with a user-friendly and intuitive Graphical User Interface (GUI) to enable amputees handling the prosthesis.

To reduce the environmental impact of the device lifetime cycle, the material and energy consumption were optimized by adopting: simple design & manufacturing, high dexterity, open source HW and SW, low cost components, anthropomorphic design.

Keywords: smart prosthetics, human-centred healthcare, sustainability, bio-mimetic.

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1. Introduction

Nowadays limb loss and amputations can be a devastating phenomenon with functional limitations and dramatic implications. One of the primary cause of upper limb and hand amputations are traumatic events, poor vascularity and neoplasia [1]. From a medical viewpoint, an association between the age of the patient and the cause of the amputation has been found as a result of higher morbidity in the older population. Moreover, especially in the western countries, vascular disease and diabetes accounted for a significant percentage of all the amputations [2]. In current developing countries, traumatic events have a main role on the amputation surgical procedures. Vascular diseases are also responsible of even high level of amputations as well [3].

Focusing on upper limb amputation and, specifically, on hand amputation, it is clearly a challenging task to provide artificial devices, which inherently replace the dexterity and functionality of the human hand [4]. Human hand, in fact, is a marvellous system performing optimized task with an integrated approach: this applies (a) to the biomechanical design of the hand, (b) to the set of superficial and inner available sensors which are embedded - either for the monitoring of the movement or the interaction with the external world - as well as (c) to the synergic control techniques, allowing the manipulation, micro-manipulation and performance of an enormous variety of daily life tasks [5, 6].

Significant progresses in prosthetics have been done, even if current devices and especially those with *high dexterity* are quite *expensive*. Moreover, most of these devices require professional technicians with *high*

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expertise to be customised to the patient and to be fixed and repaired.

Here we propose a low-cost functional robotic hand, which is inherently simple from a mechanical and integration point of view. The device is *low cost*, can be *easily assembled* and its design has been inspired by a *biomimetic approach*. In this context, the device is also *sustainable* and environmentally compatible.

2. Requirements

The main requirements and specifications behind this study are the design and the prototyping of a (i) fully integrated and (ii) environmentally compatible, (iii) low cost and (iv) anthropomorphic robotic and prosthetic hand.
Namely the device should achieve the following targets, performing:

Pd-Distal phalanx		*Pm-medial phalanx*		*Pp-proximal phalanx*	
[mm]					
21.67	±1.6			31.57	±3.13
15.82	±2.26	22.38	±2.51	39.78	±4.94
17.4	±1.85	26.33	±3.00	44.63	±3.81
17.3	±2.22	25.65	±3.29	41.37	±1.6
15.96	±2.45	22.38	±1.6	32.74	±2.77

Table 1. Average and std of phalanges lengths [1].

- *Simple design & manufacturing*: the manufacturing process of the hand should be easy and accessible to inexpert end-users requiring a short assembly time.
- *High dexterity* (i.e. inherently human-like and sustainable): the hand should be able to mimic the human grasping taxonomy. It should express six under-actuated degrees of freedom (d.o.f.) with two d.o.f. at the thumb, i.e. two rotational axes performing the adduction and abduction of the finger [4].
- *Open source HardWare (HW) and SoftWare (SW)*: sustainability will be enhanced by adopting a SW) and HW design implemented with open source tools and programming languages, respectively.
- *Low cost HW & SW*: the project should have a low economic impact in terms of the cost of the materials, the manufacturing integration and the assembly process.
- *Anthropomorphic design*: the finger design, kinematics and grasping configurations should be optimized in order to replicate human hand features [5].

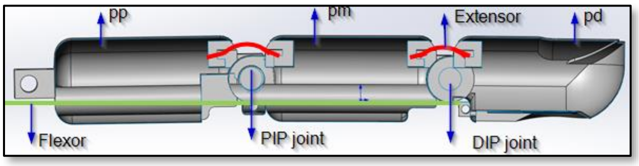

Figure 1. 3D model of finger phalanges and joints.

These requirements derive from the observation that currently prosthetic hands have many structural and functional constraints:

- *Expensive cost*: most amputees cannot afford these high costs.
- *Complex design*: complex mechanical structures - such as pulley and tendon mechanisms with number of gears and articulations - results in complexity of the motion strategies and of the repairing [6].
- *Complex & high cost manufacturing* processes.
- *Lack of open source HW & SW resources*: the availability of open sources tools enable easy customization of the device vs. the end-user needs.

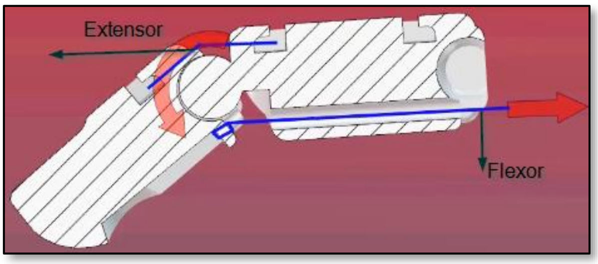

Figure 2. Joint motion

3. Anthropomorphic model

Dimensions and shape of the phalanges of the fingers and of the mechanism of the joints articulation were designed at first stage. During this stage, the design of the *patterns of the tendons*, of the *thumb* and of the *palm* of the hand were defined as well. Particularly, the size of the fingers were taken from the effective dimensions of the human phalanges (Table 1)

A 3D model of the hand was design by means of the Solid Works (from the Dassault Systèmes Solidworks Corp) 3D CAD product engineering software. Then a set of STereo Lithography (STL) files was exported to an HP Designjet 3D printer.

Figure 3. Thumb extension and flexion.

We design the *anthropomorphic kinematics* of the hand to be similar as its human counterpart in terms of similar arrangement, length, proportion and range of motion of the fingers, of the thumb and of the articulations [5, 7]. The design of every parts of the hand was then implemented into 3D models of the parts (Figures 2-6).

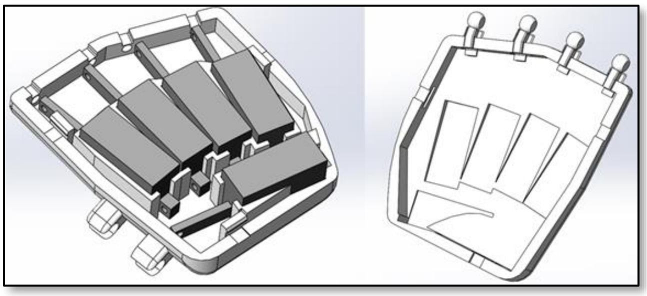

Figure 4. Actuators set-up within the palm.

3.1 Joints and phalanges design

Using the reference dimensions of the human hand, fingers and joints (Figure1), tendon patterns and kinematics (Figure 2), were designed in view of a complete hand design (Figure 3).

Finally, the hand has 5 fingers. Each finger has three phalanges, namely the proximal phalange, the middle phalange and the distal one, respectively.

The corresponding artificial joints are the MetaCarpal joint (MC), the Proximal IntePhalangeal joint (PIP) and the Distal InterPhalangeal joints (DIP), respectively [8].

The range of motion of each joint is set between 0° and 90° and the *flexion* is performed by means of a single tendon mechanism. A flexor tendon or wire is attached to the DIP: pulling the flexor results in a force torque applied to each finger joint. The *extension* is performed via a passive mechanism consisting on a low cost rubber band (Figure 2).

Figure 5. The robotic hand human-like grasping performance.

3.2 Thumb and palm design

The human thumb has a primary role on grasping capability. Because of that, a particular attention has been devoted to the design of this component of the hand.

There are about six movements of the thumb; these ones are the abduction, adduction, extension, flexion, opposition and reposition. The proposed unique hand design enables us to accomplish the flexion and extension movements of the thumb, which offer the benefit of being able to perform a lot of different types of grasping (Figures 3, 5).

Moreover, the final design of thumb allows embedding five linear actuators for the 5 fingers of the end just within the palm of the hand itself (Figure 4).

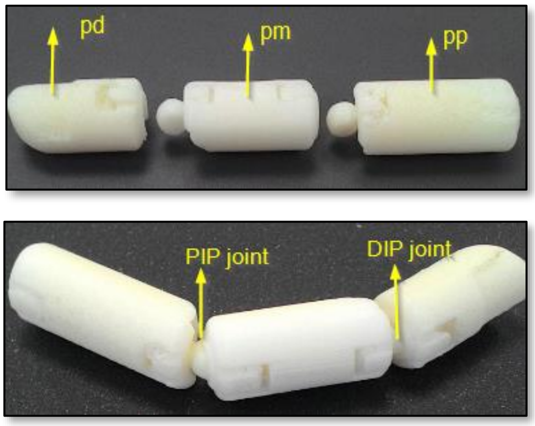

Figure 6. The 3D printed finger Phalanges and Joint articulations

3.3 Hand assembly & printing

After designing the individual components of the hand – i.e. the phalanges, fingers, joints and tunnels for the motion of the extensor and flexor tendons – the assembly of all the components is accomplished. The final result is an artificial hand with human like grasping capability: a 3D rendering of it is reported in Figure 5.

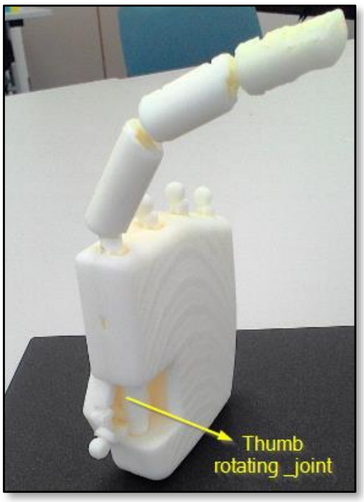

Figure 7. – Hand assembly (1).

After optimizing the 3D model and the hand kinematic [9], the device and its parts have been manufactured using the 3D printing facility.

At this stage Acrylonitrile Butadiene Styrene (ABS) has been used to print the hand components. ABS is most widely used as a 3D printing material, whose mechanical properties are shown in Table 2 [10]. In a future stage, PolyLactic Acid (PLA) filament may be used in order to reduce the environmental impact of the prototype.

A partial assembly of the palm and of the artificial hand vs. the human hand is shown in the Figure 7 and Figure 8, respectively. These figures also illustrate the anthropomorphic design of the hand.

3.4 Hand actuation & control

To actuate the fingers, different technical solutions were considered. The hand should contain a minimum set of independent actuators providing independent movements and postures [11]. A motor with compact size, fast speed and linear actuation was selected: PQ12-P Firgelli linear actuator has a maximal force, speed and stroke of 30 N, 12 mm/s and 20 mm, respectively. Five of these motors were embedded in the palm.

The motors' hand were controlled via an open source HW and SW architecture, namely an low cost Arduino board combined with its Integrated Development Environment (IDE) software.

This architecture allows the hand to be controlled via ElectroMyoGraphy (EMG) input signals: by capturing EMG signals generated from the muscular contraction of the end-user were captured by means of a MyoWare muscle sensor [12].

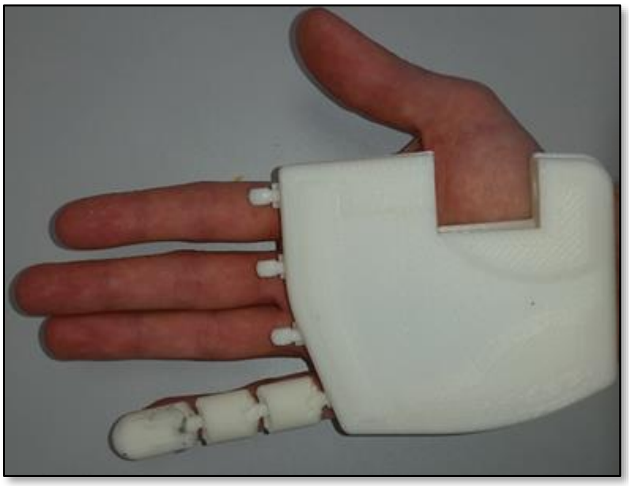

Figure 8. – Hand assembly (2).

This set up reporting the integration of the aforementioned components is shown in Figure 9.

Thanks to this architecture, different control algorithms may be implemented, such as Principal Components Analysis (PCA) based controller or systems adopting Neural Network and imitation of the natural human movements [13-16].

Property	***Value***	***Units***
Elastic Modulus	2000	*N/mm*^{2}
Poisson's Ratio	0.35	-
Shear Modulus	318.9	*N/mm*^{2}
Mass Density	1020	*Kg/m*^{3}
Tensile Strength	40	*N/mm*^{2}
Compressive Strength	42	*N/mm*^{2}

Table 2. Mechanical properties of the Acrylonitrile Butadiene Styrene (ABS).

4. Conclusion

In this work the design and prototyping of an anthropomorphic prosthetic hand has been proposed. The design of the parts mainly consists on the 3D modelling preparation with an appropriate selection of the material, the 3D printing process and the assembly of the hand.

Following the 3D printing, an integration of the controller and actuators has been defined. This approach integrates an Arduino board and the IDE software as ac central controller to manipulate senor signal and to command the motor and actuate the fingers.

This work showed the possibility of developing and controlling a simplified, low-cost and anthropomorphic hand via EMG.

The proposed biomimetic design may be further improved by incorporating fundamental features of the biological hand, either in terms of imitation of its biomechanics and motor control. For example, using more flexible material and covering the hand surface with soft skin materials an highly flexible and human-like hand may be further developed.

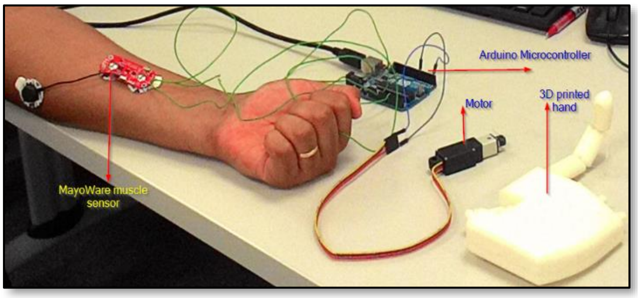

Figure 9. – Overall layout of the system.

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