Combined surface and intramuscular EMG for improved real-time myoelectric control performance

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Abstract

The four main functions that are available in current clinical prostheses (e.g. Otto Bock DMC Plus®) are power grasp, hand open, wrist pronation and wrist supination. Improving the control of these two DoFs is therefore of great clinical and commercial interest. This study investigates whether control performance can be improved by targeting wrist rotator muscles by means of intramuscular EMG. Nine able-bodied subjects were evaluated using offline metrics and during a real-time control task. Two intramuscular (targeted) and four surface EMG channels were recorded concurrently from the right forearm. The control was derived either from the four surface sources or by combining two surface channels combined with two intramuscular channels located in the pronator and supinator muscles (combined EMG). Five metrics (*Throughput, Path efficiency, Average Speed, Overshoot* and *Completion Rate*) were used to quantify real-time performance. A significant improvement of 20% in *Throughput* was obtained with combined EMG (0.90 ± 0.12 bit/s) compared to surface EMG alone (0.75 ± 0.10 bit/s). Furthermore, combined EMG performed significantly better than surface EMG in terms of *Overshoot*, *Path Efficiency* and offline classification error. No significant difference was found for *Completion Rate* and *Average Speed.* The results obtained in this study imply that targeting muscles that are involved in the rotation of the forearm could improve the performance of myoelectric control systems that include both wrist rotation and opening/closing of a terminal device.

Keywords: Fitts' Law test, targeted EMG, pattern recognition, intramuscular EMG, real-time control, wrist rotator

1. Introduction

The use of surface recordings in the control of upper limb prosthetic devices dates back for decades [1]. Clinically available prostheses make use of conventional control schemes that include proportional control, in which the velocity of a selected prosthesis function is proportional to the level of the myoelectric activity [2]. Direct control can be simple and intuitive if the control sites can be selected so that each function corresponds to the physiologically appropriate muscle. However, to implement one physiological degree of freedom (DoF) intuitively, two independent signal sites are needed. This is one of the main reasons why current commercially available prosthetic devices only provide very few controllable DoFs. To overcome this limitation, two main research streams have emerged; pattern recognition [3-10] and model based force estimation [11-16] of multiple DoF, with the main purpose of increasing the amount of information extracted from muscle signals and to eliminate the need for isolated EMG signals.

The performance of pattern recognition based control schemes has been sufficiently demonstrated in the literature that the main focus has now largely shifted to considerations about clinical robustness [17,18]. In this regard, researchers are investigating the clinical usability of pattern recognition with studies related to the influence of proportional contractions [19], limb position [20,21] and electrode shift [22] on pattern recognition, just to mention some of the challenges that face these types of systems [17]. Other studies have focused on the ability of pattern recognition to resolve dynamic [23] and simultaneous [23,24] movements, as a necessary step to assess its potential use and added value compared to the current clinical use of conventional control schemes.

Joint EMG – torque models have shown high correlation between features of the EMG and joint torque, with high predictive capability during single and simultaneous DoF [11-16]. In general, the estimators have proven able to track the torque profile well with a coefficient of determination (R^2) above 0.9. Furthermore, usability studies combining pattern recognition and proportional control with real time feedback of user performance, have also been reported [25,26,27].

The four main functions that are available in current clinical prostheses (e.g. Otto Bock DMC Plus®) are power grasp (*PG*), hand open (*HO*), wrist pronation (*WP*) and wrist supination (*WS*). Improving the control performance of these two DoFs is therefore of great clinical and commercial interest. Despite high overall classification accuracies and R^2, *WP* and *WS* have challenged classification schemes as well as force estimation using surface and untargeted intramuscular EMG [13,23,29], mainly due to the fact that the primary muscles of these movements are deeper in the forearm than the muscles that extend and flex the wrist. The solution has often been to use many electrodes in order to cover the entire circumference of the forearm and make maximal use of muscle crosstalk to improve performance. However, space, comfort and cost constraints limit the number of electrodes that can realistically be placed when fitting amputees clinically. Kamavuako et al. [15] showed that targeting the pronator and supinator muscles using intramuscular electrodes greatly improved the estimation of force during *WP* and *WS*. That analysis, however, was performed offline with no comparison to surface EMG and did not include user feedback.

The aim of this study was to assess whether including intramuscular EMG from the deeper pronator teres (*PT*) and supinator *(ST)* muscles improves the overall performance of a myoelectric control system using a Fitts' Law tracking test [29]. Fitts demonstrated that any human motor task conveys a finite amount of information that is limited only by the capabilities of the control system and exhibits a tradeoff between speed and accuracy. The control system combines pattern recognition and the ability to provide proportional control.

2. Materials and Methods

2.1. Subjects

The experiments were conducted on nine able-bodied subjects (7 male/2 female, mean age: 26.5 years old). The procedures were in accordance with the Declaration of Helsinki and approved by the University of New Brunswick's research ethics board. Subjects provided their written informed consent prior to the experimental procedures. All subjects had no history of upper extremity or other musculoskeletal disorders.

2.2. Data collection

The intramuscular EMG was recorded using two bipolar wire electrodes from the *ST* and *PT* muscles (hence the term targeted). Intramuscular wire electrodes were made of Teflon-coated stainless steel (A-M Systems, Carlsborg WA, diameter 50 µm) and were inserted into each muscle with a sterile 25-gauge hypodermic needle. The insulated wires were cut to expose 3 mm of the wire. The needle was inserted into each muscle and then removed to leave the wire electrodes inside the muscle. Muscle identification and needle guidance were confirmed using an ultrasound scanner (SonoScape A6, SonoScape Co., Ltd). Figure 1a shows the position of the *PT* muscle around one fourth proximal to the elbow. The *PT* muscle is seen between the brachioradialis and flexor carpi radialis, not as deep as the *ST* muscle. Figure 1b shows the position of the *ST* muscle with its half-circle like shape below the extensors. Intramuscular signals were analog bandpass filtered between 0.1 and 4.4 KHz. Surface EMG was recorded using four bipolar electrodes (Ag-Ag/Cl, Red Dot^{TM}, Canada) placed over the flexors and extensors compartment respectively. On the flexor side, one channel was placed over the flexor digitorum profondus (*FDP*) and flexor carpi ulnaris (*FCU*). On the extensor side, the other channel was placed over the extensor carpi ulnaris (*ECU*) and the extensor digitorum communis (*EDC*). These two surface channels were combined with the two intramuscular channels to create the *combined EMG* channels. Taking advantage of the large size of the electrode, care was taken to capture signals at the flexor compartment of the proximal forearm where the *PT* muscle is most superficial as confirmed by ultrasound. Based on the probe position shown in Figure 1a, sliding the probe more proximal to the elbow shows the *PT* muscle to be more superficial. Targeting the *ST* muscle is difficult using surface electrodes; however care was taken to place the channel at the shortest distance between *SP* and the skin. Surface EMG signals were analog bandpass filtered between 10 – 500 Hz. All signals were amplified (AnEMG12, OTbioelletronica, Torino, Italy), A/D converted using 16 bits (NI-DAQ USB-6259), and sampled at 10 kHz. A reference electrode was placed close to the carpus.

[Figure 1 about here]

2.3. Experimental procedures

EMG signals were collected during unconstrained contractions corresponding to *HO* and *PG* (DoF1), and *WS* and *WP* (DoF2). The experiment was carried out in two trials with a five minute rest in between. Subjects were prompted to elicit comfortable and sustainable contractions corresponding to five classes of motion; *WS*, *WP*, *PG*, *HO* and no motion. During training, two repetitions of 2 s were collected for each motion, during which the unconstrained subjects dynamically increased (ramped) from a low level contraction to a moderately hard level. Dynamic ramping during training has been shown to improve the robustness of proportion pattern recognition based control [19,30]. For the Fitts' Law test, subjects were required to move the cursor from a neutral position (axes origin) to a randomly ordered target location of distance, *D*, and width, W. The user was required to hold the cursor within the target for a full second (*dwell time*) in order for the test to be considered complete. If unsuccessful after 15 seconds, the test timed out and was considered incomplete. The user cursor was then reset to the neutral position between each test. DoF1 was used to control vertical movement (cursor up and down) while DoF2 was used to control horizontal movements (cursor left and right). As required by Fitts' Law, different indices of difficulties (*ID*) were tested, obtained by combining different target distances and widths as shown in Equation 1 and Table I.

[Table I about here]

$$ID = log_2(\frac{D}{W} + 1) \tag{1}$$

where *ID* is the index of difficulty (in bits), and *D* and *W* are the normalized units of distance and width, respectively.

Each *ID* was repeated twice per motion. A full trial included the concurrent collection of surface and intramuscular data for training, and separate completion of the Fitts' Law test using either the four surface channels (Surface EMG) or two channels of each type EMG as control signals (referred to as combined EMG). During combined control, the two intramuscular channels were combined with two surface channels (recording from *FCU/FDP* and *ECU/EDC* respectively). This selection was the same for both Fitts' test and offline data analysis. The selection order of the control signal was randomized.

After the Fitts' Law tests, more data were collected for offline analysis. Subjects were prompted to elicit comfortable and sustainable contractions corresponding to nine classes of motion; *WS*, *WP*, *HO*, *PG*, simultaneous *WS+HO*, *WS+PG*, *WP+HO*, *WP+PG* and no motion. Four repetitions of 2 s were collected for each motion, during which the unconstrained subjects held a medium level contraction to capture signals at a steady state. The purpose of collecting a larger offline data was to provide a basis for comparison with other offline pattern recognition studies.

2.4. Signal processing

Intramuscular and surface EMG signals were digitally high-pass filtered (3rd order Butterworth filter) with a cutoff frequency at 20 Hz to attenuate movement artifacts. Four time-domain features were extracted from signal intervals of 160 ms in duration (incremented by 16 ms); waveform length *(WL),* mean absolute value *(MAV),* zero crossing *(ZC),* and slope-sign change *(SSC)* [4]. Linear discriminant analysis (LDA) was chosen for classification. For the Fitts' Law test, the proportional control signal was derived from the same window by averaging the *MAV* values across all four channels used for each control strategy [25,31]. For the surface EMG based control, all four surface channels were used; and for the combined EMG based control, two surface and two intramuscular channels were used. The obtained value was mapped in order to control the velocity of the cursor in a given direction, as determined by the output of the LDA. The metrics used to quantify the performance of the test are shown in Table II.

[Table II about here]

For offline analysis, data were processed using a fourfold validation procedure. Each fold was comprised assigning one repetition as testing data and the remaining three repetitions as training data; the mean of the four classification errors was reported. The only difference between the control schemes was that in one case four surface channels were used and in another case two surface channels were combined with two intramuscular EMG. All other signal segmentation and processing was identical for both cases.

2.5. Statistics

For each performance metric the non-parametric Friedman's test was used to quantify the difference between surface EMG and the combined EMG based control. P-values less than 0.05 were considered significant. Results are presented as mean ± standard error.

3. Results

3.1. Offline data analysis

When tested on the five classes used for real-time assessment, the ensemble mean classification error was 4.14 ± 2.37 % for surface EMG, significantly higher than 1.08 ± 0.59 % for combined EMG ($P = 0.014$). For the nine class problem including combined motions, the difference was also significant ($P = 0.033$) between surface (9.33 ± 2.24 %) and combined EMG (5.42 ± 1.83 %).

3.2. Fitts' Law test

A strong linear relationship was found between *MT* and *ID* for both control schemes (coefficient of determination $R^2 > 0.92$), supporting the suitability of using Fitts' Law test (Figure 2).

[Figure 2 about here]

Throughput of combined EMG (0.90 ± 0.12 bit/s) was 20% and significantly ($P = 0.01$) higher than that of surface EMG (0.75 ± 0.10 bit/s). *Path Efficiency* using combined EMG (82.3 ± 2.9 %) was also significantly ($P = 0.002$) better than surface EMG (72.0 ± 4.5 %). Furthermore, significantly less *Overshoot* ($P = 0.017$) was observed with combined EMG (37.7 ± 8.6 %) compared to surface EMG (51.5 ± 7.1 %). Figures 3, 4 and 5 present subject performance for *Throughput*, *Path Efficiency* and *Overshoot* respectively, each normalized by the value obtained during combined EMG of that subject. Thus normalization is done on subject basis.

[Figure 3, 4 and 5 about here]

Completion rate for combined EMG (95.6 ± 1.7 %) was not significantly ($P = 0.07$) different from surface EMG (91.6 ± 3.5 %). *Average speed* was 41.3 ± 5.6 % and 45.6 ± 4.6 % for combined and surface EMG respectively, not significantly different from each other ($P = 0.2$). Figures 6 and 7 show the results for each subject, normalized by the value obtained during combined EMG on subject basis.

[Figure 6 and 7 about here]

4. Discussion

The aim of this study was to investigate whether targeting muscles that are involved in the rotation of the forearm could improve the performance of myoelectric control systems that include both wrist rotation and opening/closing of a terminal device. These two DoFs were selected and studied because they are the ones that are most often controlled in clinically available prostheses. The motivation for this investigation was to demonstrate the important contribution of deep muscles in movements where these muscles are required. This was evaluated using offline data analysis and a real-time tracking test based on Fitts' Law. It was possible to control the cursor using either only four surface channels or combined surface – intramuscular channels (targeted). High R^2 values obtained from regression plots of the Fitts' Law task confirmed that it is viable as a usability testing tool for velocity based myoelectric control research, as was previously shown [25,27]. This work advances, in a comparative manner, the assessment of intramuscular based targeted recordings for pattern recognition control, in the context of a real time usability test using a Fitts' Law approach.

Offline classification error, a commonly reported performance metric for pattern recognition approaches, showed that combining surface and intramuscularEMG was superior to surface EMG alone with similar classification rates as previously reported [15,30]. Real-time results showed that measuring from the supinator and pronator muscles greatly and significantly improved the *Throughput* of the control system. *Throughput* is known to describe usability through the tradeoff of speed and accuracy and, when averaged over the entire test, it is a convenient summary of performance [29]. Combined with the fact that no significant difference was found in *Average Speed*, it can be concluded that combined EMG is overall more accurate than surface EMG. When comparing the usability of intramuscular EMG and surface EMG, a recent study [27] showed significantly lower *Average Speed* using intramuscular EMG. The low speed was associated with issues arising from deriving a proportional control signal from the intramuscular *MAV* feature. In the current study, proportional control during combined control was derived by combining *MAV* feature from both surface and intramuscular EMG, which can explain why the *Average Speed* was not significantly different. Surface EMG incurs a low pass tissue filter effect, and so its amplitude correlates well with increased activity, thus providing better proportional control when measured by *MAV*.

One subject (subject 3) exhibited a contrary behavior where the *Throughput* of surface EMG was higher than that of combined EMG. Post-experimental analysis of the raw EMG data showed that, during the second trial, the wire electrodes that were initially placed in the supinator had dislodged into the extensor compartments. As a result, the signal from that particular electrode became weak during supination, affecting classification and proportional control. Wire displacement is a known issue when dealing with the supinator muscle [15] because the insertion is achieved almost perpendicularly through the extensor muscles. Depending on the displacement of the extensors during contraction, they may pull the wires in and out to some degree. This effect can be minimized by leaving a buffer of 'extra' wire outside the skin to allow transcutaneous movement, however this assumes that wires are sufficiently anchored in the targeted muscle. Anchoring can be obtained by twisting the needle before it is removed. If not properly anchored, the wire inside the supinator will be pulled out and does not return back after the contraction. Another scenario that can cause the pulling from the supinator is blood clots at the insertion point. In case of bleeding (usually from small vessels), during needle insertion, clots will be formed limiting the movements of the wires from the skin side, thus causing the wires to be pulled out from the supinator when the extensors contract. This supports the statement that a stable invasive interface is needed in order for invasive recordings to gain usability in the clinics [32]. The Throughput obtained in this study is lower compared to the study by Scheme and Englehart [25] most likely due to the experimental design. Scheme and Englehart used six surface EMG channels with highest ID of 3.46, while this study makes use of 4 channels with highest ID of 4.39.

When looking at the other descriptive metrics, combined EMG significantly outperformed surface EMG by providing better *Path Efficiency* and less *Overshoot*. *Path Efficiency* describes the ability to make correct classification decisions so that the changes in the direction of cursor during a test is minimized. It is unlikely that *Path Efficiency* was significantly affected by speed because both control schemes performed on average at similar speeds. Lower values for the *Overshoot* indicate that users were more effective at stopping on the target when using combined EMG than with surface EMG. Similar to *Path Efficiency*, this relates to the ability to make correct decision (particularly with respect to transitions to the "*no motion*" class) but also their ability to control the velocity of the cursor [27]. Similarly, *Average Speed* relates to the user's ability to travel to the target quickly before slowing down prior to target acquisition. A higher average speed, if not well controlled, may cause the cursor to move further in the wrong direction for each classification error or cause more overshoot. Given that there was no statistical difference in *Average Speed* between the surface and combined based control schemes, the results obtained confirm the efficacy of targeting wrist rotator muscles. There was no significant difference in *Completion Rate* between combined and surface EMG (partially due to high overall completion rates), but the average value for combined EMG was higher than that of surface EMG. Thus subjects were able to complete the tasks in both cases, but did so more efficiently using combined EMG.

Combined EMG has proven efficient for the following possible reasons: intramuscular EMG is less contaminated by crosstalk and provides stable control signals measured directly from deep muscles, while surface EMG incurs a low pass tissue filter and relies on a weaker signal or crosstalk to obtain signals from the deep muscles. However the risk of infection at the skin-lead wires interface has hindered the clinical use of implantable electrodes for control purposes. Although wireless implantable electrode systems [34,35] have shown promise, challenges in power transfer and bandwidth limitation have hindered the clinical deployment of these systems. Furthermore needle insertion may be uncomfortable for some subjects even for acute studies such as the present study; indeed, it is difficult to recruit volunteer subjects, especially amputees. It is nevertheless beneficial to perform such studies to provide insight into the performance of implantable systems. Alternatively, it was also encouraging for surface EMG applications that, when using only four surface channels, it was still possible to control the system well.

5. Conclusions

A real-time Fitts' Law testing approach was employed in this study in order to assess the contribution of targeted deep muscles for a control system that requires both forearm rotation and open/close of a terminal device. In general, it was possible to control the cursor using either four surface channels or a combination of two surface and two intramuscular channels. The combination of surface and targeted intramuscular EMG based control approach performed significantly better than surface EMG alone when compared using both offline and real-time metrics. These results therefore suggest that the *Throughput* (and by extension, overall performance) of myoelectric control systems that combine wrist rotation with a terminal device can be improved by targeting the associated muscles. However the results should be confirmed in future studies, including amputee subjects when possible.

Acknowledgements

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Figures

Figure 1

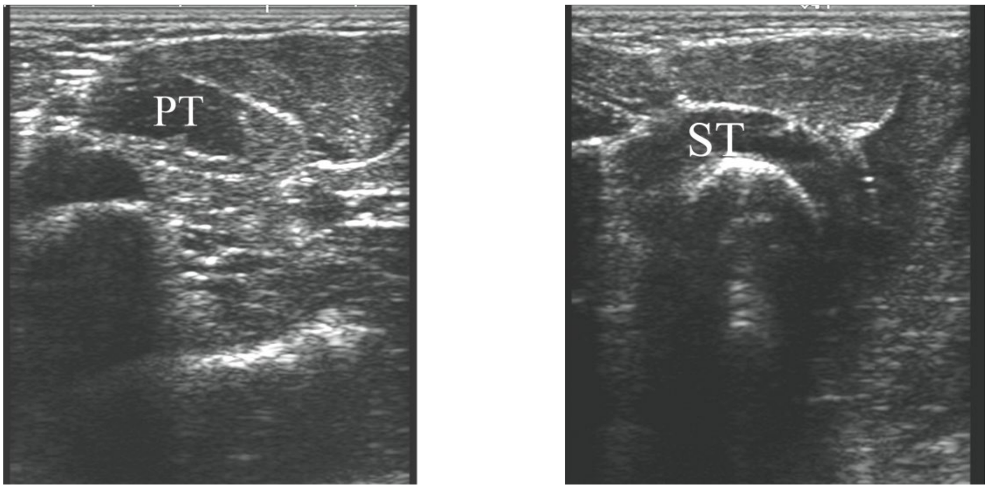

Figure 1a

Figure 1b

Figure l: Transversal Ultrasound images showing (a) the pronator teres muscle as indicated with PT and (b) the supinator muscle as ST.

Figure 2

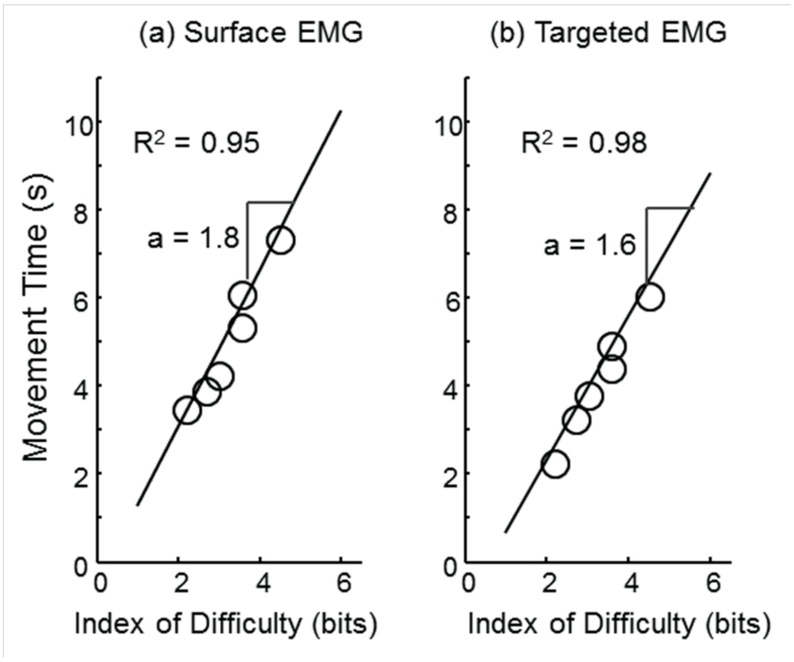

Figure 2: Relationship between movement time (MT) and index of difficulty (ID) for Surface and Combined EMG.

Figure 3

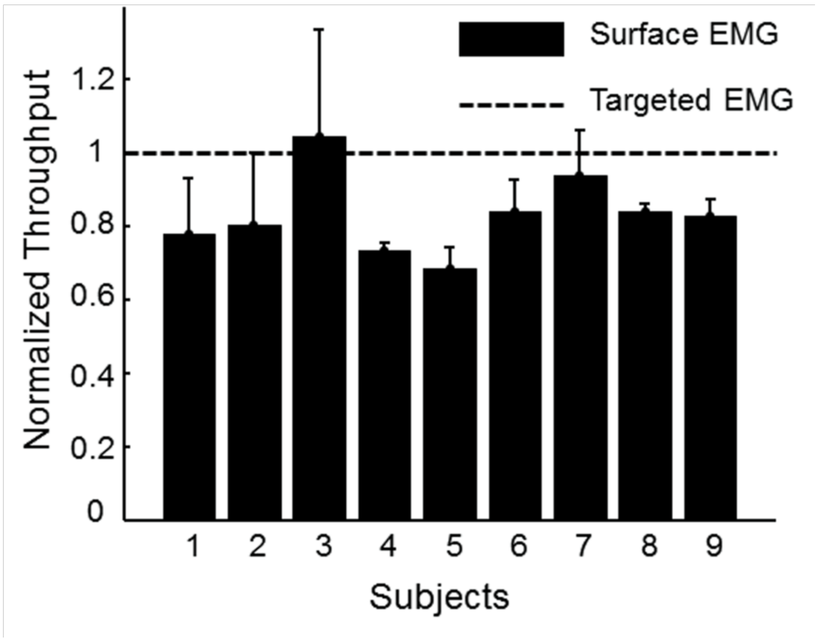

Figure 3: Surface EMG throughput values, expressed as a fraction of the each subject's combined EMG throughput. Bars represent the standard deviation of the two trials.

Figure 4

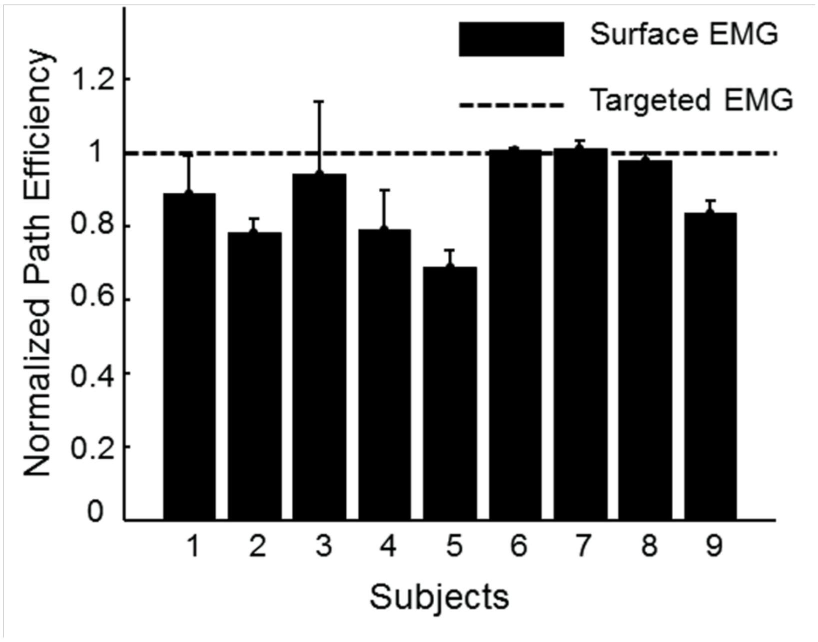

Figure 4: Surface EMG path efficiency, expressed as a fraction of each subject's combined EMG efficiency. Bars represent the standard deviation of the two trials

Figure 5

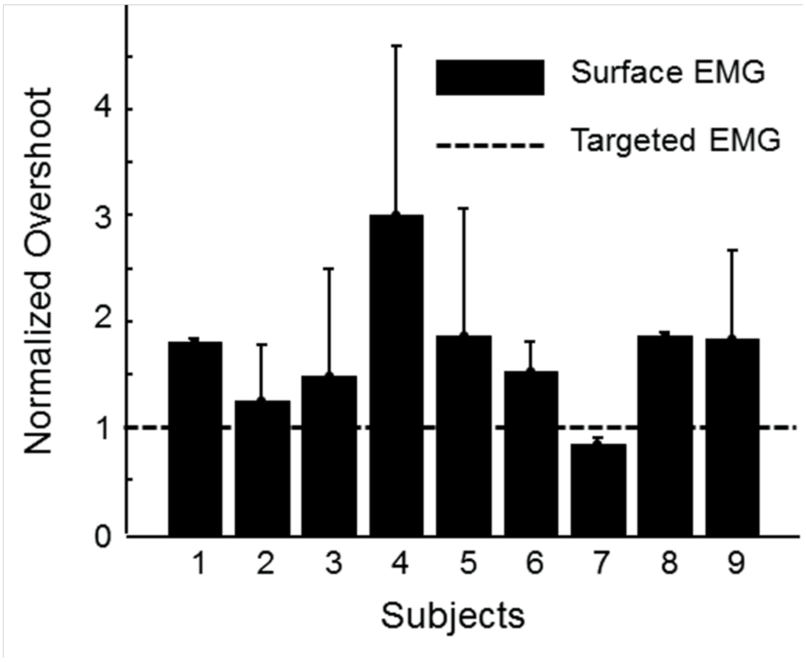

Figure 5: Surface EMG overshoot, expressed as a fraction of each subject's combined EMG overshoot. Bars represent the standard deviation of the two trials

Figure 6

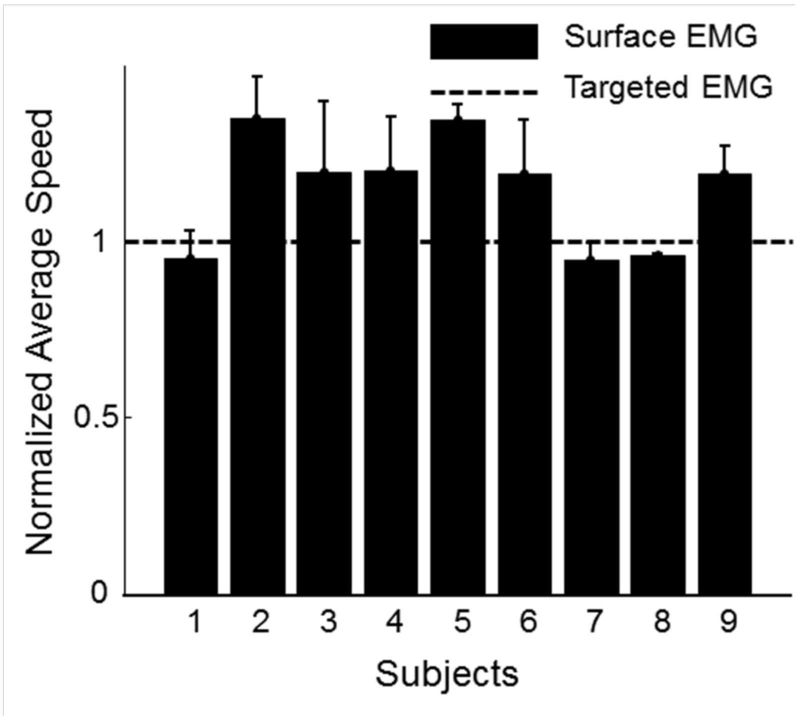

Figure 6: Surface EMG average speed, expressed as a fraction of the each subject's combined EMG average speed. Bars represent the standard deviation of the two trials

Figure 7

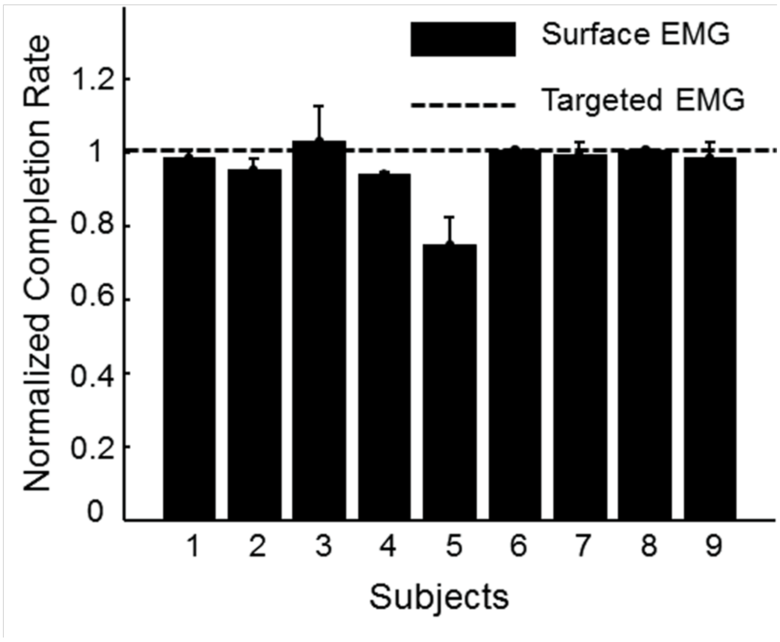

Figure 7: Surface EMG completion rate, expressed as a fraction of each subject's combined EMG completion rate. Bars represent the standard deviation of the two trials.

Tables

Table I

D	W	ID
50	5	3.46
50	10	2.59
50	15	2.12
100	5	4.39
100	10	3.46
100	15	2.94

Table I: Combinations of distances (D) and widths (W) with resulting indices of difficulty (ID)

Table II

Metric	*Description*
Throughput	Describes usability through the tradeoff of speed and accuracy and, when averaged over the entire test, it is a convenient summary of performance [30]. Throughput is mathematically defined as the ratio between the *ID* and movement time (*MT*), which is the time (in seconds) taken to acquire the target. It is a measure of the amount of information the subject can convey through a particular command source as it relates to the task.
Efficiency	Describes the systems quality of control. It is computed by dividing the straight line distance by the actual distance traveled [33].
Overshoot	Describes the ability to stop on a target. It is the number of occurrences of the cursor being on target and then leaving the target before the end of the 1-s dwell time (across all targets), divided by the total number of targets [33].
Average Speed	Describes the average nonzero speed of the cursor over the course of the trial; and illustrates the subject's gross ability to control the cursor [33].
Completion Rate	Describes overall success; the percentage of tests completed within the allowed time [26].

Table II: Performance Metrics Used for the Fitts' Law test

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