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MoBio: A 5 DOF Trans-humeral Robotic Prosthesis

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Abstract— **In this paper, a 5 DOF trans-humeral robotic prosthesis: MoBio is proposed. MoBio includes 2 DOF at wrist which is rare in other trans-humeral prostheses. Through anthropometric features MoBio prosthetic arm can achieve elbow flexion/extension, forearm supination/pronation, wrist radial/ulnar deviation, wrist flexion/extension and compound motion of thumb and index finger. An EMG based control method which uses EMG signals of the biceps brachii and triceps brachii, is used with a motion switching mechanism to control the prosthesis. Experimental results have verified the usability and effectiveness of MoBio in performing Activities of Daily Living.**

Index Terms— **trans-humeral, prosthesis, electromyography**

I. INTRODUCTION

Trans-humeral prostheses are used to replace the missing upper limb segment after an amputation between shoulder and elbow [1]. In order to make these prostheses more complaisant for amputees, researchers are working on developing functional, anthropomorphic and dexterous prostheses. However, these prostheses stay way back when compared to the natural limbs: in the sense of functionality and anthropometry [2]. Therefore, developing active upper limb prostheses with proper hardware design and human motion intention based control has become a widely researched area nowadays.

Due to trans-humeral amputation, elbow, forearm, wrist and hand motions are lost. Therefore, it is expected to replace those lost motions as much as possible through a trans-humeral prosthesis. Among lost motions elbow flexion/extension (F/E), forearm supination/pronation (S/P), wrist ulnar/radial (U/R) deviation, wrist F/E and finger motions are very much important for the Activities of Daily Living (ADL) [3], [4]. Therefore, a trans-humeral prosthesis should be able to perform these motions while having dexterity and anthropomorphic aspects.

It is evident that existing prostheses are rarely being able to achieve required DOF of a trans-humeral prosthesis while achieving dexterous hand motions [5]–[7]. Therefore, a prosthesis with simultaneously working major upper limb motions while having the relevant anthropometric aspects, is required to achieve human like motions. However, almost all the available trans-humeral prostheses do not include two wrist motions at the same time [5]. If one of the motions is absent then the shoulder has to perform the motions for the wrist. For example if a person writes a word using a trans-humeral prosthesis with absent U/R deviation, shoulder and elbow should take over the particular motion. This causes limiting the full use of the shoulder mobility and discomfort to the amputee. Therefore it is important for a trans-humeral prosthesis to have both wrist motions. Even though researches have been carried out to achieve these functions using parallel manipulators and motors [8] and using hybrid (Electrically powered+body powered) prostheses [6], they have failed to achieve the shift between two axes of two wrist motions. Intersected two axes make the wrist motions of the prosthesis deviating further from the natural motions.

Moreover, when designing a prosthesis weight is a crucial factor. Prostheses with over weight limit the ranges of motions of the prosthesis and cause musculo-skeletal disorders. Thus, the weight of the prosthesis should be similar or lesser to the actual human upper limb. Though the fact remains as such, due to the components added to achieve the required motions, prostheses tend to exceed the weight limit. Hence, keeping the co-relation between the functions of prosthesis and the weight of the prosthesis has become a challenging research.

As a solution, this paper proposes a 5 DOF prosthesis named MoBio. It has novel 2 DOF wrist which has 20mm axes shift between two wrist motions. Moreover, it can achieve full ranges of motions as of a human upper limb. Furthermore, MoBio is fabricated considering the weight of the prosthesis so that its weight becomes closer to the actual arm. In order to evaluate the controllability of the prosthesis an EMG based control algorithm with a motion switcher [9] is used. Control algorithm uses EMG signals of bicep brachii and triceps brachii for the controlling purpose. MoBio can be sequentially controlled according to the motion intention of the user, by 1 DOF at a time through a switching mechanism.

The paper is structured as follows. Section II proposes the design and actuation mechanisms of MoBio. Section III explains the prosthetic controller of the proposed prosthesis. Section IV describes the experiments and results. Section V presents the conclusion of the paper.

II. DESIGN AND ACTUATION MECHANISMS OF MOBIO

MoBio is a right arm trans-humeral prosthesis. In order to realize human like motions, MoBio is designed with 5 DOF: Elbow F/E, forearm S/P, wrist F/E, U/R deviation and compound motion of thumb and index finger. The prosthesis is shown in Fig. 2(a). The prosthesis can be attached to the stump arm of the amputee via osseointegrated implant [10] or through socket and straps. Considering the high strength to weight ratio, Aluminum is selected to build most of the

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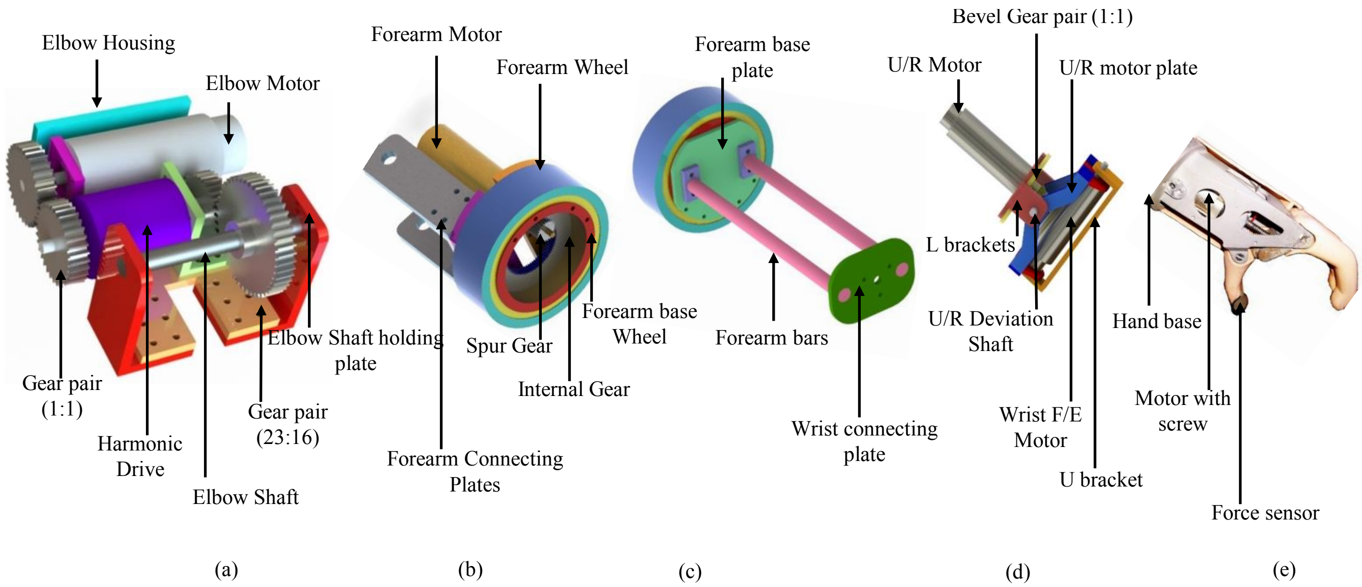

Fig. 1. (a) 3D Model of Elbow (b) 3D Model of Forearm Part 1 (c) 3D Model of Forearm Part 2 (d) 3D Model of Wrist (e) Inside of the Hand

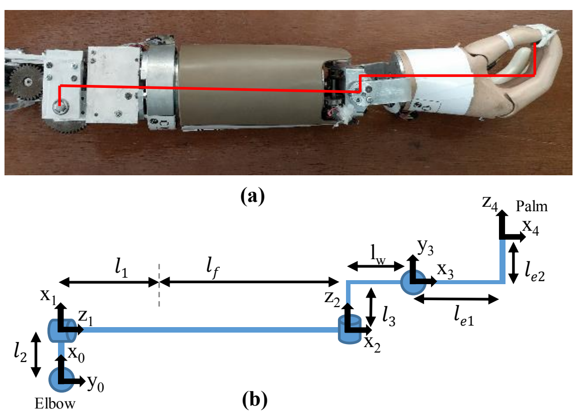

Fig. 2. (a) MoBio Prosthetic arm (b) Kinematics model of MoBio

TABLE I
D-H PARAMETERS OF MOBIO FROM ELBOW TO HAND

Link	α_{i-1}	a_{i-1}	d_i	θ_i
1	$\pi/2$	l_1	0	θ_1
2	$\pi/2$	0	l_2	$\pi/2+\theta_2$
3	$\pi/2$	l_w	l_3	$\pi/2+\theta_3$
4	$\pi/2$	l_h	0	θ_4

components of the prosthesis. Fabricated prosthesis: MoBio weighs 3.2kg which is same as the weight of actual human arm [11]. Actual human arm's weight of 75Kg human is 3Kg. MoBio has four major sections: elbow, forearm, wrist and hand in its design. The kinematic model is shown in Fig. 2(b) and table I shows the D-H parameters [12] of the prosthesis where l_1 = 75.6mm, l_2 = 16.8mm, l_3 = 4.9mm, l_f = 162.2mm, l_w = 20.0mm, l_{e1} = 69.5mm and l_{e2} = 15.6mm.

A. Elbow

The design of the elbow is shown in Fig. 1(a). A brush less DC motor (BLDC)(EC 4 Pole, Maxon motors) is used to initiate the rotary motion of the elbow. BLDC is fixed to the elbow housing. Elbow housing can be connected to a socket or to a osseointegrated implant. The BLDC motor is connected to a harmonic drive gear box (100:1) through a spur gear pair (ratio 1:1). The output of the harmonic drive gear box is coupled to the elbow shaft through a spur gear pair with gear ratio of 23:16. Elbow shaft can rotate relative to the Elbow shaft holding plates with the aid of bearings located at the two ends of the shaft. The forearm connecting plates (see Fig. 1(b)) rigidly connects with elbow shaft so that the forearm assembly can rotate relative to the elbow assembly. Thus the elbow F/E motion is achieved.

Gear wheels of the elbow are fabricated using cast iron since elbow requires high torques and applies high dynamic tooth loads on the gear wheels.

B. Forearm

The forearm design of MoBio is shown in Fig. 1(b) and Fig. 1(c). A DC motor is used (DCX22S, Maxon motors) to achieve the forearm S/P motion. To transmit the output power of the motor to the forearm, output shaft of the motor is connected to the internal gear with a spur gear. This internal gear is rigidly fixed to the forearm base wheel to enable the forearm S/P motion. In this design, forearm base wheel lies inside the forearm wheel. In order to support the relative motion between two wheels a needle roller bearing is used. Needle roller baring is press fit to the forearm wheel and base wheel is press fit to the bearing. Forearm base plate is connected to the base wheel. The forearm base plate can rotate with the forearm base wheel and achieve relative motion between two forearm parts [see Fig. 1(b) and 1(c)]. For the purpose of achieving high load bearing ability to the forearm compared to previous researches [8], forearm bars have used to connect the forearm base plate to the wrist connecting plate.

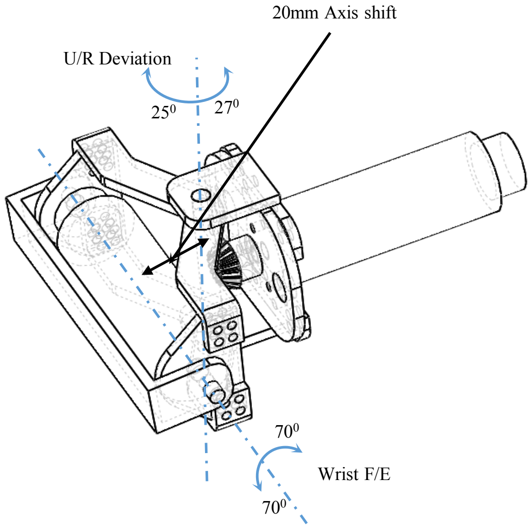

Fig. 3. Wrist design of MoBio. It can achieve 2 DOF wrist motions while maintaining the 20mm axis shift between U/R deviation and wrist F/E motions. Shape of the U/R connecting plate allows the wrist to achieve full range of motion of U/R deviation.

C. Wrist

U/R motor (DCX22S, Maxon Motors) of the wrist [see Fig. 1(d)] is connected through the wrist connecting plate. Bevel gear pair rigidly attached to the U/R motor shaft and U/R deviation shaft enables the U/R deviation. Bevel gear attached to the motor shaft transmits rotary motion generated by the motor to the U/R deviation shaft through the bevel gear attached to the U/R Deviation shaft. This mechanism gives the flexibility to the design, to adjust the distance between two perpendicular axes of the two wrist motions. Wrist of MoBio has the same feature with 20 mm shift between these two axes [see Fig. 3]. L brackets of the wrist is connected to the wrist connecting plate. Shaft for U/R deviation is supported on L brackets with two bearings, where the shaft can rotate relative to the L bracket. The shape of the U/R motor plates is designed to achieve the full range of motion of the U/R deviation. U bracket is connected to the wrist F/E motor (DCX22S, Maxon Motors) through bearing, which provides the hand-wrist connection option and the F/E motion of the wrist.

D. Hand

The hand [Fig. 1(e)] comprises of a hand base which enables the connection with the U bracket of the wrist. DC motor is located inside the hand. A screw is fixed coaxially with the DC motor shaft. A ball which moves along the screw is fit to the fingers. Therefore, when the DC motor starts to rotate, thumb and index fingers are pushed apart or towards due to the ball and screw mechanism [13].

III. Prosthetic Controller

The prosthetic controller controls the prosthesis using EMG signals from biceps brachii and triceps brachii. It is assumed that the parts of two muscles are available after the amputation and signals are similar to that of a able-body person. The human can see the prosthesis in operation and accordingly he might be able to change the muscle activation, hence required motions are achieved. Since this controlling method uses human vision feedback, the system can be considered as a Human In The Loop (HITL) system [14].

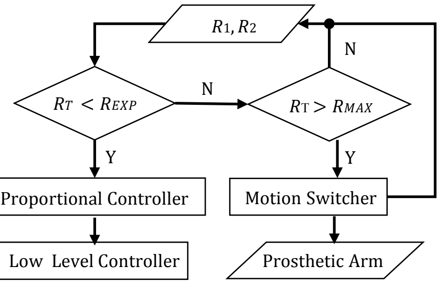

Fig. 4. EMG based controlling algorithm. RMS values of bicep brachii and triceps brachii (R_1 and R_2) are processed to calculate their addition (R_T) in order to decide whether to move the prosthesis or to switch the current motion. R_{EXP} and R_{MAX} are experimentally achieved according to amputee's EMG RMS. In order to reduce discrepancies in motion switching due to accident motions, RMS values between R_{EXP} and R_{MAX} are neglected.

EMG based controlling algorithm is shown in Fig. 4. The algorithm consists of proportional EMG controller and motion switcher. Motion switcher can sequentially switch the motion.

RMS of EMG signals for a sample size of 100 is taken as of (1).

$$R_n = \sqrt{\frac{\sum_{i=t}^{t+N} {E_i}^2}{N}} \quad (1)$$

where, R_n, E_i, N and t are the RMS of channel n (n=1,2), raw EMG of channel n at the given time, sample size and the beginning of the sample respectively.

These RMS of EMG signals of biceps brachii and triceps brachii are taken as the inputs to the EMG based controlling algorithm. The addition of two RMS of EMG values (R_T) [refer (2)] has been checked for a isometric contraction [15].

$$R_T = R_1 + R_2 \quad (2)$$

Motion switcher is activated if an isometric contraction is detected[see Fig. 4]. It switches the motion sequentially between 5 motions. The wearer can select desired motion by sequentially switching through the motion sequence.

The prosthesis controller controls the selected motion from the motion switcher, if R_T is below a specified threshold. The EMG proportional controller uses the agonist−antagonist nature of biceps brachii and triceps brachii. The elbow flexion motion makes higher signals on biceps brachii and lower signals on triceps brachii. Elbow extension makes triceps brachii signals high and biceps brachii signals low. This phenomena is used in the EMG proportional controller. EMG proportional controller is given as of (3).

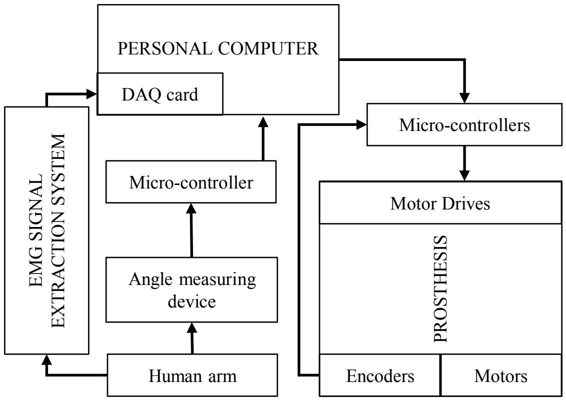

Fig. 5. Experimental Setup

$$\Delta\theta = K_1(K_2 \times R_1 - K_3 \times R_2) \tag{3}$$

where $\Delta\theta$, K_1, K_2, K_3 are the angular change of the joint and constant gains depend on the person respectively. [16]

$$\theta_{(t)} = \theta_{(t-1)} + \Delta\theta \tag{4}$$

where $\theta_{(t)}$ is current joint angle and $\theta_{(t-1)}$ is the previous joint angle.

Joint angles found from (4) are sent to the low level controllers of the respective joints.

Motion sequence of MoBio has to be remembered by the user. However this controlling method gives the flexibility for the user to skip motions if necessary. User has to perform "n+1" number of motion switchers, in order to skip "n" number of motions in the sequence. The video attached with this paper summarizes and explains further about the sequence of motions and skipping the motions in the sequence.

Proportional-Integral-Derivative controllers (PID) are implemented [17] as low-level controllers at micro-controllers (ATmega 2560, Atmel). Low level controller is used by the relevant prosthesis joint according to the angles received from the high level controller. Furthermore, each and every joint is driven by a separate micro-controller. Motor commands are sent through micro-controllers to the motor controller (L298, H-bridge).

IV. Experiments

MoBio prosthetic limb was evaluated for its effectiveness and usability. Sequence of experiments are carried out in this regard.

A. Experimental Setup

Experimental setup (see Fig. 5) consists of MoBio, angle measuring device, 3 microcontrollers (ATmega 2560, Atmel), BLDC motor controller (EPOS2, Maxon Motors), 3 H-bridges (L298), data acquisition (DAQ) card (6220, National Instruments), EMG extraction system (16 channel Bagnoli^{TM} desktop EMG system, DELSYS) and a personal computer (PC) with MATLAB. H-bridges are used for the brushed DC motors of the prosthetic device and EPOS2 motor controller is used for the controlling of the BLDC motor. In the experiments, EMG signals are sampled at 2000Hz and band pass filtered to be within 50Hz to 450Hz.

B. Experiments

In the first experiment, to monitor the joint angle responses according to the PID controller, a sinusoidal wave is generated through micro-controller as the desired motion to PID controllers for the brushed DC motors located in the forearm joint and the wrist of prosthesis. Sinusoidal input and encoder feedback (output motion) values are collected using the micro-controller.

Second experiment is carried out to validate the EMG based proportional controller. Angle measuring device was attached to the human arm. It was then connected to a micro-controller to record the real time angle measurements. At the same time encoder feedback of the elbow motor was recorded to determine the angles of the elbow motion. EMG signals extracted from biceps brachii and triceps brachii of a healthy subject were used to control the prosthesis. The joint angle values given by the micro-controller output, are plotted against the time according to the motions of both prosthetic arm's elbow and the healthy subject's elbow motions.

Third experiment is conducted to monitor the prosthetic arm's ability to reach towards a destination. Prosthetic arm was controlled by a healthy human arm. First the path of the human arm was tracked. Then the path of the prosthesis was tracked while controlling by the healthy human hand. Markers were pasted on both human hand and MoBio to track their paths. The path of the hands in the both occasions were tracked and recorded using a High Definition camera. The recorded path was plotted using the data extracted using Kinovea software. Motion paths of both human arm and robotic arm in the X-Y plane and robotic arm's path along 2 axes with respect to time were plotted afterwards. Furthermore, EMG signal variation at the same time period is also recorded.

C. Results

Fig. 7 and Fig. 8 depict the output responses of the motors for S/P, wrist F/E motions and U/R deviation. In each graph it can be seen that output motions are not reached to the same peaks as the desired motion. Since the ranges of motions prosthesis are limited to the values as shown in Table II, prosthesis cannot achieve desired peak to peak ranges of motions.

Fig. 9 shows the motion angle relationship of both human arm and MoBio in performing the elbow F/E motion. There is a lag in the robotic arm motion compared to the actual arm motion. This phenomena mainly occurs due to the delay generated by the signal processing and communication in the micro-controllers and softwares. The distortion which has occurred at the peak of the robotic arm motion curve, has generated due to the noise interferences.

Fig. 6 shows the spatial motion of MoBio in reaching an object. Fig. 10 depicts the vertical movement (along Y-axis)

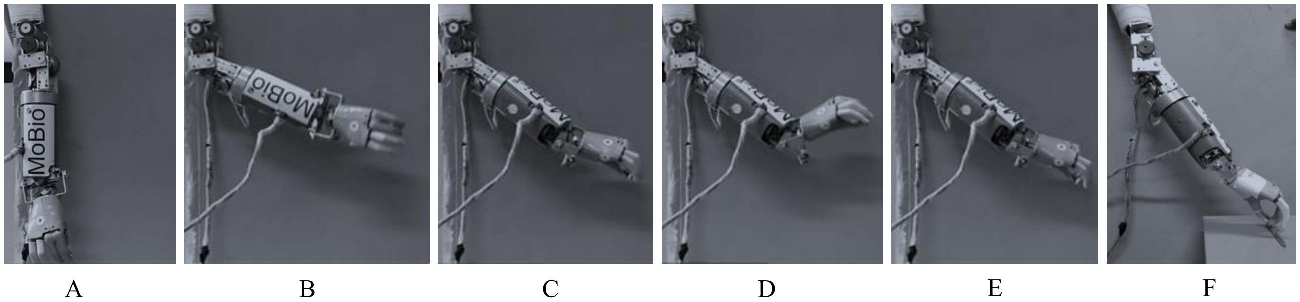

Fig. 6. MoBio's reach towards an object: User controls MoBio through his motion intentions while taking the vision feed back from the eyes, to reach the hand towards a specific object. The motion is performed in a plane parallel to sagittal plane.

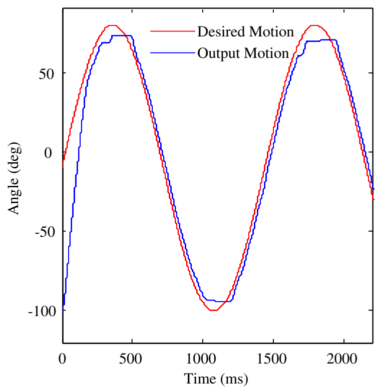

Fig. 7. Motion output of the S/P motor to a desired motion input

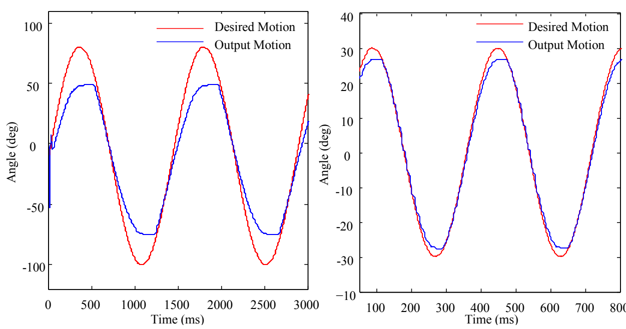

Fig. 8. (a) Motion output of the wrist F/E motor to a desired motion input (b) Motion output of the wrist U/R motor to a desired motion input

and horizontal movement (along X-axis) of the prosthesis during this task. Furthermore, EMG pattern recorded at the same time is also included in the graph so that the shifting regions can be identified. Here the hand motion is not available in the graph [Fig. 10] because it only reveal MoBio's ability to reach an object . Two consecutive isometric contractions are performed during the reaching process without any visible time gap to skip the wrist U/R deviation and hand motion at respective intervals.

A comparison of experimentally obtained ranges of motions of MoBio and ranges of motions of human arm [11] are given in the Table II.

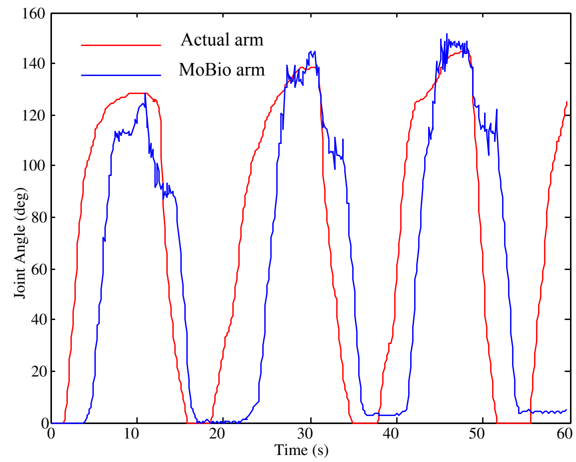

Fig. 9. Elbow motion comparison between actual human arm and prosthetic arm

TABLE II
RANGE OF MOTIONS COMPARISON OF ACTUAL ARM AND MOBIO ARM

Motion	Range (deg) Human Limb	Range (deg) MoBio arm
Elbow Flexion/Extension	0 - 145	0 - 150
Supination/Pronation	-85 - 70	-85 - 70
Wrist Flexion/Extension	-70 - 70	-60 - 60
Wrist Ulnar/Radial deviation	-35 - 20	-27 - 25

V. CONCLUSION

This paper proposed a 5 DOF trans-humeral prosthesis which can mimic the human motions. A novel 2 DOF mechanism is proposed to realize the wrist motions. Experimental results verified that the prosthesis can achieve the full range of motions of elbow F/E, forearm S/P, U/R deviation and wrist F/E, just like the actual human arm. MoBio weighs about 3.2kg which is same as grown human's upper limb. Furthermore, results confirm the fact that the proposed prosthesis can reach a desired object successfully, which is an essential activity in performing ADL.

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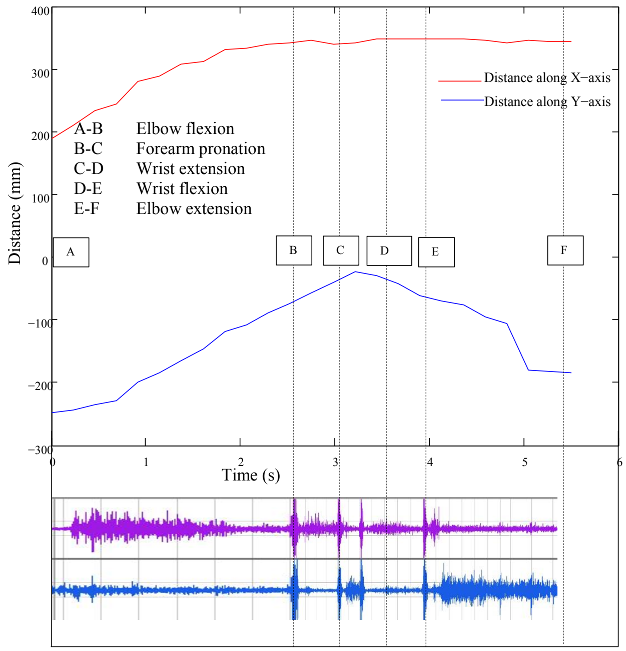

Fig. 10. Spacial motion of MoBio along X and Y directions in reaching a object and EMG signal pattern change with time

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