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Co-contraction of antagonist muscles during knee extension against gravity: Insights for functional electrical stimulation control design

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Abstract— **Functional electrical stimulation (FES) involves electrically stimulating the neuromuscular system to generate skeletal muscle contractions in paralyzed muscles. Several new FES applications have been proposed that require closed-loop control systems. Co-contraction of antagonist muscle groups has been postulated as a promising approach for closed-loop control of FES systems. However, this control approach has not yet been used in practical FES applications, in part due to a lack of information concerning how able-bodied subjects use co-contraction of antagonist muscles during standard control tests such as unit step and sinusoidal responses. The purpose of this work is to elucidate how able-bodied individuals use co-contraction by analyzing the EMG activity of antagonist muscles during voluntary knee extension against gravity. The results clearly demonstrate that able-bodied subjects use a co-contraction strategy when executing standard control performance tests, and strengthen the argument for using a co-contraction strategy for closed-loop FES control algorithms. These data will inform the development of new and effective controllers for FES applications.**

I. INTRODUCTION

Restoring motor function to individuals who have spinal cord injuries (SCI) is a priority in the field of rehabilitation engineering. The most commonly used technology for accomplishing this goal is functional electrical stimulation (FES), which involves electrically stimulating the neuromuscular system to generate skeletal muscle contractions. These contractions can be coordinated to produce functional outcomes. FES has been used for a wide range of applications in individuals with SCI, including facilitating standing [1], providing cardiovascular exercise [2], and reinforcing gait patterns during walking [3]. However, several new FES applications have been proposed that require the system to work autonomously, including neuroprosthesis systems for precise grasping, balancing during standing, and torso control during sitting, and FES-assisted walking. Such autonomous FES application will use closed-loop control systems that work with minimal user intervention.

Co-contraction of antagonist muscle groups has been postulated as a promising approach for closed-loop control of FES applications [4]. The joints of individuals who have SCI are often underdamped due to muscle atrophy. However, co-contracting the antagonist muscle groups that actuate a joint effectively stiffens the joint, thereby improving its damping. This increased damping causes the dynamics of the controlled joint to more closely resemble those of an able-bodied person. However, this control approach has not been used in practical FES application to date, in part because of a lack of information to inform the control design concerning how able-bodied subjects use co-contraction of antagonist muscle groups during standard control tests such as unit step response and sinusoidal response.

The purpose of the work described in this paper is to elucidate how the neuromuscular control system in able-bodied individuals regulates co-contracting muscles by analyzing the activity of antagonist muscles during voluntary knee extension against gravity. Knee extension against gravity is a commonly used test bed for designing closed-loop FES control systems. The results of this work will inform FES control design algorithms that use co-contraction. We recorded the electromyogram (EMG) of the knee flexors and extensors during standard control systems tests, namely maximum velocity knee extension (which corresponded to a unit step response test) and sinusoidal tracking. The EMG of a muscle is proportional to the tension produced in that muscle during a contraction, and yields information about the amount of co-contraction between two or more muscle groups. These co-contraction data will inform how artificial controllers should be regulating co-contracting muscles during electrically stimulated muscle contractions in autonomous FES applications. Importantly, the data collected during standard control tests of knee extension against gravity can be generalized to functional movements and other joints.

II. METHODS

A. *Experimental Apparatus*

The experimental apparatus consisted of a padded bench, a dual-camera motion tracking system (Optotrack 3020, Northern Digital Inc., Waterloo, Canada), an electromyogram (EMG) recording system (Bagnoli-8, Delsys Inc., Boston, USA), and a data collection computer. The padded bench allowed the subject to sit with his or her feet suspended off the ground so that the knee was free to move.

The motion tracking system used small adhesive, reflective dots that were affixed to the subject's body at specific points, as described in the following section. The cameras tracked the motion of these dots, and the motion tracking software converted this camera data into Cartesian coordinate data for each of the dots. The sampling rate for the motion tracking system was 100 Hz. The EMG recording

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system used adhesive, single-use electrodes and sampled the EMG data at 2 kHz. The data collection computer ran a custom LabView application (National Instruments, Austin, TX, USA) that collected and logged the motion tracking and EMG data. This application also provided auditory cues to the subject to guide the subject's knee movements.

B. *Experimental Protocol*

Our local research ethics board approved the experimental protocol used for this study. We recruited able-bodied subjects between the ages of 18 and 35 who had no history of knee or back injuries. Since this study used a single-subject design, we did not perform sample size calculations. We collected sinusoidal tracking data from 17 subjects and maximum velocity knee extension data from 7 subjects, which exceeded the maximum number of subjects used in other studies that collected knee movement data relevant to FES control systems [5-7].

The subject removed his or her shoes and then seated him or herself on the padded bench so that his or her lower legs were free to swing between the rest position (approximately 90 degrees flexion) and full extension.

We affixed adhesive, reflective motion tracking dots to bony landmarks on the lateral surface of the subject's right leg and body to determine the motion of each of these points. The landmarks were the acromion process (shoulder), trochanter major (hip), epicondylus lateralis ossis femoris (knee), malleolus femoris (ankle), processus lateralis tuberis calcanei (heel), and v. phalanx distalis (toe).

Next, we affixed single-use adhesive EMG electrodes to the subject's right leg to record the EMG of the knee extensor (rectus femoris, vastus medialis, and vastus lateralis), knee flexor (biceps femoris), plantarflexor (soleus), and dorsiflexor (tibialis anterior) muscles. We applied the electrodes by gently abrading the skin at the electrode application site with fine sandpaper to slough off any dead skin cells, then cleaning the site with an alcohol wipe before applying the adhesive electrode. We attached the lead wires to each of the electrodes to connect them to the EMG recording system, and then used wrapping tape to secure the lead wires to the leg, which prevented movement artifacts from contaminating the EMG data.

Once the experimental apparatus had been set up, we tested the data collection system to ensure that the motion tracking system could track the position of all of the dots. We explained the experimental protocol to the subject and demonstrated the auditory cueing system. We instructed the subject to extend and flex his or her knee in time with the sinusoidally rising and falling pitch of an auditory cueing signal. We instructed the subject to cover the full 90 degree range of knee extension from the rest position to full extension during each knee movement cycle, as best as he or she was able. The subject was then allowed to practice the knee movement protocol until he or she felt comfortable.

During each sinusoidal tracking trial, the subject was allowed to listen to the auditory cue until he or she was comfortable with the frequency of the sound before beginning to extend and flex his or her knee. The subject executed a series of 60 s knee movement trials at 20, 40, 60, and 80 cycles per minute (cpm). We chose this range of frequencies to represent knee movements during a wide range of functional activities such as walking and cycling [8,9]. The subject rested for one minute between each of the knee movement trials.

Once the subject had executed a sinusoidal tracking trial at each of the four frequencies, the subject executed a series of maximum velocity extension trials. For these trials, we gave the subject a verbal cue to initiate the trial, at which point he or she attempted to extend his or her knee from the rest position to full extension as quickly and accurately as possible, and then maintain the extended position for approximately two seconds before relaxing to the rest position. The subject executed the maximum velocity knee extension trial five times, with a one minute rest between each trial.

C. *Data Analysis*

We processed the kinematic data from the motion tracking system to yield the knee angle as a function of time for each trial. We discarded any maximum velocity knee extension trials for which the knee was held in the extended position for less than 1.5 seconds, since the knee did not achieve a steady-state extension angle before being flexed again. We identified the onset time of the resting, rising, holding, and relaxation phases of each maximum velocity knee extension trial and the onset time of the rising and falling phases of each sinusoidal trial.

We de-noised the EMG data with a 2nd-order zero-phase Butterworth filter. For the maximum velocity knee extension trials, we averaged the EMG data to yield the mean EMG of each muscle on the extension test for each subject. For the sinusoidal tracking trials, we averaged the EMG data to yield the mean EMG of each muscle on the sinusoidal tracking test for each subject and each frequency. Next, we analyzed the co-contraction of the following muscles for each subject: knee extensors (rectus femoris, vastus medialis, vastus lateralis), knee extensors and knee flexor (biceps femoris), knee extensors and dorsiflexor (tibialis anterior), knee extensors and plantarflexor (soleus). For the maximum velocity knee extension trials, we determined the duration of co-contraction of each muscle set during the resting, rising, and holding phases of the knee extension test by calculating the percentage of each phase for which all the muscles in the set exceeded an activation threshold of 1 μV. We determined the amount of co-contraction of each muscle set during each trial phase by integrating the curve that corresponded to the minimum EMG of the muscles within the set whenever the muscles were co-contracting, and was zero elsewhere. For the sinusoidal tracking trials, we determined the duration and amount of co-contraction of each muscle set during the rising and falling phases of the sinusoid for each subject and each frequency.

III. RESULTS

Fig. 1 shows an example of the maximum velocity knee extension trial. Fig. 2 shows an example of the sinusoidal tracking trial.

Fig. 3 shows the mean co-contraction across all subjects during the maximum velocity knee extension trial, for each muscle set. Fig. 3a shows the duration of co-contraction during the resting, rising, and holding phases of the knee extension trial as a percentage of the duration of the corresponding phase. Fig. 3b shows the amount of co-contraction during each phase in μVs.

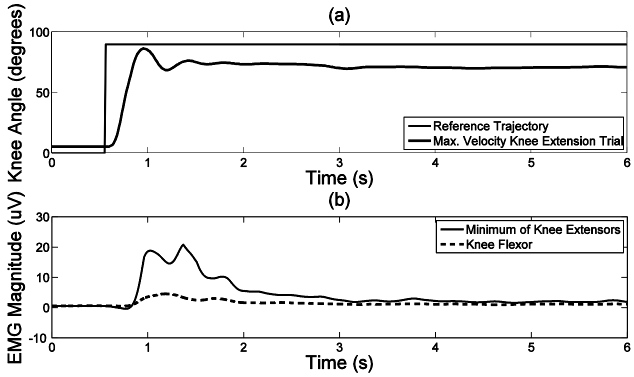

Figure 1. Example of maximum velocity knee extension trial. (a) Knee angle versus time. (b) EMG magnitude in μV versus time for minimum of knee extensor muscles (rectus femoris, vastus medialis, vastus lateralis) and knee flexor muscle (biceps femoris). Note that up to two extensor muscles may start contracting before the solid line crosses zero.

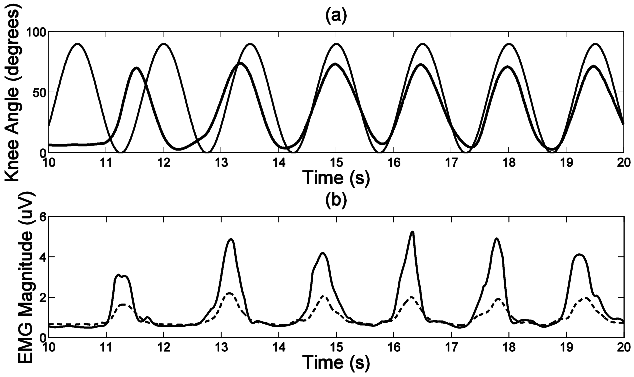

Figure 2. Example of sinusoidal tracking trial for 40 cpm trajectory. (a) Knee angle versus time. Thin line is reference trajectory, and thick line is knee angle. (b) EMG magnitude in μV versus time for knee extensor muscles (rectus femoris, vastus medialis, vastus lateralis) and knee flexor muscle (biceps femoris). Solid line is minimum EMG of knee extensors and dashed line is EMG of knee flexor.

Fig. 4 shows the mean co-contraction across all subjects during the rising phase of the sinusoidal tracking trials, for each sinusoidal frequency and each muscle set. Fig. 4a shows the duration of co-contraction as a percentage of the duration of the rising phase. Fig. 4b shows the amount of co-contraction during the rising phase in μVs. Fig. 5 shows the mean co-contraction across all subjects during the rising phase of the sinusoidal tracking trials, for each sinusoidal frequency and each muscle set. Fig. 5a shows the duration of co-contraction as a percentage of the duration of the rising phase. Fig. 5b shows the amount of co-contraction during the rising phase in μVs.

IV. DISCUSSION

This result reflects the important role that the antagonist knee flexor muscle plays in damping the knee dynamics, thereby preventing the knee from overshooting and experiencing a long settling time during the maximum velocity knee extension trial. The small amount of co-contraction exhibited by the knee extensor and flexor muscles is due to the relatively low EMG magnitude of the weaker flexor muscle. The dorsiflexor and plantarflexor muscles also show co-contraction with the knee extensors. This result varied widely between subjects because some subjects executed the knee extension trials with a flaccid ankle, while others tensed all of their leg muscles.

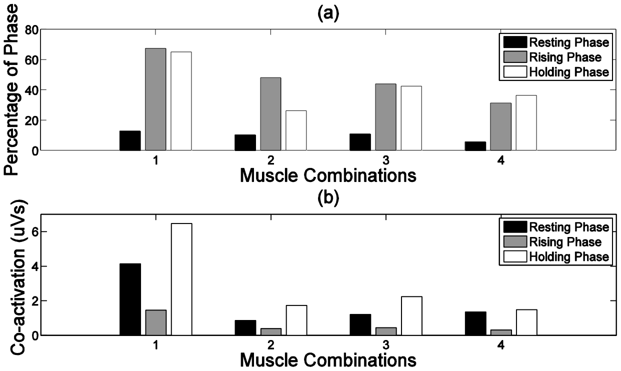

Figure 3. (a) Mean co-contraction of muscles during step trials as a percentage of trial phase. (b) Amount of co-contraction of muscles during step trials in μVs. Muscle combination 1 is co-contraction of knee extensor muscles (rectus femoris, vastus medialis, vastus lateralis), 2 is co-contraction of knee extensor muscles and knee flexor muscle (biceps femoris), 3 is co-contraction of knee extensor muscles and ankle dorsiflexor muscle (tibialis anterior), and 4 is co-contraction of knee extensor muscles and ankle plantarflexor muscle (soleus).

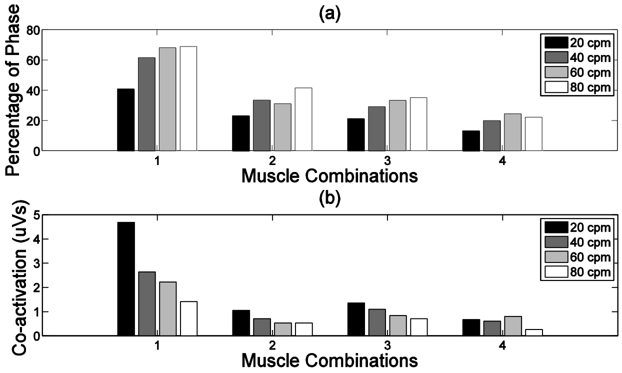

Figure 4. a) Mean co-contraction of muscles during rising phase of sinusoidal tracking trials as a percentage of trial phase. (b) Amount of co-contraction of muscles during rising phase of sinusoidal tracking trials in μVs. Muscle combination 1 is co-contraction of knee extensor muscles, 2 is co-contraction of knee extensor muscles and knee flexor muscle, 3 is co-contraction of knee extensor muscles and ankle dorsiflexor muscle, and 4 is co-contraction of knee extensor muscles and ankle plantarflexor muscle.

Figs. 4 and 5 show that the co-contraction of the muscle groups during the sinusoidal response trials is similar to the co-contraction during the knee extension trials. However, co-contraction also increases with increasing sinusoidal frequency, most likely due to the increased difficulty of tracking higher frequency sinusoidal trajectories.

It is also interesting to note that the knee extensor muscles are active during the falling phase of the sinusoidal tracking trials, as shown in Fig. 5. This result is consistent with the role of the knee extensors as the antagonist muscle group to the knee flexors during this phase of the movement.

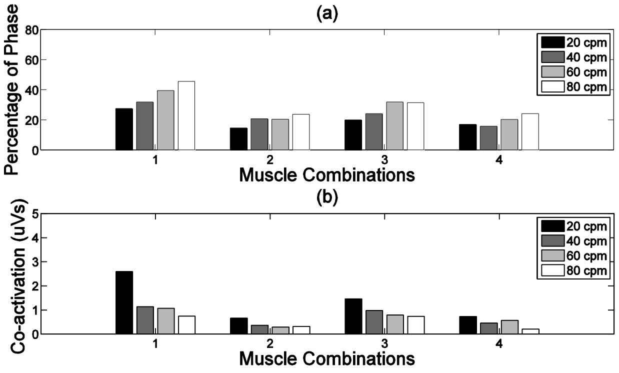

Figure 5. (a) Mean co-contraction of muscles during falling phase of sinusoidal tracking trials as a percentage of trial phase. (b) Amount of co-contraction of muscles during falling phase of sinusoidal tracking trials in µVs. Muscle combination 1 is co-contraction of knee extensor muscles, 2 is co-contraction of knee extensor muscles and knee flexor muscle, 3 is co-contraction of knee extensor muscles and ankle dorsiflexor muscle, and 4 is co-contraction of knee extensor muscles and ankle plantarflexor muscle.

These results clearly demonstrate that able-bodied subjects use a co-contraction strategy when performing standard control performance tests, and strengthen the argument for using a co-contraction strategy for closed-loop FES control algorithms.

In future work, we plan to quantify the performance of able-bodied subjects on these standard control tests. These data will form a benchmark for the performance of FES control systems, and can be used in conjunction with the co-contraction data contained in this conference paper to develop new and effective controllers for FES applications.

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