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Estimation of distal arm joint angles from EMG and shoulder orientation for transhumeral prostheses

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ABSTRACT

In this paper, we quantify the extent to which shoulder orientation, upper-arm electromyography (EMG), and forearm EMG are predictors of distal arm joint angles during reaching in eight subjects without disability as well as three subjects with a unilateral transhumeral amputation and targeted reinnervation. Prior studies have shown that shoulder orientation and upper-arm EMG, taken separately, are predictors of both elbow flexion/extension and forearm pronation/supination. We show that, for eight subjects without disability, shoulder orientation and upper-arm EMG together are a significantly better predictor of both elbow flexion/extension during unilateral ($R^2 = 0.72$) and mirrored bilateral ($R^2 = 0.72$) reaches and of forearm pronation/supination during unilateral ($R^2 = 0.77$) and mirrored bilateral ($R^2 = 0.70$) reaches. We also show that adding forearm EMG further improves the prediction of forearm pronation/-supination during unilateral ($R^2 = 0.82$) and mirrored bilateral ($R^2 = 0.75$) reaches. In principle, these results provide the basis for choosing inputs for control of transhumeral prostheses, both by subjects with targeted motor reinnervation (when forearm EMG is available) and by subjects without target motor reinnervation (when forearm EMG is not available). In particular, we confirm that shoulder orientation and upper-arm EMG together best predict elbow flexion/extension ($R^2 = 0.72$) for three subjects with unilateral transhumeral amputations and targeted motor reinnervation. However, shoulder orientation alone best predicts forearm pronation/supination ($R^2 = 0.88$) for these subjects, a contradictory result that merits further study.

1. Introduction

In this paper, we quantify the extent to which different combinations of shoulder orientation, upper arm electromyography (EMG), and forearm EMG are predictors of distal arm joint angles during arm movements. Prediction of these joint angles is useful for enabling position-based control of upper-limb prostheses (Blana et al., 2015; Muceli and Farina, 2012; Jiang et al., 2012; Ameri et al., 2014; Ameri et al., 2014). In particular, the results of this study are important to improving simultaneous control of elbow flexion/extension and forearm pronation/supination in prostheses used by people with transhumeral amputations. A list of notation is given in Table 1.

1.1. Prediction of distal arm joint angles using EMG or shoulder orientation

Two prior studies have shown that shoulder orientation and upper arm EMG, taken separately, are predictors of both elbow flexion/extension and forearm pronation/supination. Pulliam et al. (2011) used EMG recordings from the upper arm and chest to predict the angles of the elbow and forearm simultaneously. Specifically, they implemented a time-delayed adaptive neural network (TDANN) to predict the angles of elbow flexion/extension (E_{FE}) and forearm pronation/ supination (F_{PS}) (Au and Kirsch, 2000; Kirsch et al., 2001). Their results showed that across multiple types of reaching movements (single-joint movements, single-joint movements with a load, simultaneous degree-of-freedom movements, and activities of daily living), the network could on average predict elbow flexion/extension within 10-15° and forearm pronation/supination within 20–25° of their actual values. A separate

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Table 1
List of notation.

Abbreviation	Meaning
EMG	Electromyography
TMR	Targeted Motor Reinnervation
E_{FE}	Elbow Flexion/Extension
F_{PS}	Forearm Pronation/Supination
TDANN	Time-Delayed Adaptive Neural Network
LWPR	Locally-Weighted Projection Regression
RMSE	Root Mean Square Error
R^2	Coefficient of Determination
SO	Shoulder Orientation
EMG_U	Upper Arm EMG
EMG_{U+F}	Upper Arm EMG + Forearm/Reinnervated EMG
SO+EMG_U	Shoulder Orientation + Upper Arm EMG
SO+EMG_{U+F}	Shoulder Orientation + Upper Arm EMG + Forearm/ Reinnervated EMG

study by Kaliki et al. (2008) suggests that when reaching, distal arm kinematics can be predicted by using shoulder orientation as the input to a cascade correlation neural network. In this study, subjects were seated and asked to reach to a vertical handle that moved to uniformly distributed positions in the subjects reaching workspace. Motion capture was used to determine the joint angles at the shoulder. Their network resulted in R^2 values above 0.7, denoting a strong correlation.

1.2. Combining EMG and shoulder orientation for prediction

Preliminary results from a single subject without disability have suggested that the combination of shoulder orientation and EMG can improve the accuracy of estimating distal arm joint angles (Akhtar et al., 2012). Blana et al. (2015) showed that subjects without disability could control a virtual arm using EMG and arm kinematics, suggesting that this combination of inputs could be feasible for prosthesis control. However, they did not quantify the extent to which this combination outperforms EMG and kinematic inputs individually, nor did they test their control strategy on subjects with amputations. In this paper, we compare the performance of our predictors for eight subjects without disability and three subjects with unilateral transhumeral amputations and targeted reinnervation when using shoulder orientation, upper arm EMG, forearm EMG, and combinations of these as inputs. In principle, these results provide the basis for choosing inputs for control of transhumeral prostheses, both by people with targeted motor reinnervation (when forearm EMG is available) and without reinnervation (when forearm EMG is not available).

1.3. Simultaneous control of multiple degrees of freedom

The results of this study are important in enabling simultaneous control of distal arm joint angles in upper limb prosthetic devices. Simultaneous control of multiple degrees of freedom in the arm are required to easily complete activities of daily living, such as pouring water from a bottle or reaching for objects (Muceli and Farina, 2012). Muceli and Farina (2012) and Jiang et al. (2012) have shown that wrist kinematics during mirrored movements of multiple degrees of freedom simultaneously could be predicted using neural networks from forearm EMG, which would be useful for people with transradial amputations to control a prosthetic hand. Ameri et al. (2014) used support vector regression and artificial neural networks to estimate multiple wrist joint angles and forces in subjects without impairment. Young et al. (2013) classified simultaneous hand movements using EMG-based pattern recognition. Our work looks at predictors for elbow and forearm joint angles from EMG and shoulder orientation in order to enable simultaneous control of prostheses for people with transhumeral amputations.

It should be noted that the prediction of the distal arm joint angles was done in an offline context—data collected from subjects were not used in real-time for myoelectric control. Jiang et al. (2014) have shown that when simultaneous control of hand kinematics is performed online in real-time, predictors that performed significantly differently in offline studies gave similar performances in online tasks, with respect to R^2. We discuss this limitation of our study in Section 4.4.

1.4. Outline of paper

The paper is organized as follows. In Section 2, we explain the methods used for acquiring upper arm EMG and arm joint angles during reaching, as well as the predictors we use for estimation. In Section 3, we present the results of the predictors in estimating the distal arm joint angles using different inputs consisting of EMG, shoulder orientation, and their combinations. We give recommendations on choosing inputs for transhumeral prosthetic controllers as well as discussing the rationale for these recommendations in Section 4, followed by our overall conclusions in Section 5.

2. Methods

Eight adult subjects (ages 20–25, four male, four female) without disability and three adult subjects (ages 28–48, three male) with unilateral right transhumeral amputations and targeted motor reinnervation (TMR) surgery volunteered for the experiments. Subjects were asked to perform a standard center-out reaching task (Blana et al., 2015; Pulliam, 2013), simultaneously actuating elbow and forearm joint angles to achieve various target arm configurations (Fig. 1). Subjects without disability were used as controls and performed two experiments on separate days. In the first experiment, the control subjects were asked to make unilateral reaches with their right arms, while in the second experiment they were asked to make mirrored bilateral reaches. Finally, the TMR subjects participated in an experiment in which they were asked to perform mirrored bilateral reaches as though both of their arms were unimpaired. Further details for the three experiments are given below. All subjects gave informed consent to participate in this research study and to have their data published. The study was approved by the Institutional Review Board at the University of Illinois at Urbana-Champaign (IRB #12823).

2.1. Experimental setup

2.1.1. Control: unilateral reaches with ipsilateral EMG placement

The control subjects were seated in a chair, placing their right forearms on their laps, palms down, elbows bent at 90° with respect to the humerus. Subjects were asked to make four types of center-out reaches, as shown in Fig. 1(a). The reaching types can be described as (1) full length, forearm supinated (open hand with thumbs pointing up), (2) half length, forearm supinated, (3) full length, forearm pronated (open hand with thumbs pointing down), and (4) half length, forearm pronated). The subjects were asked to perform each type of reach to four mediolateral locations at three heights for a total of 12 reaches per type (Fig. 1(b)). The four mediolateral locations were across the body, directly in front, 45° lateral to the front, and directly out to the side. The heights were at waist, shoulder, and eye levels. Subjects were asked to hold the reach for a count of three seconds before returning to the start position. As soon as the subject completed the 12 reaches for a particular type, recording stopped. All 48 of these reaches were repeated twice. The first set of 48 reaches was used as the training