Mechanical Design of a Prosthetic Human Arm and its Dynamic Simulation

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Abstract. In this paper the mechanical design of a prosthetic human arm with 7 DOFs that includes the shoulder, elbow and wrist is presented. The objective of this design is to have an anthropomorphic, functional and low cost prosthesis. A set of dynamic simulations were performed to determine the feasibility of the mechanism as well as the torque required to perform the activities. The results show that the design could be a good solution due to the physical characteristics and the kinematic of the system.

Keywords: Biomechanics · Upper limb · Prosthetic arm · Prosthetic design

1 Introduction

The aim on this work is to present the design of a low-cost functional prosthetic upper limb. Losing the human arm affects the life of a person due to the reduced capability to perform many daily life activities. Shoulder disarticulation is one of the cases with the minor incidences, and for this reason people in this condition do not have many available options [1].

The movement of the human arm is complex and its reproduction is usually achieved artificially with few degrees of freedom (DOF) [2]. Rejection of prosthetic arm is dependent of the amputation level; the most proximal the amputation is, the bigger the rejection rate is [3]. The main reasons of prosthesis abandonment include technical limitations of the device, discomfort, appearance and lack of user training [4]. Nowadays many commercial solutions exist for people with upper limb amputation but they have less degree of freedom than required. Some other systems are not practical for real life and others are not affordable for most of the population.

In [5] a prosthetic shoulder is presented with two actuated DOFs and one passive DOF for the humeral rotation. The first joint is a revolute joint and the second is an inverted slider mechanism. This module was tested with commercial upper limb prosthesis. The MPL [6] is the result of a 6 years program that was sponsored by the Advance Research Projects Agency of USA. It allows patients with different amputation levels to use it. The upper arm is composed by the shoulder with two actuators, a

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humeral rotator, elbow and the battery. Its main features are 26° of freedom (including the hand), 17 motors, and a total mass of 4.8 kg with battery and a payload of 155 N with the static wrist. A low-cost prosthetic arm was reported in [7]. This arm includes the shoulder but is limited only to a planar movement. It is made of plastic and the total weight is 1.5 kg. The DEKA Arm [8] is another prosthetic arm, product of a project of DARPA. It is the 3rd generation after 2 years of research. This prosthesis weighs 4.45 kg and has 3 configurations, one for transradial amputation, another for transhumeral and the 3rd one for shoulder disarticulation. The prosthesis includes 10 powered DOFs that are distributed in 6 for the arm and 4 for the hand. This prosthesis can be controlled with different signals like switches, myoelectric signals, and even with targeted re-innervation. He et al. [2] designed the IIR prosthetic limb of 4.45 kg, which consists of a fully actuated arm with 7 DOFs and an underactuated hand with 15 DOFs. It uses differential gear mechanisms at shoulder and wrist in order to minimize the size of the joints and to share the load with two small motors.

The objective of this paper is to present a light prosthetic arm for people with shoulder disarticulation that is able to mimic as much as possible the kinematics of a person during a selected activities of daily living.

2 The Human Arm and its Characteristics

The upper limb is composed by the shoulder complex, the arm, the elbow, the forearm, the wrist and the hand, Fig. 1a. Its main bones are the clavicle, scapula, humerus, radius, ulna and the bones of the hand, Fig. 1b. They are connected by different articulations that allow a great mobility to the upper limb. It is one of the most complex and important part of the human body due to its high dexterity.

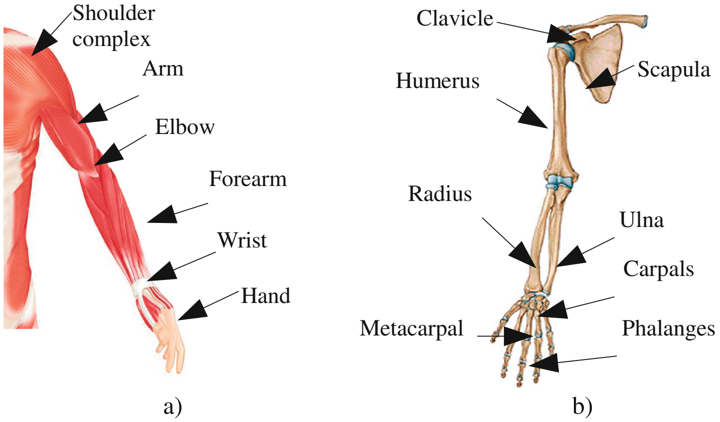

Fig. 1. Anatomy of upper limb: (a) body segments with muscles; (b) main bones

The shoulder is composed by the sternoclavicular joint (sternum and clavicle union), acromioclavicular joint (scapula and clavicle union), glenohumeral joint (humerus and scapula union) and the scapulotoracic joint (union of the scapula with the thorax through muscles of the back). The shoulder is capable of translations and rotations over a very wide range. The movements of the glenohumeral joint are the abduction-adduction of the humerus, flexion-extension and internal-external rotation [9]. The elbow joint is composed by two articulations and allows flexion and extension of the forearm. These articulations act in conjunction with the joints present in the forearm and make possible the pronation and supination of the hand. The radiocarpal joint (wrist) is a biaxial joint that is composed of the distal end of the radius and the carpal bones. The active movements of the wrist are flexion-extension, adduction (ulnar deviation)-abduction (radial deviation). These two movements are performed around oblique axes [10]. The hand is the most complex part of the upper limb and presents 22 DOFs distributed in the fingers to perform many gestures and grasps. All the above-mentioned articulations give to the arm a mobility whose range of motions is summarized as in Table 1.

Table 1. Range of motion of human arm [10]

Articulation	Movement	Range of motion [°]
Shoulder	Extension - Flexion	50–180
	Abduction- Adduction	180–30
	Internal – external rotation	100–80
Elbow	Extension-Flexion	0–145
	Pronation- Supination	85–90
Wrist	Flexion -Extension	85–85
	Adduction- Abduction	45–15

Due to the high complexity of the joints in the upper limb, in general the structure of the arm is simplified for prosthetic designs. The shoulder joint is modelled as a socket and ball joint to represent the movements of the flexion-extension, abduction-adduction and internal-external rotation [9]. The elbow is described as a cardan joint, despite in reality the flexion-extension and pronation-supination axes are not perpendicular [11]. In order to represent the two axes of movement of the wrist joint a cardan joint is again considered. Therefore, the kinematic model of human arm can be identified as an anthropomorphic 7-revolute joint serial arm.

3 Conceptual Design and CAD Solution

The design of a prosthetic device must be capable to reproduce as close as possible the human motion. The lack of dexterity of the prosthetic arm yields to compensatory movements [4] that could cause injuries in the long term. Although there are many prosthetic arms already available, there are still issues that need to be solved.

The design of an upper limb prosthesis involves the selection of appropriates actuators and mechanisms that will move the device. The anthropomorphic shape limits the size of the actuators whose high power density is crucial to allow the prosthesis to exert the required torques and forces during the activities. The control system in

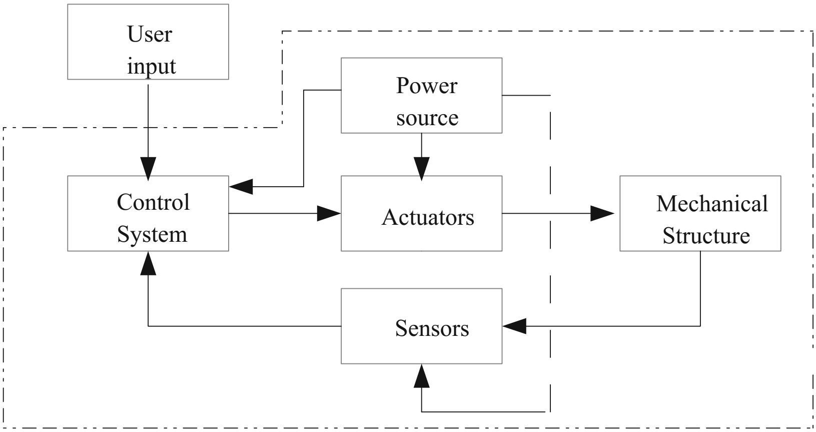

Fig. 2. A block diagram describing a system design for a prosthetic arm

conjunction with the sensors makes possible to the user to operate in a proper way the prosthetic device. A block diagram in Fig. 2 shows how the different components of the prosthetic arm can work together.

The shoulder of the prosthetic arm can be designed as a spherical parallel manipulator like the one that was conceived by Gosselin for other purposes [12]. This manipulator is formed by three identical arms. Each arm is made by three revolute join arranged in such a way that every axis of rotation converges to the same centre of rotation, Fig. 3. This arrangement gives to the manipulator 3 rotational degrees of freedom. These DOFs permit the motions of shoulder abduction- adduction, flexion-extension and inter-external rotation.

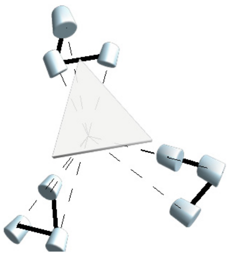

Fig. 3. Kinematic diagram of the 3 DOFs manipulator conceived by Gosselin

The flexion-extension elbow motion is achieved by means of a four bar mechanism. This makes possible to host the actuating motor in a location near the shoulder. Placing the weight closer to the shoulder reduces the rotational inertia. Furthermore, the four bar linkage can be set in a configuration in which the motor delivers higher torque in the position where it is most necessary.

The wrist is formed by the spherical manipulator that allows the forearm pronation-supination, ulnar-radial deviation and wrist flexion extension movements.

The proposed mechanism is assembled to form an anthropomorphic prosthetic arm, Fig. 4a. The shoulder contains the 3DOF spherical manipulator with its actuators. The end effector of the manipulator is rigidly attached to the forearm structure by means of a link. The motor that actuates the elbow is fixed at the base of the forearm, Fig. 4b. The spherical mechanism allows the three movements that the shoulder requires and the 3 motors share the load with small motors. Hence the prosthetic arm can be designed with anthropometric shape and volume. The focus of this work is on the design of the upper limb without the hand but for simulation purposes a mass of 500 gr to represent the load of the hand is included. The overall weight of the design, including the hand is 1,250 gr. Inside of the structure of the prosthesis there is enough room to allocate the power supply and control system.

a) b)

Fig. 4. Prosthetic arm (a) CAD model; (b) View of the mechanism actuating the elbow

4 Motion Simulation and Results

The proposed designed was modelled in Solid Works ®. A dynamic simulation was performed to evaluate the behaviour of the device when following three different trajectories. The output torques were obtained in order to design the actuation system. In all the simulations, a load of 10 N was applied in the hand to represent the payload that the prosthesis must be able to move.

The first task simulated was the flexion motion of the shoulder, Fig. 5a. The amplitude of the movement was planned of 90° starting with the arm totally vertical. The duration of the motion was 2 s with a sinusoidal velocity. The second simulation motion

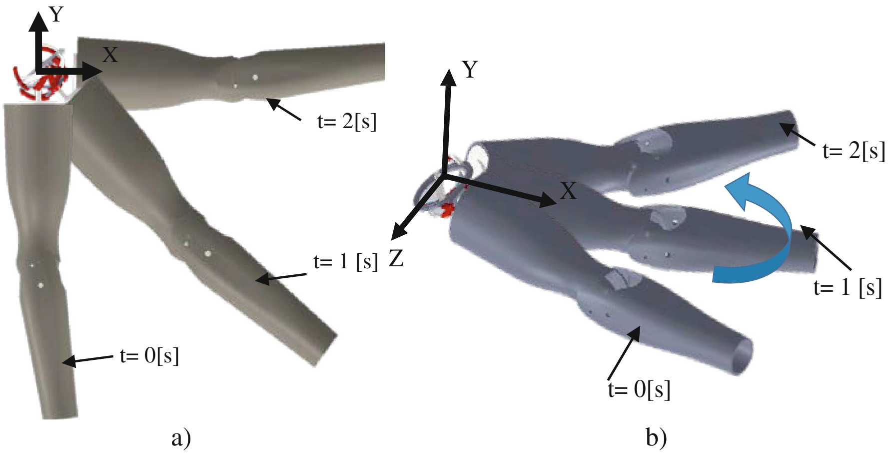

Fig. 5. Position of the prosthesis at different moments of the simulation: (a) first simulation; (b) second simulation

was an abduction movement with the prosthetic positioned in the horizontal plane, Fig. 5b. The amplitude of the movement was of 70° with duration of 2 s. The last simulation consisted in a flexion of the elbow from 0° up to 100° of with duration of 3 s.

The results show for the first and second simulations that when the prosthesis follows the desired trajectories, the three motors perform smooth movements, Fig. 6a and c. In Fig. 6b shows the torques to perform the prescribed movement of the test. The maximum torque occurs in a different moment than the maximum velocity. It can be seen that the maximum torques for the motor 1 and 3 take place at the end of the movement while motor 2 produces its largest torque at t = 1.4 s. But the maximum torque is 6 Nm. For the second test the main part of the movement is due to one motor, Fig. 6c. The largest torques occur at the very beginning of the test for motors 1 and 2. Motor 3 has a sudden increase at the final stage of the movement, reaching its maximum value at the end of the action. The maximum torque is 15 Nm. For the elbow flexion the motor performs a smooth sinusoidal movement, Fig. 6e, with a limited torque variation with respect to the maximum torque of 6.2 Nm occurring at the middle of the motion.

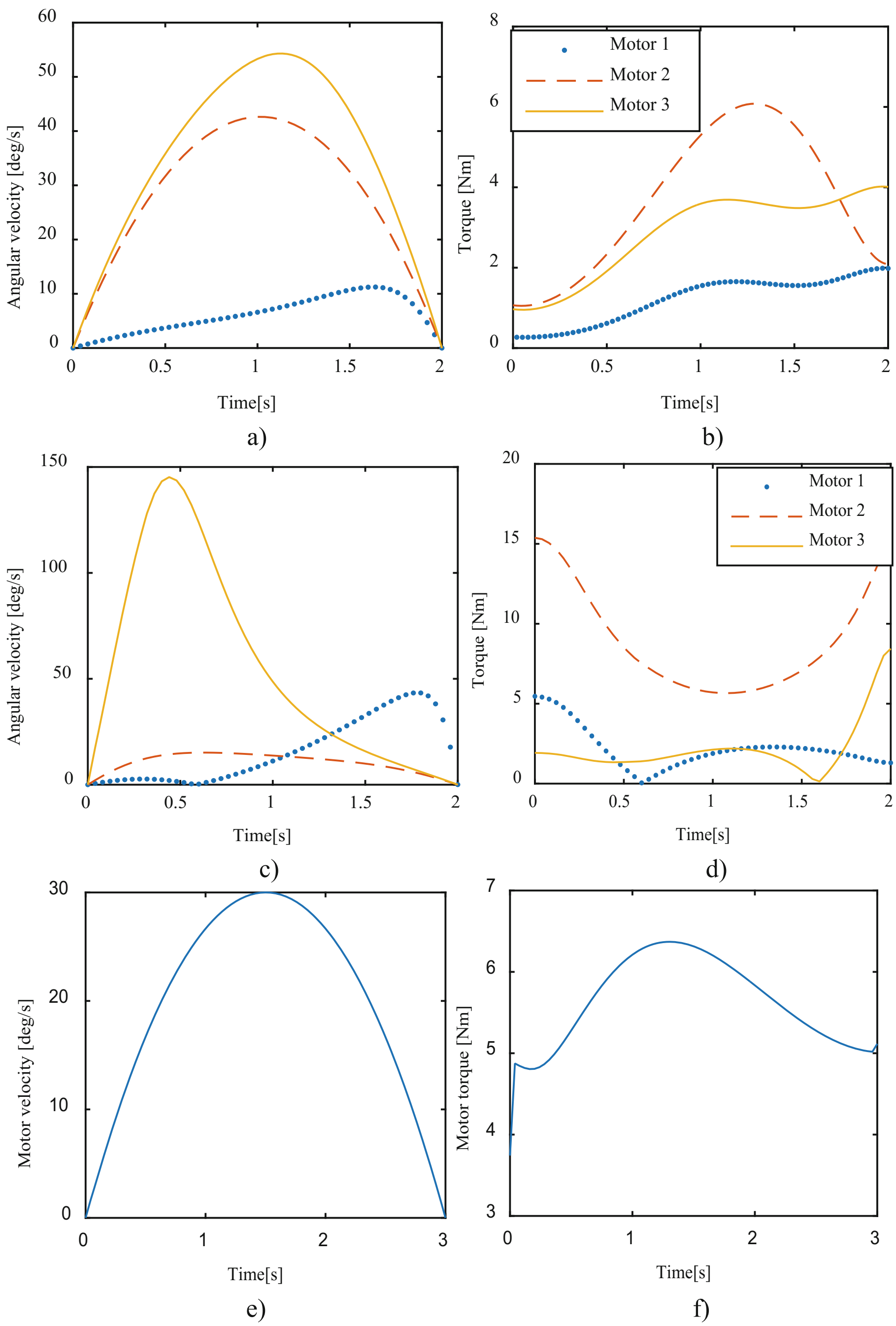

Fig. 6. Results from the simulations: (a) angular velocity from simulation 1; (b) motor torque from simulation 1; (c) angular velocity from simulation 2; (d) motor torque from simulation 2; (e) angular velocity from simulation 3; (f) motor torque from simulation 3

5 Conclusions

In this work the design of a 7 DOFs prosthetic arm is presented with an anthropomorphic shape. The simulations show that typical motions are performed with a minimum of 15 Nm for the torque of motors. The actuators' torque is highly dependent of the configuration of the designed mechanisms that can be properly sized for more efficient operation. It is worth to mention that during the simulations the mechanisms did not reach any singular configuration. The simulation results show the feasibility of the operation with a mechanical design with light human-like structure.

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