Differential Activation of Biceps Brachii Muscle Compartments for Human-Machine Interfacing*

Eva Lendaro, *Student Member, IEEE*, Simon Nilsson, and Max Ortiz-Catalan, *Member, IEEE*

***Abstract*— A central challenge for myoelectric limb prostheses resides in the fact that, as the level of amputation becomes more proximal, the number of functions to be replaced increases, while the number of muscles available to collect input signals for control decreases. Differential activation of compartments from a single muscle could provide additional control sites. However, such feat is not naturally under voluntary control. In this study, we investigated the feasibility of learning to differentially activate the two heads of the bicep brachii muscle (BBM), by using biofeedback via high-density surface electromyography (HD-sEMG). Using a one degree of freedom Fitts' law test, we observed that eight subjects could learn to control the center of gravity of BBM's myoelectric activity. In addition, we examined the activations patterns of BBM that allow for the decoding of distal hand movements. These patterns were found highly individual, but different enough to allow for decoding of motor volition of distal joints. These findings represent promising venues to increase the functionality of myoelectrically controlled upper limb prostheses.**

I. Introduction

Amputation, regardless of cause, can considerably diminish quality of life due to loss of functionality, and often onset of chronic pain. While the latter remains challenging to treat, it is nowadays possible to restore functionality of the lost limb thanks to advances in prosthetic research. Myoelectric prostheses use electrical signals from the remaining muscles of the upper limb as control input, and currently represent the best commercially available option for upper limb amputees. A central challenge in the design of these prostheses resides in the fact that as the level of amputation becomes more proximal, the number of functions to be replaced increases while the number of muscles available to collect input signals decreases. Each lost muscular control site translates in lesser controllable functions of the prosthesis. Targeted Muscle Reinnervation (TMR) is way to recover control sites that was introduced by Kuiken *et al.* in 2004 [1]. This surgical procedure consists in reinnervating available muscles with the severed nerves formerly directed to the lost limb and left without a target. However, TMR is an approach that requires surgery followed by a lengthy rehabilitation program [2].

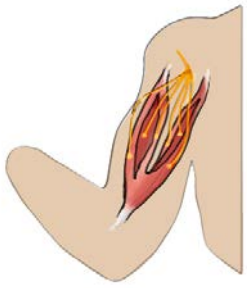

Figure 1: Representation of the Biceps Brachii (BB) showing the different compartments innervated by separate nerve branches. Courtesy of Irene Boni.

Skeletal muscles consist of sub-units called neuromuscular compartments. In the perspective of control of myoelctric prostheses, volitional activation of these compartments, independently from each other, would represent an important increase of control sources without the need of surgical intervention. In 1983, Haar Romeny *et al.* showed with intramuscular electrodes that some motor units of the long head of the bicep brachii muscle (BBM) are active during flexion of the elbow, while other only during pro/supinations of the hand [3]. The anatomical basis for these findings was confirmed by Segal in 1992, who discovered the existence of six parallel individually innervated muscular compartments in each head of the BBM [4] (illustration in Fig 1). In 1996, Brown *et al.* went on to investigate the amount of differential activation of the BBM during rapid supination movements, and found that joint position had a significant effect on the relative activation of the two heads of the muscle [5]. In the same year, it was shown that the two heads (long and short) contribute in different amount to supination and flexion, however, the relative differences vary largely between subjects [6]. Overall, there seems to be a complicated functional relationship between the two heads of the BBM. The current understanding indicates that arm posture has a major impact on the amount of differential activation [5]. This was confirmed by Nejat Nahal who showed that changes in arm posture have a large impact on the relative activation of the two heads [7].

In this study, we investigated whether it is possible to enhance differential activation of the BBM by training. A possible venue to allow this type of training is biofeedback, which consists in providing the subject with information about physiological parameters in order to increase control over them. Previous work has demonstrated the use of biofeedback for motor learning [8], [9]. We developed a GUI based on biofeedback that was used for both training and probing the ability of a subject to differentially activate the two heads (long and short) of the BBM. In addition, we set out to determine how patterns of activation of the BBM differ when executing distal movements, and to ascertain if there is any commonality

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E. Lendaro and S. Nilsson are with the Dept. of Electrical Engineering, Chalmers University Of Technology (CTH), Gothenburg, Sweden (e-mail: lendaro@chalmers.se). M. Ortiz-Catalán is with the Dept. of Electrical Engineering, CTH, and Integrum AB (e-mail: maxo@chalmers.se).

between these patterns among different subjects. This is important as myoelectric pattern recognition is a promising technology that allows to translate such patterns into corresponding artificial limb motions [10]–[13].

II. Materials and Methods

This study consisted of two experiments involving high-density surface electromyography (HD-sEMG) aimed at investigating two alternative potential methods of myoelectric control: 1) voluntary differential activation of a muscle with more than one compartment, and 2) myoelectric pattern recognition of distal movements.

A. Preparations

Eight able-bodied subjects (4 males and 4 females, aged 23 to 64) were enrolled in the study. Upon enrolment each participant was instructed on the protocol and made aware of the possibility to withdraw from the experiment according to their will. Participation required signing a consent form. Only subjects without any previous muscular injuries in the BBM of their dominant arm were selected. The studywas approved by the Västra Götalandsregionen ethical committee.

For each subject, the medial acromion and fossa cubit of the dominant arm were identified: a line was drawn between the two landmarks and a mark (central point of the electrode matrix) was placed at one third of the line's length from the distal end. The BBM was identified by palpation, while having the subject performing elbow flexions, and covered with a 6x5 electrode matrix centered around the mark previously drawn, with the rows along the muscle and the columns perpendicular to it. Single-use, pre-gelled, Ag/AgCl adhesive electrodes with a diameter of 1 cm were used. The matrix had an inter-electrode distance of approximately 15 mm and slight deviations from the marked position were accepted to ensure optimal coverage of the BBM. The reference electrode was placed on a bony area of the ipsilateral shoulder while the ground electrode was placed on the elbow. This ensured placement over areas with low myoelectric activity and proper separation between reference and ground electrodes. Anatomical landmarks and electrode placement were chosen in accordance with the SENIAM guidelines [10]. Fifteen minutes between application of the electrodes and start of the experiment were allowed in order to obtain a stable skin-electrode interface. The subjects were seated in a regular office chair with armrest.

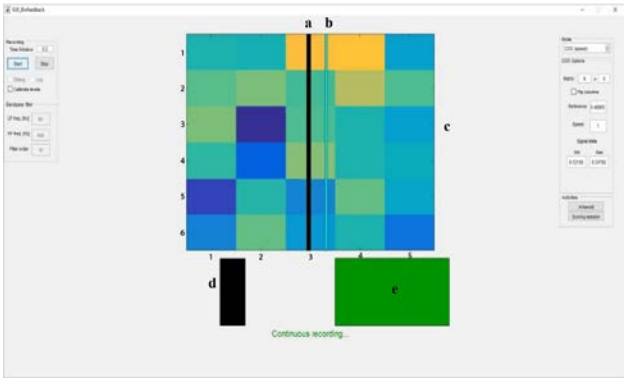

Figure 2: The GUI used to guide the biofeedback training and its main components: (a) the reference bar (black) represents the lateral center of gravity (COG) of the neutral activation; (b) the COG bar (turquoise) representing the center of gravity of the current activation as represented by (c) the EMG map. The EMG map is color coded: blue is assigned to low values and yellow to high. (d) the sliding bar (black), which moves in function of the position of COG bar with respect to reference bar. (e) Shows the target area of a repetition of the Fitts' law test.

All the GUIs used for this study were developed within the framework of BioPatRec, a modular research platform developed in Matlab by Ortiz-Catalan, and several other contributors [14]. All software developed in this project is integrated with, and freely available through BioPatRec [15]. The EMG was acquired using a RHA2132 32-channel monopolar amplifier with an amplification of 200 V/V and separated ground and reference connections. The data was sampled using a custom-built ADC circuit at a rate of 1000 samples/s per channel over USB using Matlab version R2015b. The data was collected and transferred to the PC using a Texas Instruments TM4C123G microcontroller.

B. Experiments

1) Biofeedback training

The first experiment used biofeedback training as a means to enhance differential activation on a voluntary basis. The experiment was divided into two sessions: one in which the subject was able to freely move their arm and the other in which the subject had their arm fixated to the chair armrest. The intention of the second session was to isolate the contribution of pure neural drive by minimizing the effects of skin stretching and sliding of the muscles under the skin and shifting the active area with respect to the electrodes. The training was carried out with the support of a GUI (developed for this purpose and seen in Fig. 2). This interface enables the visualization of BBM activation as a sEMG map (Fig. 2a). Each tile of the map represents the RMS of the last collected time window (200 ms) by a single channel. Collectively, the tiles form a 6x5 matrix. The lateral centre of gravity (COG), as calculated in the formula, was chosen as the representative measure of differential sEMG activation in the lateral dimension.

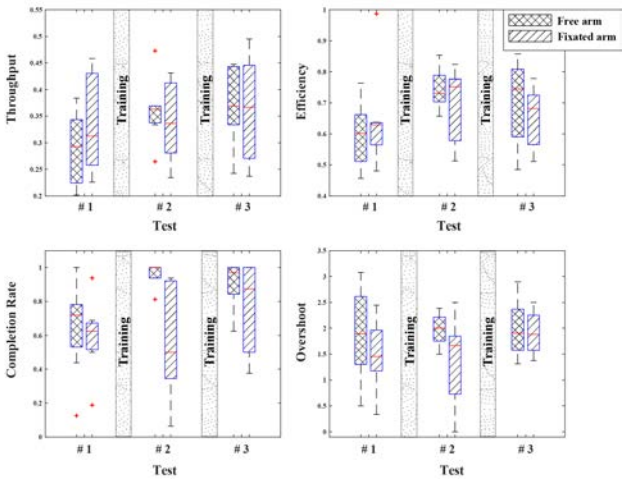

Figure 3: Box plots showing the results of the Fitts' law tests. Two different sessions were run for each subject: one with non-fixated arm (NF) and one with the arm fixated to the arm rest (F). Three Fitts' law tests were run per session (Trial #1, #2 and #3). Each box represents the spread across subjects of the four performance metrics of the Fitts' law test. Starting from the top left corner and proceeding counterclockwise: throughput, efficiency, overshoot and completion rate.

$$COG = \frac{\sum_{(i,j)} jM(i,j)}{\sum_{(i,j)} M(i,j)}$$

Where the notation $M(i,j)$ denotes the pixel value at row *i* and column *j* of the sEMG map *M*.

The COG at quiet state defines the reference bar while the turquoise bar is located by the COG of the currently displayed map. The training component of this GUI consists in controlling the movement of the black sliding bar (left or right) by shifting the turquoise bar. For instance, stronger activation of one of the BBM's head will result in a shift of the COG towards it, consequently the black sliding bar will move in that direction. Each biofeedback training session lasted 40 minutes, during which the subjects alternated between free training and a Fitts' law [16] based scoring task. During the free training, subjects were instructed to experiment with different postures and varying strengths with the purpose of moving the sliding bar left or right. No other instruction was given on how to perform the training. Three Fitts' law tests were performed at 5, 20 and 35 minutes into the training session. The test required the subject to move the sliding bar of the biofeedback GUI to a randomly generated goal area of a predefined width (2 possible values) within a timeout period (15s) and hold it within the area for a certain dwell time (2s). Two repetitions of four possible distances per width were performed, giving rise to 16 repetitions per test.

2) Patterns of BBM activation

The second experiment consisted in recording EMG activity from the BBM during eight different upper limb tasks (hand opening, hand closing, hand extension, hand flexion, forearm pronation, forearm supination, elbow extension, elbow flexion) in order to assess whether, and to what extent, there is differential activation between the two heads of the BBM. The pattern measurements were performed using the "Recording Session" GUI of BioPatRec. No control of the contraction force was performed but the subject was asked to contract at what they perceived to be 70% of the maximal voluntary contraction force. All tasks except the elbow extension and flexion were performed with the forearm resting on the lap to avoid any activation of the BBM from keeping the forearm elevated. Isometric elbow extension and flexion were performed with the forearm neutrally pronated and the elbow approximately 90° flexed using the desk to inhibit movement. Each task was repeated five times with a contraction time of three seconds and three seconds of rest in between contractions with an added non-recorded dummy contraction to help prepare the subject. The recording session was performed three times in total to allow the subject to get used to the recording procedure and only the results from the last session were used.

III. Analysis

A. Analysis of biofeedback training

The first experiment consisted of biofeedback training, which the effect was measured using Fitts law test. The following performance metrics were collected: completion rate (percentage of completed repetitions); overshoot (average number of times the target was acquired and then lost per repetition); efficiency (ratio between length of optimal path and the taken path) and throughput (general measure of performance) as calculated in [17]. Statistical analyses were performed with a 2-way Anova for unbalanced design since not all the subjects completed all trials successfully. Post-hoc multiple comparisons were performed only when statistical significance was found. Bonferroni method was used as correction to obtain the same equivalent relevance of a p-value < 0.05.

B. Analysis of activation patterns

The second experiment was aimed at the study of the activation patterns of the BBM. This was carried out with a cluster analysis of the COGs of each movement. The COGs (x and y coordinates) were calculated from a sEMG map. In this case, each movement repetition was deprived of the first and last 15% of the samples in order to avoid transients in the EMG. The repetitions were then concatenated and the signal segmented with an overlapping time window of 1 s. This yielded a total of 115 windows per movement and channel. The RMS was then computed to form the sEMG map and eventually result in 115 COGs per movement. To verify the hypothesis of differential activation of the BBM, we conducted a subject wise analysis of the separability of clusters representing different movements. To determine whether patterns recur in different subjects, we conducted a task-wise analysis were each cluster represented the activation of a subject. The main metric used was the Separability Index (SI) as suggested by Nilsson et al. [30]. The SI was based on the Bhattacharyya distance which is a measure of the distance between two statistical distributions. Both the Bhattacharyya distances and SIs were calculated using the appropriate functions integrated in BioPatRec. An average of all the SIs was computed to give a measure of the average separability of the tasks for each subject.

IV. Results

A. Biofeedback training

The results of the biofeedback training are presented in Figure 3 using box plots. The edges of each box represent the 1st and the 3rd quartile, the whiskers indicate the data range and the red crosses possible outliers. Each boxes represent the spread across subjects of the average values of one particular performance metric. In both sessions, all metrics showed an improvement except for overshoot, which presented a slight increase. The statistical analysis found significant difference only for the completion rate, both between sessions ($p=0.004$) and among trials ($p=0.043$). Pairwise comparisons showed that the marginal means of trial 1 and 3 where statistically different ($p=0.037$).

B. Activation patterns

Figure 4 shows cluster scatter plots of each movement, where separable clusters imply distinct pattern of activation among subjects. Figure 5 shows box plots summarizing SIs for individual subjects, and all subjects combined. The box plots for the individual subjects indicates that some clusters are separable (SI > 1), but such separability disappears when all subjects are grouped together, which indicates that patterns of activation are highly individual.

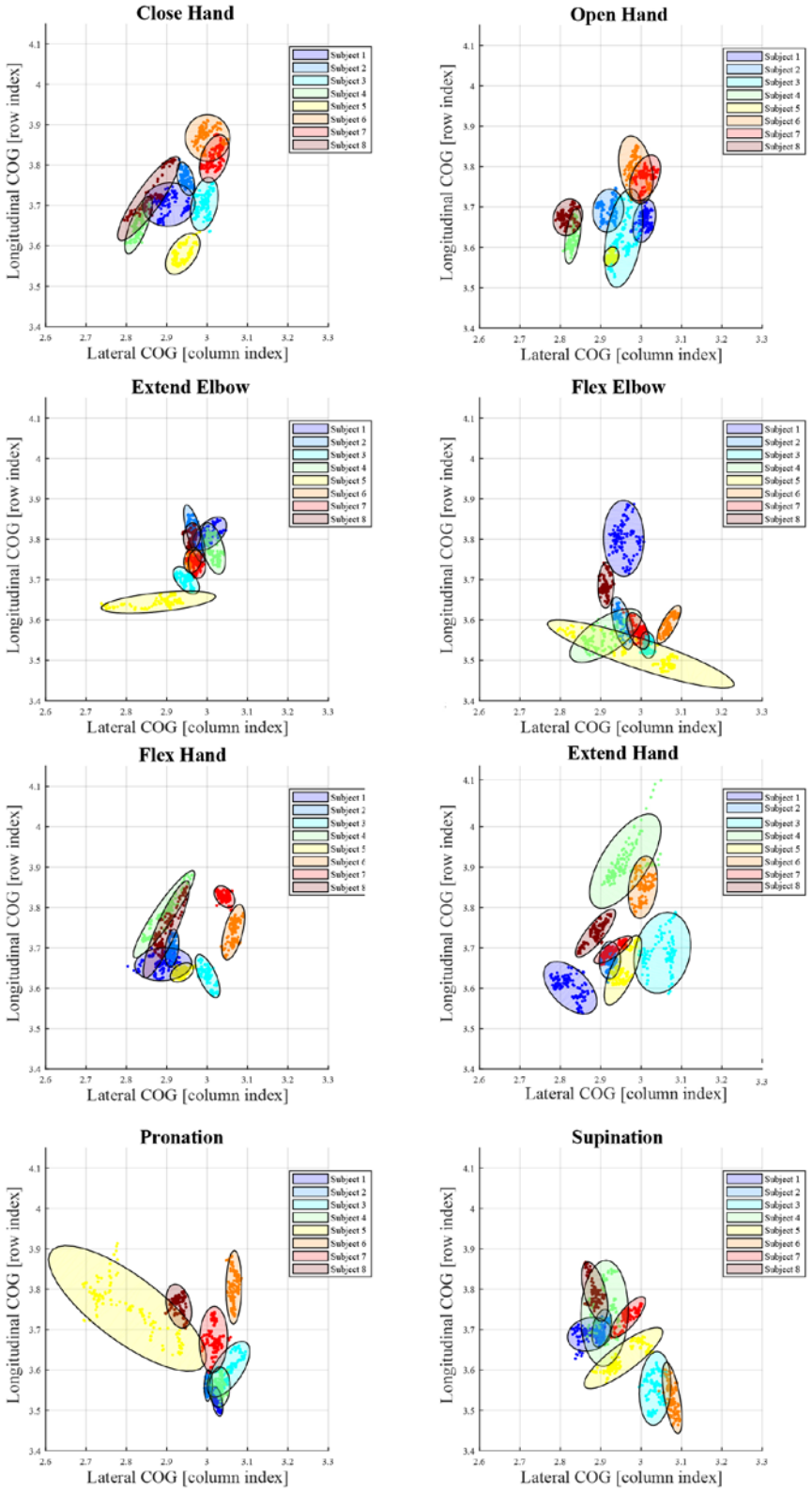

Figure 4: Cluster scatter plots of the different movements performed during the second part of the experiment. The points plotted represent the center of gravity (COG) during a time window of 1 second. Each cluster represents a subject, the same color represents the same subjects across the different scatter plots. The units of the axes represent the index of the column or row of the EMG map, as it has been used for the calculation of the COG.

V. Discussion

Most subjects showed improved control over the myoelectric COG between the two heads of the BBM. This indicates that the biofeedback training allowed them to intentionally differentiate the activation of the two heads in this muscle. All the metrics improved from trial 1 to 3, with exception of the overshoot. This might be due to an increase in speed of the sliding bar as the subject acquired better controllability. It is worthy of notice that the session conducted with the free arm yielded significantly better results than when the arm was fixated. This possibly indicates that part of what we observed and interpreted as shift in the COG might be due to displacement of the muscular bulk under the skin and to cross-talk. A way to overcome this potential methodological limitation would be to record the myoelectric signals using intramuscular electrodes. Another limitation of this study was the length of the training, as each subject received biofeedback for only 40 minutes per condition. Longer training time could had yielded improved controllability. A further limitation is the lack of exact measurement of contraction force: subjects were merely asked to maintain the contraction strength around what they perceived as 70% of their maximal voluntary contraction force. This limit the strength of the results as contraction force affects the recruitment of motor units, which in turn characterize the EMG pattern.

The cluster analysis for distal movements showed that all the subjects had a varying degree of task-depended activation. However, it also clearly emerged that the patterns are highly individual. The COGs coordinates of the HD-sEMG map was used to represent the activation of the BBM. However, other methods such as cluster analysis of the most active electrodes, or analysis of cross-correlation matrixes of the different channels, represent analysis alternatives worth further exploration.

VI. Conclusion

In this study, we have shown that real-time myoelectric feedback can be used to train subjects to activate portions of the same muscle at different strengths and we make a case for the viability of biofeedback training to enhance motor learning. Further work is needed to translate this work into clinically useful technologies.

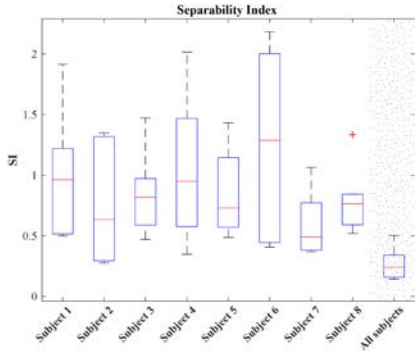

Figure 5: Box plot of the Separability Index (SI) spread for individual subjects and all subjects combined (far right). Values of SI > 1 are generally sign of good separability. "All subjects" represents the SI of task clusters formed by COGs formed by all the subjects.

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