Biomimetical Arm Prosthesis: A New Proposal

Daniel Proaño-Guevara, Javier Procel-Feijóo, Johnny Zhingre-Balcazar, and Luis Serpa-Andrade(✉)

Grupo de Investigación en Ingeniería Biomédica GIIB-UPS, Universidad Politécnica Salesiana sede Cuenca, Cuenca, Ecuador
{Dproanog,cprocelf,jzhingreb}@est.ups.edu.ec, luiserpandrade@gmail.com

Abstract. In Ecuador, as in the world the most commonly used prostheses are only aesthetic, and the problem with the people that uses them is that they don't feel fully comfortable and independent with their activities, so in looking for solving this problem, researchers have designed different active prostheses but as the technology advances, these equipment gets more complex, heavy and expensive, so the people who need them doesn't feel acceptance. The goal of this and the further investigations is development of a new design that can properly integrate the top technologies in a skeletal design which makes natural movements and will improve the quality of life of the people who uses it. This paper analyses the different designs on the available prosthesis and extract from them the best characteristics of the upper limb prostheses design.

Keywords: Bionics · Powered prosthesis · Biomechanics · Transhumeral prosthesis

1 Introduction

The CONADIS (Consejo Nacional para la Igualdad de Discapacidades) of Ecuador registers that physical disabilities cover about 47% of total disabilities. Annually it is reported that there are about 117,889 people who have suffered trauma, where is a tendency in which young adults, generally male live this situation, being a pattern that is reflected worldwide [1].

Trans-humeral prosthesis offer help to people with amputations to redevelop daily activities (ADLs), improving their quality of life even allowing their reintegration into work [1, 2].

Emulating the level of functionality of the human hand has proved to be extremely complicated, from a mechanical perspective it is very difficult to integrate a large number of degrees of freedom and their corresponding actuators within a dimensioned structure for a purpose [3]. Roboticists have always sought inspiration in nature and have been intrigued by the most skillful and dexterous element of the human body: the hand [4]. The hand is considered one of the final actuators of greater complexity in the human body, and this gives its importance given the amount of degrees of freedom and consequent movements that can perform [3]. Following this information, the possibility of

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recovering the entire member would give the patient a multipurpose tool, which is not limited to the hand, but to a whole system that would not only allow the patient to perform specific activities but also to live his life with normality and possibly reinserted into a job.

Developing prostheses should be compared to devices available on the market, unfortunately its architecture is not open source in terms of sensing, actuators and embedded systems, which considerably limits the ease of comparison and freedom of development on these systems [2]. Active prosthesis have been developed mainly on mechanical systems that provide functional movements, and few degrees of freedom, which are limited solely to reproducing movement, using systems such as planetary gears, or much more complex systems that are governed by a motor directly on the articulation since they are mechanically based on previously developed systems [2, 5, 6]. The development of an anthropomorphic and anatomically correct system based on musculoskeletal systems has proven to be a very complicated challenge, but once it is completed, it completely changes the range of movements and favors a greater acceptance of the patients that will use it, since, as they resemble a human hand, they feel more comfortable with it and their movements are much more natural and those designs that can be used in other areas of biomechanics [3, 7]. Although the development of prosthesis has been concentrated mainly in hands, the development in transradial or transhumeral prosthesis is considerably smaller, so there is no extensive bibliography demonstrating the development of biomimetic systems that support these areas in the development of common active prosthesis. Estimates and comparisons with various systems are used to determine the speed and range of mobility of a joint [6, 8].

The state-of-the-art for robotic hands always strive to increase design simplicity without compromising efficiency in terms of grasping skills and positions that can take the hand and that same trend should have the other segments of the upper extremity, offering variety of efficient movements [4].

Over time, different forms have been developed to simulate the limbs, and movements that they perform, among them are the prosthesis activated by the body, which are anchors arranged in the patient's stump that allow him to operate systems of grasping or flexion elbow extension, these systems are friendly to the environment, relatively inexpensive and offer some proprioception and feedback to the user about the force he is exerting [2, 5]. Since 1940 the engineers have focused on simulating the movements of a human arm using myoelectric prosthesis which unlike body-activated prostheses, do not require complex wiring and can operate at higher ranges of motion, allowing them to access a greater work area [2, 5, 9].

Developing a prosthesis based on an anthropomorphic skeletal system that simulates as many movements as necessary by a subject of productive age so that extra space is available for the placement of sensory elements (exteroception), so that it has more natural movements and in this way the patient can feel more identified with the device and can decrease the percentage of rejection to active upper limb prosthesis [3, 10].

A very important objective in the development of the prosthesis is that it should be as light as possible, cosmetically pleasing, comfortable for daily use and providing sufficient functions for ADLs [2, 6].

2 Development (Design)

2.1 Anthropomorphism

Currently the study of robots based on musculoskeletal systems is performed to explore the advantages of these systems have based on the biological design of the same and have evolved to achieve the ideal design to perform the functions expected of them [7]. So, it helps a lot in the consideration of the design and functions that the anthropomorphic prosthetic will perform.

Hand. The main idea is to use the human hand as a reference of design in terms of functionality of movements and morphology, since in this way a completely bio-inspired and functional design can be realized.

For a correct anthropometric design you must have a constant feedback from a physician who supervises the forms and methods used to develop the movements [4].

Wrist. The wrist has three degrees of freedom: pronation - supination, flexion - extension and radial – ulnar deviation [2].

2.2 Forms of Design Carried Out

Ikemoto developed a robotic arm consisting of 7 DOFs driven by pneumatic muscles that seek to simulate the nature of human humerus and humerus movements, movements that are generally not considered for prosthesis development, and a radio junction was designed in the forearm formed by two bones, radius-ulna and the wrist that consists of an ellipsoidal coupling to achieve the natural movements [7]. The RIC arm has 5 DOF, 2 in the hand, 2 in the wrist and 1 in the elbow in addition that it is modular, which means that it can be used by people with transhumeral or transradial lesions and can also connect a prosthetic hand that the patient wants because it has a universal connection socket [6] system similar to the one made by Resnik that developed 3 prosthesis configurations: Radial Coupling (RC) for transradial amputations, Humeral Coupling (HC) for transhumeral amputations and Shoulder Coupling (SC) for people with transhumeral amputations with minimal or no residual limb [9].

3D printed prostheses have been developed, which have 4 DOFs, that are controlled with surface electromyography (EMGs) and use servomotors for their movement [10]. It makes it very low cost, but the main problem with this type of prosthesis is that they are not strong enough to perform properly all the movements of daily activities.

The forms of elbow movement proposed by Bennet [2] use planetary gears and a proportional differential system to reach different degrees of freedom. Foglia proposes that the study must be focused in the optimization of actuators to achieve all the necessary postures and thus develop a system of transmission by tendons being that the DEKA arm only offers flexion and extension with a system that looks for to minimize the dimensions and the weight of the actuators to achieve a better acceptance [11] it is corroborated by Kim showing that of the 7 DOFs that have the human arm, only 6 DOFs are necessary to perform the basic movements for wrist positioning and palm orientation [12].

Regarding the design of the wrist, it is important to take into consideration the degrees of freedom that it can perform, since in the development of daily activities these have a greater impact than the degrees of freedom present in the hand [2].

Some forms of handheld design studied occupy 5 independent actuators, wire guiding to control the fingers, and there are also results show that the 10 most important movements of the hand for different grip positions can be executed by three actuators and a differential system can be incorporated to develop more movements [4, 13].

Konnaris [3] proposes a hand of 24 degrees of freedom and pulley systems that were implemented in each joint of the fingers to avoid that the tendons move away of the central axis, minimizing the losses by movement, uses 7 motors to control 20 of the 34 degrees of freedom supporting with its 5 fingers a maximum of 2.3 kg.

Tendon-based hands have the advantage of locating actuators away from the hand with relatively more torque but the relationships at finger joints are really complex and require a specific kinematic study for their functioning, so they use link systems, unions by blocks and springs that transmit movement to achieve the same effects as the tendons [14].

A recent clinical study showed that a hand with 22 DOF with a wrist of 1 DOF is functionally equivalent to a hand of 1 DOF and a wrist of 2 DOF when performing daily activities [6].

As for the movement of the fingers, Kontoudis [4] recommends using elastomeric materials to perform the digital extension while for flexion cables are used, attached to actuators suitable for this movement.

To develop improvements in prosthesis functionality, researchers need to develop a prosthesis hardware structure to build and test virtual control, which can be very beneficial in early stages of development but this can't replace physical tests [2].

As for the acquisition of signals, one of the main problems in myoelectric prosthesis is in the location and repositioning of electrodes and is something that could be solved by analyzing common distributions and configurations of electrodes and rethinking it to be more comfortable for the patient [15]. In practice, what most limits the use of EMG is the change of electrodes, variations of force, involuntary activation of muscles [16]. For an adequate control it is necessary to recognize the muscles that perform the different movements and to study the myographic signals and from here determine the mechanics and ranges of movement of an arm to achieve a more natural movement [17, 18].

2.3 Design Features

The simultaneous action of multiple degrees of freedom of the fingers of the human hand is fundamental and shows its importance from evolutionarily relevant behaviors such as the clamp action, to actions performed day by day. Since there are no clear guidelines for the anthropomorphic design of a robotic hand and especially the thumb, the current state-of-the-art does not contemplate the full versatility of thumb movement [3]. The hand design features found after reviewing previous designs are (1) the entire structure has a weight less than 500 g so the actuators do not see compromised its efficiency and there are no overexertion (2) Make a highly functional design that minimize the actuators needed to perform the movements and (3) focus on a mechanical design that allows to meet the points previously described [4]. Sekine proposes the use not only of motors and metal parts for the construction of the prosthesis but also the integration of different materials and systems in order to make the design of the prosthesis more suitable for daily use [19]. In fact, current prostheses should be designed to provide sufficient torque, velocity, and range of motion to develop the person's daily activities (ADLs) [2] thus giving the patient independence of activities in his daily life. In order to determine the amount of degrees of freedom required, first, one must acquire information about a healthy arm and study the movements, in many cases systems such as the "CyberGlobe" are used, which show different variations of potential depending on the movement and this in conjunction with the myoelectric information offers a model and adequate data of the behavior of the arm [20].

The majority of developed prostheses manage the wrist rotation (pronation and supination) in a passive way, which forces the user of the prosthesis to place them in the position they think fit best to perform a job [2] [3].

The torque exerted by the elbow of the device must supply the exerted by the average of healthy subjects that is 5.8 Nm in flexion [2].

It should be noted that pronation/supination does not occur in carpal bones but in the forearm when the radius covers the ulna when overlapping. For a healthy wrist, the range of motion is 76°/85°, 75°/75° and 20°/45° for pronation/supination, flexion/extension, and radial-ulnar deviation [21].

At the development of the prosthesis, it is necessary to analyze the load applied to a degree of freedom and to see how much this affects its range of mobility and agility [2], to achieve a better result external rotor motors have proved to have a significantly better torque than the internal rotor motors [6].

For an information feedback on the behavior of the prosthesis, an adequate control of position and follow-up in the rehabilitation of the patient when it is being used, the use of IMU (inertial magnetic units) in different parts of the prosthesis is recommended [9, 22].

Complete control of artificial hands in an intuitive way remains an irresolute problem in the context of robotic teleoperation and prosthesis [3].

3 New Proposed Design

Despite the technological advances, it is estimated that between 50% and 60% of people with amputations do not use any type of prosthesis and this is due to the fact that current devices reach their skill increasing weight, size and complexity. Which results in the loss of robustness [13, 23, 24] also leads to the device falling into the uncanny valley which is the feeling of strangeness and non-belonging that a user feels when seeing the device, which effect could be reduced or eliminated with a suitable design of the prosthesis [25].

The use of artificial hands with the same dexterity as a human hand is a challenge since the intentions of movement of the users do not always freely control the most advanced prostheses [16] or they must make uncomfortable movements to activate more movements due the limited availability of biometric signal sources [26].

There are no existing devices that offer pronation-supination movements in the market, but perform a twisting movement, without taking into consideration that the main function of a transhumeral prosthesis is to position or reposition the orientation of the hand to facilitate the grip or release of various objects, in several axes within a working environment instead of leaving a free and unnatural movement of wrist twist [2].

Since there are no clear guidelines for the anthropomorphic design of a robotic hand and especially the thumb, the state-of-the-art does not contemplate the full versatility of thumb movement. The replication of the natural kinematics of the thumb in artificial hands has only been performed by Konnaris [3].

The main forms of signal acquisition and device control are through electromyography and often used in conjunction with controls at the user's feet to perform very specific functions [9].

There are a large number of research prototypes in academia and very few commercial ones, this is due to the acceptance of the patients towards the devices, however it is necessary to create a comparison between the different prostheses and evaluate their anthropomorphism and thus to be sure of the acceptance of the device [27].

Konnaris established an interdisciplinary precedent in the field of biorobotics, quantifying the dexterity and anthropomorphism of its design with respect to human, prosthetic and robotic hands [3].

The proposal is to design a prosthesis that copies the skeletal anatomy of the human arm as shown in Fig. 1. Where will be analyzed the different Degrees of Freedom that the person need to develop ADLs with fluency and dexterity, also considering the design goals analyzed before such as low weight and easy control, contributing to a robust design to be presented to a patient and a further clinical introduction.

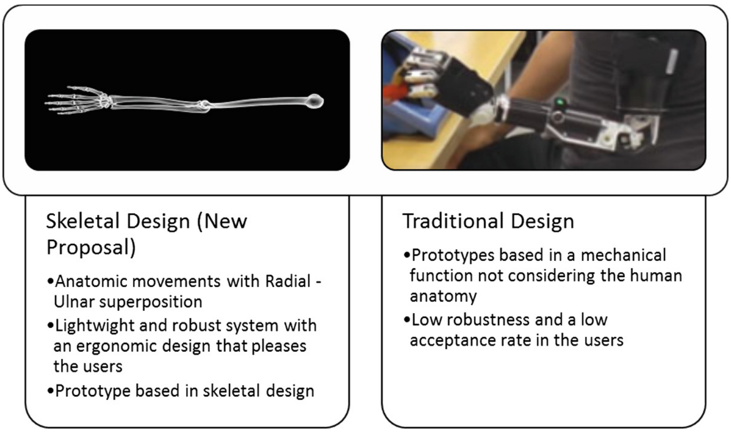

Fig. 1. Comparison between the new proposed design and the traditional design of the prostheses, showing advantages and improvements in the design. The imaged presented in "Traditional Design" belongs to Lenzi [6].

One of the most important design goals is to select the number and localization of active DOF in the design of a prosthetic arm is critical to find the perfect balance between dexterity and weight, thus improving the clinical benefit [6]. Recent research has debated whether enhancing prosthetic wrist serves better amputees than a highly skilled hand [21].

The main characteristics of the new proposed prosthesis design are that it should have an anatomic design, and based in anthropometric measures of the patient as shown in Fig. 2. The prosthesis should adapt to the needs of the patient offering only the degrees of freedom he need to develop the ADLs controlling it with biometric signals that could be obtained from the remaining muscles or a mix of them with the brachial plexus, in further studies we could obtain the signals from EEG.

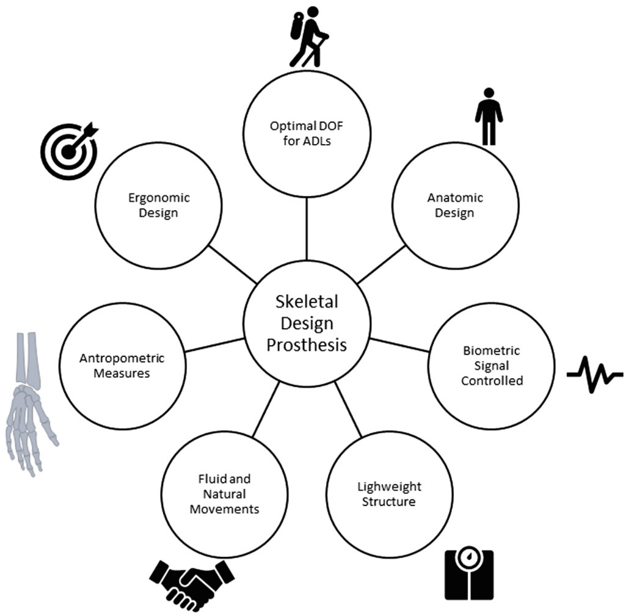

Fig. 2. The following diagram shows the integral parts that conform the new prosthesis proposal, where is highlighted the anatomic mimetic importance and the patient comfort.

4 Conclusions and Future Works

All amputation is a great challenge, but when they are above the elbow they become even more complicated, since it requires not only replacing the functional part of the elbow but also the hand. So, the transhumeral prosthesis proves to be a great design challenge, but at the same time it will be possible to make the person perform practically natural movements.

A very important part of the design is the hand because it is not only a prehensile organ, but also is responsible for performing many activities such as writing, catching an object, identifying things and doing many daily activities, so that their study is an important part of the research. Achieving the delicacy of holding a pencil or holding an egg or tightening an object tightly is one of the biggest challenges that can be achieved.

To achieve a better acceptation of the patients of the arm prostheses the design looks for an ergonomic, light, and easy to control design that serves the user for all the daily activities with the strength required to perform them, but also the prostheses should be an integral part of the person, and should be recognized as a part of them, and the way to achieve it is to make them the most similar to the human anatomy, not only cosmetically but in a functional way.

Basing in a musculoskeletal design of the arm, the half of the designing work is done, because the nature has improved the arm design to be useful in all the activities that requires repositioning the ubication and rotation of the hand so it can be used as a tool. Also, the whole mechanical distribution of forces is changed protecting the actuators from suffering direct impacts, and with this design the actuators over a DOF could be more than one, maybe a small group could control the fine motor and when strength is required other actuators, stronger but slower could act to develop the activity with property.

This kind of design will free a lot of space specially on the hand where sensors could be installed so the patient could 'recover' their senses with the prostheses and have exterior information that could prevent injuries to the patient and also the equipment, this, applied with a correct automatic control could help the patients to develop almost every daily activity with normality, and this will represent an acceptation of the equipment, an improvement in the quality of life of the user and a possible job reinsertion which offers independence of the patient.

This paper should work as a basis for the future design of upper limb prostheses including mechanics, signal acquisition and processing for an adequate and easy control of the equipment.

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