Upper extremity prosthetics: current status, challenges and future directions

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Abstract: There is a drastic increment of the demand for prosthetic devices over the last few decades. This is caused by the increased amputees because of casualties due to civil wars, injuries due to accidents, *etc*. Therefore, the robotic prostheses are one of the highly interested research areas in recent robotic research. The target is to make sure the amputee gets a better chance to interact with the real world, in spite of the amputation he has. The paper presents the results of a comprehensive literature analysis towards a development of an upper-limb prosthetic arm. This study identifies the methods of prosthetic classification as the segment of application, number of degrees of freedom (DoF), types of applied actuators, types of power transmission methods and control methods. In this study, the upper extremity prosthetic devices are classified based on the segment of application. Thus, they can be mainly classified into shoulder prosthetics, transhumeral and elbow prosthetics, transradial and hand prosthetics. This study considers all the above categories of recent upper extremity prosthetics, and reviews their key technologies by taking state-of-the-art robots as examples.

Keywords: robotic prosthetics, transhumeral, transradial, upper-extremity.

1 INTRODUCTION

A prosthetic is a device that replaces an amputated body part of a person. It is expected to restore the physical appearance and the lost functions of the amputated body part. Limb replacements are taking place at a higher frequency, affected by casualties due to war, accidents, cardiovascular disease, tumors and congenital anomalies.

In 490 B.C., it was a Persian soldier who cut off his own feet in order to escape from a prison and later replaced it with a wooden foot which is the first prosthetic [1]. However, the development and the fabrication of the prosthetics dated back to about 500 years [2]. Recent development of the prosthetics was influenced by the World War I and II, which resulted in a remarkable loss of man power in USA and Europe. In 1948, the concept of Cybernetics, *i.e.*, the study of control and communication between human and machine [3], played a significant role later on for the improvement of the prostheses. Samuel Anderson created the first electrically powered prosthetic arm that uses external power, with the support of the US government and IBM in 1949 [4]. Russians in 1958 developed the first myoelectric arm and soon after, Otto Bock Company came up with a commercially available prosthetic arm for common application which was the first finished versions of the Russian design [4]. The researchers have been making effort to develop a perfect prosthetic system, which will mimic the exact human motion pattern, power requirement and anatomical/cosmetic features.

The advancement of the mechatronic technology over the recent years leads to a number of upper extremity prosthetics both commercially available and still in the research level [6]-[16]. Nevertheless, they are not that popular among the amputees due to their inability to meet the user expectations up to a desired level in real world. Most of them are with poor functional and controlling properties, which is the major, concern of the prosthetic user to loss their interest on the prosthetics [5].

During the last decade number of research work [6]-[11] had been carried out and some of research works are still ongoing. At present, Utah Arm [17], Boston Elbow and Otto Bock [12]-[16], which are commercially available can be considered as the pioneers in this filed. Dean Kamen's Luke Arm, Proto 2 and MANUS-HAND are still at the developing stage [18]. Most of these commercially available prosthetics [16] are capable of generating only few limited degrees of freedoms (DoF): elbow flexion/ extension, forearm pronation/supination, and prehension. Forearm pronation/supination is generated in a terminal device forfeiting the human upper limb anatomy. Therefore, the adaptation of the wearer to the real world might be an extra burden. Some prostheses are developed to generate the functions of the human hand. Touch Bionics's i-Limb [19] is the state-of-the-art upper limb prosthetic and before that it was Otto Bock's SensorHand Speed, which was a basic open and close mechanism only. The dexterity of hand prosthesis is still far from that of the state-of-the-art non-prosthetic mechanical hands, such as the DLR II [20].

Main target of this review paper is to cover brief history, challenges, current status and future developments of upper extremity prosthetic devices. Authors tried to review the state of the art prosthetics developed in the last six years.

Biomechanics of upper-limb toward the development of an upper-limb prosthetic device, challenges to the development of prosthetic limbs, a brief review on the state-of-art upper limb prosthetic limbs and a brief idea on future research directions are presented respectively.

2 BIOMECHANICS OF UPPER EXTREMITY

Before developing a robotic prosthetic device to mimic the upper extremity, a thorough understanding of its physics should be there. Three major components of the upper extremity are shoulder complex, elbow complex and wrist. Shoulder complex is built with three bones: clavicle, scapula and humerus and four articulations. Shoulder can be modeled into a ball-and-socket joint. The proximal part of the humerus, humeral head and the female part of the scapula, glenoid cavity respectively act as the ball. The main motions of the shoulder joint are shoulder flexion/extension, abduction/adduction and internal/ external rotation. During each motion, the position of the centre of rotation of the shoulder joint changes.

Three bones of the arm and the forearm, humerus, radius and ulna are connected to the elbow (radioulnar) joint at the distal part of thehumerus. The ulnohumeral and the radiohumeral articulations are contributing to the motions of the flexion/extension of the forearm. Further, the radioulnar articulation contributes the motions of supination/pronation of the radius and ulnar bones [21].

The wrist is a collection of eight carpal bones. It has two major articulations, radiocarpal and midcarpal based on their functionality. The radiocarpal joint allows motions in two planes: flexion/extension and radial/ulnar deviation of the wrist, which are generated around an instantaneous center. However, the centroide travels in a small path, therefore the displacement of the instantaneous center of rotation is ignored and the axes of rotation for the motions are considered to be fixed. These axes pass through the capitate. Even though the wrist joint motions are considered to be generated with respect to the two axes, some research work [14] has shown that they are generated with respect to four axes. The wrist flexion axis and the extension axis are different, but intersects at a point at capitate. Similarly the radial and ulnar deviation axes are also different and intersect at capitates [22]. The slight offset of the rotational axes of the flexion/extension and the radial/ulnar deviation is approximately 5 mm [22].

3 CHALLENGES

Even though the existing upper limb prosthetic devices are able to cater the amputees' requirements to a certain degree, still there are lot of improvements and design challenges that have to be addressed. They are briefly discussed here. Amputees expect a prosthetic not to be overweight, anthropomorphic in appearance and cosmetics [23] and the functionality of the prosthetic to provide expected motion intentions of the user as a normal human limb. Ultimate objective of a prosthetic limb is to make sure both user and the surroundings do not feel the difference of the amputation which the user is having. In addition, the prosthetic limb should demonstrate a significant decrease in the metabolic demands which will be equivalent to a human being without any amputation, for daily motions.

These expectations are still constrained by different technological barriers which needed to be overcome to develop a perfect prosthetic device. Most of the actuation methods that are being used are heavy and if not they are with limited torque and power. Furthermore, the actuator sizes and the operational behaviors such as smooth and simultaneous motion of joints, noises also should be rectified towards the anthropomorphism. Prehension, grasping or holding of an object is one of the main functions expected from the human hand. It is capable of holding anything and will not effect by the object to be hold. The surface finish, geometry, stiffness or strength of the object will not affect the grasping function of the human hand. All these requirements are not yet integrated at one place.

Further, tactile sensing is another important input from the human upper limb to the robot making a good interaction of the human being with the environment. It helps to make accurate motions which sensory inputs are required. Tactile sensing and force sensing are essential outcomes of a human upper extremity and yet to be developed such a system. Furthermore, the unavailability of proper accessory devices such as power sources with tolerable weight for long time use, material types for more anthropomorphic features, is also a challenge to develop a perfect upper extremity prosthetic. The motions of the robot should to be with required power and the joint movements have to be simultaneous. Since most of the amputees wear the prosthetic more than 8 hours per day [23] the user fatigue is a great concern in prosthetic design. When the actuators are large enough to provide the desired power they may be with a much weight and will be uncomfortable to use for longer time periods. In addition, the concern should be on the prosthetic sockets as well. It should be comfortable enough to wear for a longer period of time. Moreover, different control signals are available for the prosthetic devices. Electromyography (EMG) signals are mostly preferred by most of the researchers since EMG signals directly convey the human motion intention to the control system. However, the amputees have already lost their body part and muscles obviously. It limits the amount of control signals that can be gained through the EMG. This ultimately leads to a limitation of the number of communication channels available for the control of a multi-DoF upper limb prosthesis resulting them to underperform on showing the correct motion intention of the user.

4 REVIEW OF UPPER EXTREMITY PROSTHETICS

In recent years, a number of upper-limb prosthetic devices have been proposed [19], [24]-[33]. Available prosthetic devices can be classified considering different criterion. This study identifies the methods of prosthetic classification as the segment of application, DoF, types of applied actuators, types of power transmission methods and control methods. The methods of classification of prosthetic are shown in Fig. 1(a). Since this paper is mainly focused on application of the robotic upper limb prosthetics, the classification is carried out based on the location of application of the prosthetic. The classification is shown in Fig. 1(b).

Table 2 shows a comparison of existing prosthetic limbs. In the next sub sections recent upper-limb prosthetics are reviewed by explaining their basic designing concepts. They are selected based on their key technological features in their designs. Transhemral prosthetics and elbow prosthetics, Transradial and hand prosthetics are combined together in following subtitles for the ease of the presenting.

4.1 Shoulder Prosthetic Devices

Shoulder prostheses are worn by amputees with shoulder disarticulation. The following section presents the state-of-the art shoulder prosthetics.

4.1.1 DEKAs (DARPAs) Luke Arm [24]

The Luke Arm is the latest upper arm prosthesis developed by Defense Advanced Research Projects Agency (DARPA), designed by Dean Kamen [24]. Its advanced dexterity makes the Luke Arm better than the prosthesis currently in the market. The arm has 18DoF and it is more than the 03DoF other available in arm prosthesis today. In addition, high quality electronics and software allow for fine control of the arm which will allow amputees to perform many complex tasks such as to pluck chocolate-covered coffee beans one by one, pick up a power drill, unlock a door, and shake hands. The Luke arm is modular based, adjustable to use by anyone with any level of amputation since shoulder, elbow, forearm and the hand are independent from each other.

4.1.2 Proto 2 [25]

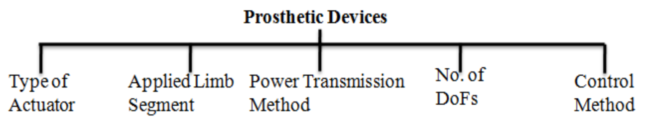
Proto 2 was launched as one of the phases of a four-year program to create prosthetic arms that can be better imitated natural limbs by Defense Advanced Research Projects Agency (DARPA) [25]. It is built with 100 sensors that connect the natural neural signals of body to the mechanical prosthetic arm making a sensory feedback loop. Thus the wearer interacts with an object and the arm feeds back in real time. The user could get a feeling of where the arm is in space, what object it is touching, whether that object is smooth or rough, how hard the hand is holding it, and what temperature the object is. Further, the motions of Proto 2 are smooth and not with jerks.

4.2 Transhemural & Elbow Prosthetic Devices

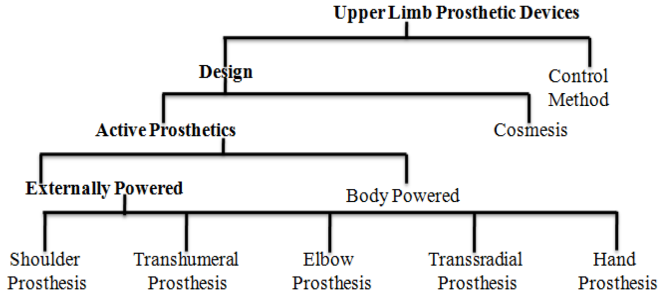
These are worn by amputees with elbow disarticulation or transhumeral amputation. State-of-the art transhumeral and elbow prosthetic devices are explained below.

4.2.1 A Gas-Actuated Transhumeral Prosthesis [26]

This is an anthropomorphic 21DoF, 9 degree-of-actuation prosthesis arm for transhumeral amputees. The arm utilizes a monopropellant, hydrogen peroxide as a gas generator to power nine pneumatic type actuators that drive elbow, wrist and a 17DoF compliant hand. The design makes the arm compact. Elbow and wrist joints are integrated with position and force sensing. The prosthesis is expected to approach the dexterity of an anatomical arm and is projected to deliver half of the force and power output of an average human arm. The usage of the gas-type actuators let the arm to achieve better volumetric and gravimetric power density.



(a) Methods of classification of prosthetic devices



(b) Classification based on applied limb segment

Fig. 1. Classification of Robotic Prosthetic devices

4.2.2 Saga University Prosthetic Arm [27]

The robotic prosthetic arm developed by Saga University is with 05DoF and targets to mimic the human anatomy as much as possible [27]. A T–mechanism is introduced here to mimic the human alike forearm motion and it contributes to the supination/pronation with the introduction of two shafts which act as the ulna and radial bones of the human arm. In order to achieve the objective of prehension, hand with a single DoF is attached to the distal end of the ulna and radial shafts with a ball joint.

4.2.3 MSUM elbow–2 [28]

The prosthetic is mainly capable of providing elbow flexion/extension. In the design the gears are substituted with linkages with ball bearing and by screw ball transmissions, when possible which has been lead to an increment of the mechanical efficiency of the hand [28]. In the initial design the axis of the ball screw is connected to a brushless motor via an epicyclical transmission and a belt-pulley system. The measured overall mechanical efficiency of this system was increased up to 64%. Later as an improvement, the screwball axis is oscillating and is directly connected to a "pancake" brushless motor. This architecture raises the efficiency to over 80%. The prosthetic could be integrated with other mechanisms to develop a transhumeral or shoulder prosthetic.

4.3 Transradial and Hand Prosthetic Devices

Transradial and hand prostheses are worn by amputees with wrist disarticulation or transradial amputation. Below mentioned devices are the state-of-the art transradial and hand prostheses.

4.3.1 Touch Bionics i-Limb [19]

Touch Bionics i-Limb is the first commercially available prosthetic device with five individually powered digits. Its inclusion of a thumb that works like the human thumb, let the hand to achieve different positions, enables important grip configurations [19], many of which have not been available to amputees before. The articulating fingers are able to close tightly around objects. Furthermore, the built-in stall detection for the each individual finger can detect the power cut-off position to the finger. Each individual finger will be locked in the position until the patient triggers an open signal through a muscle signal.

4.3.2 Under-actuated Hand Prosthesis [29]

Nasser *et al* proposed this hand to overcome the drawbacks of commercially available hand prostheses [29]. The hand design is based on an under-actuated 15DoF, 1DoF actuation configuration, fully capable of performing activities of daily living. Each finger is fully independent from each other and adaptable to grasp any object of any geometry. The system is capable of providing safe and reliable grasping without the need for feedback sensors, multiple servos, or any type of data processing. The design is focused towards providing upper limb amputees with the prosthetic hand that is cosmetically appealing, functionally comparable by means of DoFs, weight and cost.

4.3.3 FLUIDHAND III [30]

FLUIDHAND is hand prosthesis with enhanced functionality, cosmetic; enable security, and adaptive grasping as well as aesthetically appealing properties [30]. The combination of flexible fluidic actuators and soft passive elements reduces the required grasping force for a wide range of objects. Further, the enhanced actuator system allows high grasping forces if necessary. Two myoelectrodes in the socket together with the developed controller board and software enable quick selection of the most important grasping patterns. Vibrotactile force feedback and wireless programming and control options complete the characteristics of the FLUIDHAND III.

5 CONCLUSION AND FUTURE DIRECTIONS

This paper briefly reviewed available upper limb prosthesis developed over the recent years. It covers both commercially available upper limb prosthetics and the upper limb prosthetics still in the development stage. Nevertheless, following research goals could be followed for the future developments of a prosthetic device.

A biomechanical investigation should be carried for the upper-limb with and without the state-of-the-art prosthetics to identify the main problems of the state-of-the-art in the field. Using the results of the investigation the goals can be set for the future developments of the prosthetics limb. The goals can be standardized by means of weight, size, durability, actuation speeds, level of activity, and professional needs at a global level. In addition, a proper scheme can be proposed to evaluate the available prosthetic limbs by means of anthropometry, dexterity, user acceptance, etc. A measuring criterion should be defined for each different requirement of a prosthetic in order to achieve the objective of proper evaluation. The metabolic cost of transport (COT), which is the measuring of oxygen consumption and carbon dioxide production of human breathing during a task, can be used to benchmark the future developments of the prosthetic devices. Identification of the factors affecting the COT of a prosthetic user and the direct addressing of them in the designs will give better

Table 1. Comparison of Upper-Limb Prosthetic Devices

Reference	Location of Application	DoF	Actuator	Power Transmission	Special Feature	Control Method/ Input
DARPA's Luke Arm [24]	Shoulder, Elbow,	18	DC Motors	Gear Drives	Adjustable to use for any level of amputation	EMG-TMR foot pad in shoe
Manus Hand [31]	Hand	3	DC Motors	Gear Drives, Geneva Mechanism,	Underactuateddesign principle	EMG
Proto 2 – John Hopkins University [25]	Shoulder and Elbow	25	DC Motors	Tendons	Real time feedback for grasping	EMG- TMR
i-Limb – Touch Bionics [19]	Hand and Fingers	11	DC Motors	Tendons	Five individually powered digits	EMG
Under-actuated Hand Prosthesis [29]	Hand and Fingers	15	Motors	Gears and steel rods	Independent fingers, Adapt to any geometry	Under development
The FLUIDHAND III [30]	Hand and Fingers	8	Fluidic Actuators	Pressurized Fluid	Vibrotactile force feedback	EMG
Prosthetic Arm – SAGA[27]	Elbow and Wrist	5	DC Motors	Cables and Gears	Anatomical Design Approach	EMG
Gas-Actuated Transhumeral Prosthesis[26]	Elbow	21	Pneumatic Actuators	Pressurized Fluid	Half of the force and power of a human arm	Under development
Prosthetic Hand Driven by Shape Memory Alloy Actuators [32]	Hand and Fingers	7	SMA Actuators	Shape Memory Alloys wires	lightweight, multifunctional, silent and cosmetically appealing	EMG
Bebionic Hand [33]	Hand and Fingers	11	DC Motors	Mechanical Links	position sensor to achieve the desired grip pattern	EMG

results. In addition, the existing actuation and power transmission methods have to be developed to meet the requirements towards a perfect prosthetic device. Improvements should be done on under-actuation topologies, artificial muscles and tendons.

To give a better prosthetic handling to the amputee, the number of control inputs has to be increased and more effective pattern recognition methods to extract detailed data from surface EMG signals from the residual muscles have to be invented. Furthermore, the usage of implantable EMG electrodes and the targeted muscle reinnervation also will lead the researchers to get more comfortable with the number of controller inputs available. In addition, mechanomyography (MMG) signals which is the detection of sound produced by contracting muscles and the pressure signals generated due to pressure exerted by the residual limb on the socket are also used as inputs to the control system. With properly developed pattern recognition methods, two or more hybridization of these control methods will ultimately produce a better control method for the prosthetics, which will operate according to the human motion intention.

Electroencephalogram (EEG) signals, which are the measurement of brains spontaneous electrical activity, will also become a control input when used with a proper signal classification mechanism. Furthermore, electrocorticogram (ECoG) signals and spike recordings from the primary motor cortex will also become future trends in prosthetics controlling.

Furthermore, biomechanical energy harvesting methods to harvest energy from body heat and from motions of various parts of the body during walking, such as heel strike; ankle, knee, hip, shoulder, and elbow joint motion; and center of mass vertical motion could be improved to power the prosthetic devices without making the power source and extra burden to the wearer.

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