A Biomechatronic EPP upper-limb prosthesis controller and its performance comparison to other topologies

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***Abstract*— Historically, Classic Extended Physiological Proprioception (EPP) as an upper-limb prosthesis control topology has been outperforming functionally all other topologies of the past. A novel Biomechatronic EPP controller has been designed to overcome shortcomings of the classic EPP control topology, and has been hypothesized to be functionally equivalent to the classic EPP topology. Using the dSpace real-time hardware platform and other mechanical and electronic components, the following were developed in the lab: (a) A Biomechatronic EPP controller, (b) a classic EPP controller, (c) an "unconnected" controller and (d) an EMG controller. All four topologies were tested in the lab using the target experiments methodology. Initial results of one subject show that performance of (a) is superior or comparable to (b) and superior to (c) and (d).**

I. Introduction

The replacement of the human upper limbs by mechanical ones is a solemn scientific challenge. A control method that now dominates the field of prosthetics and is widely used is Proportional Myoelectric Control. A proportional myoelectric control system employs a microcontroller or computer that receives electromyography (EMG) signals from sensors on the muscle(s) and activates the corresponding joint actuator(s) proportionally to the EMG signal [1]. Although myoelectric signals are widely considered as the best available control interface for powered prostheses, many amputees abandon their devices out of frustration due to the lack of precision of the prosthesis' movements [2].

Another control method, dominant in the early to mid 1900s, is the Classic Extended Physiological Proprioception (Classic EPP). The term EPP was first coined by Simpson D.C. in 1974 [3], although the same principle was the control topology of choice for the amputees of the first and second World Wars. As shown in Fig. 1, the prosthetic limb is connected directly to cineplasty sites of residual arm with Bowden Cables [4-5]. Thus, the alien prosthetic becomes an extension of the remaining limb [6]. Consequently, the position, the velocity, and the forces that are applied to the prosthetic are transferred from the cables to the muscles, stimulating the neural receptors of the body, activating the proprioception of the amputee. However, this control method has the disadvantage that it is not aesthetic for the human user (Bowden cables) and in addition a plastic surgery is required. In this paper, we present an experimental comparison between

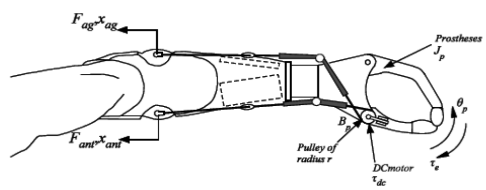

Figure 1. Classic EPP control topology (Adapted from [18]).

the aforementioned control topologies and a novel, but functionally equivalent to EPP, Biomechatronic EPP controller [7-8] (see Fig. 2). The equivalency of the proposed topology to Classic EPP is shown, and the target experiments methodology, along with the experimental setup used for the evaluation, are presented. The results of the target experiments help us to form an initial evaluation for the capabilities of the proposed controller, with early data from one subject. Superiority of the Classic EPP over the myoelectric, and similarity of the performance of Classic EPP to natural hand performance has been shown in the past [9]. In addition, the EPP topology benefits have been studied recently [10], validating our interest in the EPP revival.

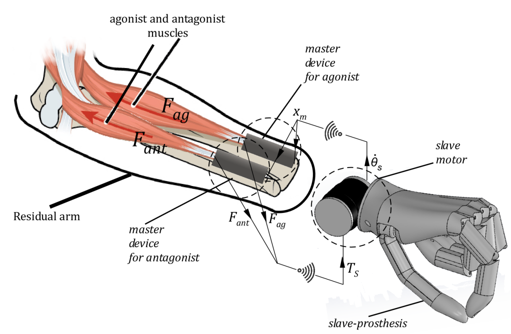

Figure 2. Proposed control topology of Biomechatronic EPP.

II. Methods

At the Control Systems Laboratory of NTUA, a new topology (Fig. 2) of EPP, coined Biomechatronic EPP [7-8], was proposed to eliminate the drawback of cineplasty and Bowden cables, which render the EPP unaesthetic for the user. The core of this concept is based on principles of the field of Telerobotics and Teleoperation [11]. In this topology, a master - slave position-force control scheme is applied, using an implanted leadscrew driven by a dc-motor as the Master, and the prosthetic hand as the Slave. The implanted

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leadscrew takes a force command signal from the muscle/tendon attached to. The force command then wirelessly is transmitted to the Slave, and a position feedback comes back from the Slave to the dc-motor controller, which then moves.

To simulate the desired topologies and proceed to the experimental phase, an appropriate setup had to be prepared. The real-time controller dSpace board DS1103, an all-rounder in rapid control prototyping, was used for the implementation of the control schemes. The board can be mounted in a PC or a dSpace Expansion Box to test control functions in a laboratory.

A. Experimental Setup

The electro-mechanical setup used to realize all four control topologies is shown in Fig. 3. For the *Classic EPP*, the prosthesis (slave) motor is connected directly to the force input via the Bowden cables, while for the *Biomechatronic EPP*, two master dc-motors connected to leadscrews replace the mechanical linkage. For the *Unconnected* and *EMG* topologies there is no linkage between the prosthesis and the muscle. Depending on the applied force, the prosthesis motor rotates to the desired position in all Classic EPP, Biomechatronic EPP, and Unconnected topologies. To electronically read the force applied as input, force sensitive resistors, along with the appropriate signal conditioning circuit, and an in-house fabricated housing, were used. The placement of the FSR sensors depends on the control topology. In Classic EPP they were placed at the terminations of the Bowden cables, in Biomechatronic EPP at the screw drivers, and in the Unconnected at a fixed place. On the other hand, in the EMG control method, the reference input is provided by muscle myoelectric signals. To acquire these, the Myo Armband, developed by Thalmic Labs, was used.

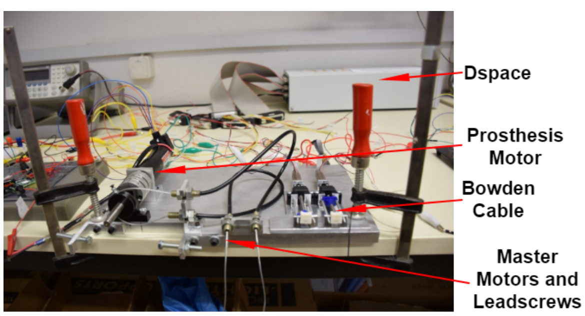

Figure 3. The bench prototype of all four topology controllers.

B. Fitts' Law and Throughput

Fitts' motivation was to investigate whether human performance in target acquisition tasks could be measured or quantified using an information metaphor. He reasoned that a human operator that acquires targets over a certain amplitude (signal), and with variable success (noise) is demonstrating a "rate of information transfer" [12]. Fitts' index of performance, now throughput (TP), is:

$$TP = \frac{ID_e}{MT} \quad (1)$$

where ID_e is a task effective index of difficulty (in bits) computed from the target distance (A) and target width (W), and MT is the mean movement time (in seconds), recorded over a sequence of trials. The ID_e-term in Eq. (1) expands as follows:

$$ID_e = \log_2(D_e / W_e + 1) \quad (2)$$

Use of the effective values (subscript "e") is a change proposed by Crossman [13,14], and subsequently endorsed by Fitts [15] to include spatial variability or accuracy in the calculation. With this, W_e is computed as 4.133 × SD, where SD is the standard deviation in the selection coordinates and D_e is the mean of the actual movement amplitudes in the sequence of trials. Adjusted in this manner, throughput is a single human performance measure that embeds both the speed and accuracy in human responses [16].

Throughput computed using Eq. (1) is a measure of human performance in the context of the task, device, and environmental conditions when each experiment is performed [17]. If testing over two or three separate test conditions, the differences in throughput can be used to assess performance differences between the conditions. This is also in agreement with [9].

C. Target Experiment

In this experiment, a rectangular shaft was added in the gearhead of the slave motor. As the motor rotates, the shaft movement is similar to the movement a hand makes during wrist flexion and extension. Two mechanical stops were added, the first at 90 degrees in the clockwise direction, and the second at 75 degrees in the counterclockwise direction, modeling the wrist flexion and extension bounds, respectively. This way, the shaft served the role of the prosthetic hand and the slave motor of its movement actuator.

The aim of the experiment was to compare the ability of the subject to control the rotational displacement of the slave motor, therefore the position of the shaft, using the four alternative control methods, the Classic EPP, the Biomechatronic EPP, the Unconnected, and the EMG.

1) Procedure

The Subject performed multiple trials on a simple task using the four aforementioned control topologies. He used a forearm cuff which allowed only wrist flexion and extension. For Classic EPP, Biomechatronic EPP and Unconnected topologies, the FSR sensors were connected via a system of ropes and pulley to the cuff, while for the EMG topology the subject used both the cuff and the Myo Armband. The operation of the experimental setups and the requirements of the task were explained and demonstrated to the Subject before starting the experiment and the Subject signed an IRB form which contained the description of the experiment and all the risks involved. One "warm-up" block of trials was given prior to data collection.

The task is proportional to Fitts' serial task [12]. The position of the shaft was displayed on a computer monitor as the position of the cursor. The Subject did reciprocal pointing on a pair of circular targets. The targets appeared on the periphery of a semicircle, which corresponded to the shaft orbit. Their position was determined as the angle in which their center lied upon the semicircle. One circle was the starting point (GREY COLOR) and the other the target point (RED COLOR) (see Fig. 5). The Subject had to try to reach the target and remain inside it for one second (dwell time); otherwise if he was reaching it and then overshooting it, the attempt was considered to be a failure. After each iteration, the targets switched colors, guiding the Subject through the block of trials. The Subject was instructed to balance the speed and accuracy. He was told that if too many errors were made, he was moving too fast, and if he never (or rarely) made an error, he was not moving fast enough.

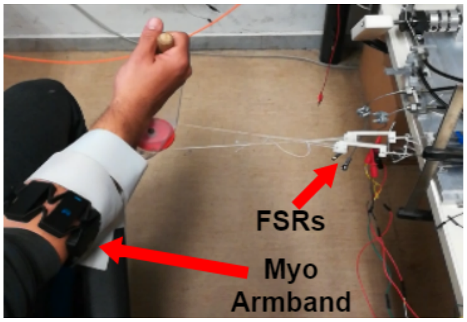

Figure 4. The subject during the experiment.

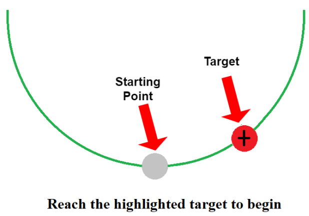

Figure 5. Monitor display during the experiment.

2) Design

A 1 × 4 × 5 × 5 design was used. Controlled variables were the control method (four levels), the task (one level), the target distance (five levels), and the target width (five levels). Dependent variables were the movement time (MT), the error rate (calculated from the reaching angle), and the throughput (TP). The movement time was measured from the beginning of a move to the reaching of a target (Dwell time and Reaction Time excluded from the measurement of Movement time). The beginning of a move occurred with the first cursor position change after the end of the previous move.

The experiment was sequenced by trials, blocks and sessions. Each trial was a single target-select task; each block was a series of 15 trials for the same target-select task; each session was a series of 25 blocks covering randomly, in descending target width, the 25 combinations of target distance and target width. Sessions were conducted on four separate days, using a different control method. After one session for all control methods, the subject had completed a total of 15 × 5 × 5 × 4 = 1500 trials.

The width (W) of the targets and the center-to-center distances (D) between the circles were set at W = 2,3,5,10 and 15 degrees and D = 27.5,67.5,80,95 and 135 degrees, resulting in IDs from 1.5025 to 6.0298 bits.

III. Results

Prior to the results of the target experiment, the transparency of Biomechatronic EPP controller had to be shown. To achieve the desired equivalence between the Classic EPP and the Biomechatronic EPP, the delay between the master and the slave motors must be zero. Figure 6 demonstrates the responses of the slave and master motors. A time-delay estimation was made by computing the cross-correlation of the slave motor displacement and the respective displacements of the master motors. Using the "xcorr" function in Matlab, the maximum lag was computed and it turned out to be practically zero (less than sampling period of 1ms) for both the agonist and the antagonist master motor. Thus, it can be insinuated that the master motors connected to the power screws can produce a displacement that resembles the exact displacement of the pulley used for the prosthetic limb of the Classic EPP.

After that, the delay of the system depends only on the delay between applying the force and the displacement of the prosthesis motor. As shown in Fig. 7, for our experimental setup, this is approximately 78 ms.

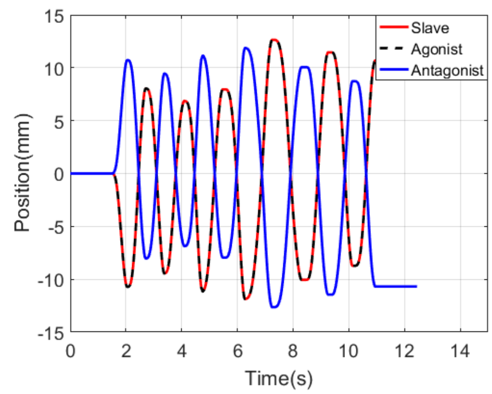

Figure 6. Responses of the Slave and Master motors.

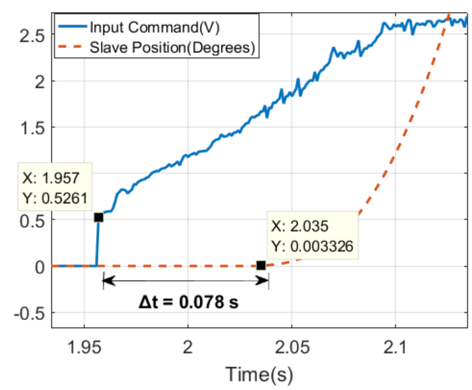

Figure 7. Measurement of the delay between the applying force and the displacement of the prosthesis motor.

Fig. 8-10 display the results after the realization of the target experiment. As indicated from Fig. 8, the mean movement time for the EMG control topology was by far the greatest (1.8715 s). Using the Biomechatronic EPP (1.3431 s) the subject moved a little bit faster than using the Classic EPP (1.3851 s) or the Unconnected (1.416 s).

Fig. 9 illustrates a very interesting point. The bar plots show that in terms of error rate, the subject did less mistakes using the Biomechatronic EPP (15.47%). Classic EPP (23.73%) had the second smaller error rate, while Unconnected (38.93%) and EMG (61.07%) presented much greater error rates. The error rate was computed using the following formula (3):

$$\%Error = \frac{\#Trials - \#Hits}{\#Trials} x100 \quad (3)$$

Last but not least, Fig. 10 demonstrates the Throughput achieved for the four different control topologies. Throughput was better for Biomechatronic (2.82 bits/s) and Classic EPP

(2.90 bits/s), while it was worse for EMG (2.34 bits/s) and even worse for Unconnected (1.50 bits/s).

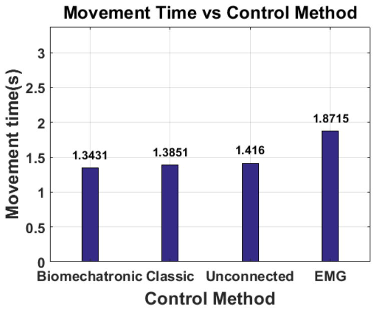

Figure 8. Movement time vs. control method.

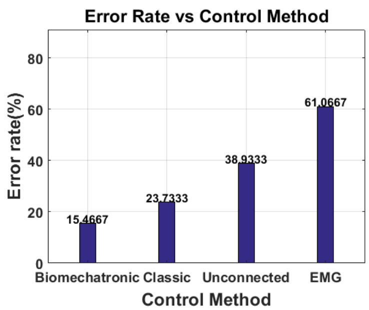

Figure 9. Error rate vs. control method.

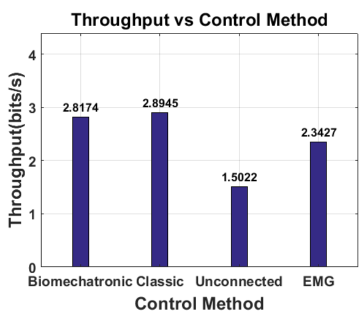

Figure 10. Throughput vs. control method.

IV. Discussion

In this work, we compared the performance of the Biomechatronic EPP, a novel upper-limp prostheses controller, to three other control topologies using the target experiment methodology. From the results conducted, we proved the transparency of the Biomechatronic EPP controller, as well as its equivalency to the Classic EPP. Moreover, this pilot single subject target experiment revealed encouraging results about the ability of this novel technique to compete with commonly used control methods and even surpass them. Additional experiments are being executed with the participation of more subjects, so that we can come to more confident conclusions.

V. Conclusion

We believe that the proposed EPP topology has the potential to become more acceptable for perspective users and become in future the core of many DOFs prosthetic systems. Our initial results are encouraging to invest more in this control topology. A physically implemented bio-compatible Biomechatronic EPP prototype is our future ultimate objective.

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