THE EFFECTS OF ELECTRODE IMPLANTATION AND TARGETING ON PATTERN CLASSIFICATION ACCURACY FOR PROSTHESIS CONTROL

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INTRODUCTION AND BACKGROUND: Many researchers have attempted to recognize patterns of muscle activity associated with different movements of the phantom limb and link these patterns to movements of the prosthesis. Researchers have examined a variety of different classifiers and extracted complex features from the electromyographic (EMG) signals to maximize classification accuracy. However, nearly all of these efforts used surface electrodes. Surface electrodes are advantageous because they are cheap, non-invasive and have a large pickup area. Extracting features from these recordings can allow the classifier to parse out the activity from the different muscles that sum together to produce the myoelectric signal and may increase the information available to the classifier.

Alternatively, intramuscular electrodes may be advantageous for multifunctional prosthesis control because they record focally from deep muscles, provide consistent recording sites as the user changes arm orientation or dons and doffs the prosthesis and reduce crosstalk. However, only two groups have investigated intramuscular EMG for pattern recognition based control [1-4] and only Hargrove, et al. [1] compared surface and intramuscular electrodes, recording from sixteen untargeted surface and six targeted intramuscular channels.

As well as almost solely utilizing surface electrodes, previous studies in pattern recognition-based multifunctional prosthesis control have either targeted the electrodes to specific muscles or used untargeted electrode arrays. However, no previous work has attempted to determine which approach is superior by directly comparing targeted and untargeted electrodes.

Untargeted electrodes are simpler to implement and are preferable for both intramuscular and surface recordings. Socket fabrication can be simplified if the surface electrodes only need to be arranged in an array instead of targeted to specific muscles. Additionally, targeting implantable sensors (such as the IMES [5]) to specific muscles is not a trivial task and would likely require approaches such as ultrasound guidance to properly orient the implants in specific muscle bellies.

Given that the effect of either electrode targeting or electrode implantation has rarely been examined, the goals of this work were to compare the classification accuracies of multifunctional prosthesis classifiers that use either surface or intramuscular EMG as well as those that use either targeted and untargeted electrodes. Further details are available in Farrell and Weir [6].

METHODS: The study investigated four different electrode conditions: targeted surface (TS) and untargeted intramuscular (UI) recordings were collected in one half of the experiment while targeted intramuscular (TI) and untargeted surface (US) data were collected in the other half. Eight proximal forearm muscles were chosen for the targeted electrode sites (Fig. 1).

The untargeted surface (US) and untargeted intramuscular (UI) electrode arrays were equally spaced around the forearm. The insertion depth of the untargeted intramuscular electrodes was varied based upon the size of the subject’s forearm and ranged from 1.5 to 2.0 cm. Closely spaced fine wire electrodes were used to acquire the intramuscular signals.

The targeted surface (TS) sites were located by finding the site that produced the largest amplitude signal as the subjects repeatedly produced movements specific to each targeted muscle.
(e.g., pronation was the test movement for pronator teres). The targeted intramuscular (TI) sites were primarily found via palpation and prior experience. Proper location of the intramuscular electrodes was verified by electrically stimulating the muscle and observing the induced movement.

Each of the eleven subjects (mean age 29 +/- 8 years; 7 males, 4 females) performed a series of trials in which they alternated between relaxing and performing one of twelve movements of the hand and wrist (Fig. 2). Four contractions were contained in each trial and four trails were collected for each movement. A four-fold cross-validation technique was used to increase the robustness of the classification accuracy estimate.

Time domain features (TD), auto-regressive coefficients (AR) and root-mean-square (RMS) data were extracted from each analysis window. Classification accuracy is dependent upon a number of different variables. Farrell [7] optimized each of these variables for the data collected in this study before comparing the effects of the different electrode conditions. The reported accuracies were obtained from a state-based linear discriminant analysis (LDA) classifier with overlapped 160 ms analysis windows (no majority voting) and training data that included the onset transient of each contraction.

Accuracies were calculated for feature sets that both included and excluded additional signal features (TD+AR). A two-factor, two-level (targeted/untargeted and surface/ intramuscular) repeated-measures ANOVA with Bonferroni correction was conducted on each data set.

Twelve different movement classes were chosen to make the classification problem difficult in an attempt to highlight the potential differences between the electrode conditions. However, current commercially available devices are not capable of producing the full set of twelve movements. Therefore, classification accuracies were calculated for smaller numbers of output classes to examine the potential differences in the electrode conditions for more currently clinically relevant problems. A two-factor (electrode type and number of classes) repeated-measures ANOVA was conducted on the resulting classification accuracies. The subsets were: 2, hand open/close; 4, hand open/close + wrist pronate/supinate; 6, hand open/close + wrist pronate/supinate + wrist flex/extend; and 8, hand open/close + all wrist movements.

![Figure 1 - Electrode sites: Targeted electrodes were located in/over the muscles shown and the untargeted electrodes (large black dots) were equally spaced around the forearm.](image1)

![Figure 2 – The twelve movement classes investigated in this study.](image2)
RESULTS: The average classification accuracies for each of the four electrode conditions classifying all twelve movement classes are shown in Fig. 3. When only EMG amplitude was used (Fig. 3A), the targeted surface (TS), targeted intramuscular (TI) and untargeted surface (US) conditions produced similar classification accuracies ($p = 1.000$) while the accuracies resulting from the untargeted intramuscular (UI) electrodes were significantly lower ($p < 0.02$). However, the ANOVA analyses found no difference between the electrode conditions when the additional signal features were employed ($p > 0.05$) (Fig. 3B).

The classification accuracies for the ‘clinically relevant’ subsets of output classes using all available signal features are shown in Fig. 4. The repeated-measures ANOVA results showed differences between the numbers of output classes ($p<0.0005$). However, post-hoc tests from the ANOVA found no differences between the electrode conditions ($p > 0.08$ for all comparisons).

DISCUSSION: Since classification accuracies can be substantially increased for all conditions by extracting additional signal features (compare figure 3A and 3B) and the relative cost of doing so is minimal, the results from the data using all available features will be used to address the primary goals of this paper. When additional features are extracted from the EMG signals, there were no statistical differences between the electrode conditions, i.e. similar classification accuracies were obtained from both 1) surface and intramuscular electrodes and 2) targeted and untargeted electrodes.

Targeting either type of electrode did not increase the classification accuracy. This data indicates that surface electrodes do not need to be placed over specific muscles and thus socket fabrication can be simplified by arranging the electrodes in a symmetric array around the circumference of the forearm. Also, since targeting the intramuscular electrodes to specific muscles did not improve
classification accuracy, procedures such as ultrasound guidance may not be necessary to target the electrodes if a pattern recognition-based control scheme is implemented. The similarity in the classification accuracies between surface and intramuscular recordings shows that intramuscular electrodes can perform as well as surface electrodes. Therefore, the choice of using implanted versus surface electrodes should be made, not based upon classification accuracy, but on other clinical factors. These clinical factors include comfort, cost, consistent electrode contact (i.e., surface electrode ‘liftoff’), invasiveness, signal consistency with donning and doffing, signal robustness and skin impedance changes.

**Class Subsets:** As expected, classifiers attempting to differentiate between smaller numbers of output classes tended to have higher classification accuracies for each electrode condition. Twelve output classes were used to make the classification problem difficult in an attempt to tease out differences between the electrode conditions. However, the analyses performed on the class subsets chosen using clinical criteria showed similar accuracies between the electrode conditions regardless of the number of output classes. Therefore, the conclusions from the previous section also hold for prostheses that utilize commercially available componentry.

**Summary:** From the point of view of strictly maximizing the classification accuracy, the untargeted surface electrodes provided similar classification accuracies to the other three conditions and did so with the lowest cost, invasiveness and difficulty in socket fabrication. However, good clinical performance encompasses more than having a high accuracy in a laboratory setting. These experiments did not account for: variable electrode positions as the user dons and doffs the prosthesis, motion artifacts, surface electrodes ‘lifting off,’ skin impedance changes throughout the day, other motions of the arm being conducted (i.e., flexion/extension of the elbow) while the hand/wrist are being controlled, etc. Intramuscular electrodes have the potential to address each of these clinical issues. These other sources of noise, etc., may affect the relative performance of each electrode condition differently, which could affect the relative advantages/disadvantages of each electrode. However, this study successfully provided a comparison of the electrodes in a laboratory setting and concluded that further investigation into the clinical advantages of the different electrodes is warranted.

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**REFERENCES:**


