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Short communication

A biomechanics-based method for the quantification of muscle selectivity in a musculoskeletal system

Jun Yao[a], Ana Maria Acosta[a], Julius P.A. Dewald[a,b,c,d,*]

[a]Department of Physical Therapy and Human Movement Sciences, Northwestern University, IL, USA
[b]Department of Physical Medicine & Rehabilitation, Northwestern University, IL, USA
[c]Department of Biomedical Engineering, Northwestern University, IL, USA
[d]Sensory Motor Performance Program, Rehabilitation Institute of Chicago, IL, USA

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Abstract

In this paper, we have developed a novel and simple method to quantify the ability to selectively activate our muscles in an effective pattern to achieve a particular task. In the context of this study, we define an effective pattern as that in which muscles whose mechanical contribution to the task is greatest, are mostly active, while the antagonist muscles are mostly silent. This new method uses biomechanical parameters to project the multi-channel EMGs into a three-dimensional artificial torque space, where the EMGs are represented as muscle activation vectors. Using the muscle activation vectors we defined a simple scalar, the muscle selection index, to quantify muscle selectivity. We demonstrate that by using this index we are able to quantify the muscle selectivity during the generation of isometric shoulder or elbow torques in brain-injured and able-bodied subjects. This method can be used during both static and dynamic motor tasks in a multi-articular musculoskeletal system.

Keywords: Muscle selectivity; Musculoskeletal system; Multi-joint motor tasks; Muscle coordination; Brain injury

1. Introduction

The human musculoskeletal system is a redundant system, with more muscles involved in the generation of torque than the number of degrees of freedom (DOF) of the joint (Bernstein, 1967). The main implication from a motor control standpoint is that we can generate the same joint torque with an infinite combination of muscle activation patterns. Individuals can thus use different muscle activation patterns to achieve a motor task, which may or may not be effective. Previous studies have shown that a lack of muscle selectivity is commonly expressed in subjects with brain injury (Beer, et al., 1999; Dewald and Beer, 2001; Dewald et al., 1995, 2001) or during motor learning (Osu, et al., 2002). In these studies, electromyographic recordings (EMG) are widely used as measures of the muscle selectivity. However, it is difficult to interpret the data due to the large number of the EMG recordings that are usually obtained.

In this paper, we introduce a new method, which provides a novel and simple tool to quantify the muscle selectivity using multi-channel EMG data. We will demonstrate the ability of our method to quantify muscle selectivity during static shoulder and elbow torque generation.

2. Methods

2.1. Quantification of muscle selectivity

Muscle activation results in joint torque generation in multiple DOFs. In order to show the muscle selectivity

*Corresponding author. Department of Physical Therapy and Human Movement Sciences, Northwestern University, 645 N. Michigan Ave, Suite 1100, Room 1159, Chicago, IL 60611, USA. Tel.: +1 312 908 6788; fax: +1 312 908 0741.

E-mail address: j-dewald@northwestern.edu (J.P.A. Dewald).

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of a specific torque generation task, we project each of the EMGs to a muscle activation vector in the corresponding torque space. In this study, we examined shoulder/elbow torque generations; therefore, we defined an artificial three-dimensional (3D) torque space composed by elbow flexion/extension (EF/E), shoulder flexion/extension (SF/E), and shoulder abduction/adduction (SABD/ADD). In this space, we assigned a unit action vector ($\vec{d}$) representing the mechanical action of the muscle. The unit action vector was computed as follows:

$$\vec{d} = \frac{\vec{r} \times \vec{F}}{||\vec{r} \times \vec{F}||}, \tag{1}$$

where $\vec{r}$ is the moment arm and $\vec{F}$ is the unit line of action vector for each muscle. These biomechanical parameters were extracted from the Dutch shoulder and elbow model (DSEM (van der Helm, 1994)). The unit action vector describes the direction of the contribution from each muscle to the torque generation in the defined space. The contribution of each muscle was further weighed by its physiological cross-sectional area (PCSA) and scaled by the corresponding normalized EMG amplitude to account for muscle strength and its activation during the task. The muscle vector ($\overrightarrow{\mathrm{MV}}$) for the ith muscle during a motor task is, therefore, defined as

$$\overrightarrow{\mathrm{MV}}_i(t) = \sum_{i=1}^{I} \vec{d}_i \cdot \mathrm{PCSA}_i \cdot \mathrm{EMG}_i^{\mathrm{norm}}(t), \tag{2}$$

where PCSA_i is the normalized physiological cross-sectional area for the ith muscle, and $\mathrm{EMG}_i^{\mathrm{norm}}(t)$ is the ensemble average of the rectified, low-pass filtered and normalized EMG from the ith muscle over all trials for the same task. (Note: Subjects performed multiple (60) trials for each task.) In this study, we normalized the EMG from each muscle to its maximum value obtained during the maximal voluntary torque generation in each of the six directions (i.e., SF/SE, SABD/SADD and EF/EE). The muscle unit vector and physiological cross-sectional area for each of the nine muscles investigated are listed in Table 1. When normalizing PCSA, we separated the investigated muscles into four groups, i.e., elbow flexors (BIC and BRD), elbow extensors (TRILA and TRILO), shoulder abductors (ADL, IDL and PDL), shoulder adductors (PMJH, PMJV) and normalized the PCSA to the sum of PCSAs of each of the muscles within the group. The resultant muscle vector ($\overrightarrow{\mathrm{rMV}}$) for a specific task is defined as the sum of all $\overrightarrow{\mathrm{MV}}$s, i.e., $\sum_i \overrightarrow{\mathrm{MV}}_i(t)$.

In order to quantify the muscle selectivity, we defined the muscle selection (MS) index as follows:

$$\mathrm{MS}(t) = \frac{||\sum_i \overrightarrow{\mathrm{MV}}_i(t)||}{\sum_i ||\overrightarrow{\mathrm{MV}}_i(t)||}. \tag{3}$$

It is clear that MS is a scalar ranging from 0 to 1. An MS index close to 1 indicates a high degree of muscle selectivity during a motor task, i.e., only the muscles that contribute to the specific torque direction are activated. (Note: a MS index equals to 1 cannot be achieved because virtually all torque generation tasks are associated with at least some antagonist co-activation that is expected to lead to a quantity smaller than one.) An MS close to 0 indicates a lesser degree of muscle selectivity, i.e., muscle co-activation/co-contraction is present during the motor task. The MS index takes into account the presence of both single- and multi-joint muscle co-activations.

2.2. Experiment

Nine subjects with chronic hemiparetic stroke and five control subjects participated in this study. All the control subjects are right-hand dominant and have no history of neurological illness. The subjects gave written informed consent prior to participation in the study.

During the experiment, subjects were casted at the wrist and secured to a six DOF load cell with the shoulder at a 75° abduction angle and a 40° flexion angle, and the elbow at an angle of 90° with 0° representing full extension.

Subjects were asked to generate 25% of the maximum voluntary SABD or EF torque using their impaired arm (stroke subjects) or right arm (control subjects) within 2 s after appearance of a visual cue, and to maintain it for a period of 0.3 s. Each subject repeated the same task 60 times in blocks of 20 trials with 30-s rest periods between individual trials and 5-min rest periods between blocks to avoid fatigue. Online visual feedback of the SABD or EF level was provided.

During the torque generation (i.e., starting from the appearance of the visual cue to 2 s later), the forces and torques generated at the wrist were measured and converted online to reflect the torques at the shoulder and elbow. Simultaneously, EMGs from nine muscles (biceps brachii (BIC), brachioradialis (BRD), triceps brachii lateral head (TRILA), triceps brachii long head (TRILO), anterior- (ADL), intermediate- (IDL), posterior-deltoid (PDL), and pectoralis major vertical and horizontal fibers (PMJV and PMJH)) were recorded for further analysis.

3. Results

The group mean and standard error of normalized EMGs in stroke and control subjects are shown in Fig. 1. One-way ANOVA (group) analysis showed that the activities of BIC in stroke subjects during the generation of SABD were significantly greater than that observed in control subjects ($p < 0.0001$), which suggests a higher