Posture-Dependent Changes in Corticomotor Excitability of the Biceps after Spinal Cord Injury and Tendon Transfer

Carrie L. Peterson-*EMBS Member*, Lynn M. Rogers, Jeremy P.M. Mogk, Michael S. Bednar, Anne M. Bryden, Michael W. Keith, Eric J. Perreault-*IEEE Member,* and Wendy M. Murray

Abstract— **Following tendon transfer of the biceps to triceps after cervical spinal cord injuries (SCI), individuals must learn to activate the transferred biceps muscle to extend the elbow. Corticomotor excitability of the transferred biceps may play a role in post-operative elbow extension strength. In this study, we evaluated whether corticomotor excitability of the transferred biceps is related to an individuals' ability to extend the elbow, and whether posture and muscle length affects corticomotor excitability after SCI and tendon transfer similarly to the nonimpaired biceps. Corticomotor excitability was assessed in twelve nonimpaired arms and six arms of individuals with SCI and biceps-to-triceps transfer using transcranial magnetic stimulation (TMS) delivered at rest. Maximum isometric elbow extensor moments were recorded in transferred arms and the fiber length of the transferred biceps was estimated using a musculoskeletal model. Across the SCI subjects, corticomotor excitability of the transferred biceps increased with elbow extension strength. Thus, rehabilitation to increase excitability may enhance strength. Excitability of the transferred biceps was not related to fiber length suggesting that similar to nonimpaired subjects, posture-dependent changes in biceps excitability are primarily centrally modulated after SCI. All nonimpaired biceps were most excitable in a posture in the horizontal plane with the forearm fully supinated. The proportion of transferred biceps in which excitability was highest in this posture differed from the nonimpaired group. Therefore, rehabilitation after tendon transfer may be most beneficial if training postures are tailored to account for changes in biceps excitability.**

I. INTRODUCTION

After spinal cord injury (SCI) at the C5 or C6 cervical level, individuals retain active elbow flexion, but lack active elbow extension due to triceps paralysis. Active elbow extension is needed for many activities of daily living. Thus, voluntary control of elbow extension significantly improves functional abilities and independence for individuals with C5/C6 quadriplegia. Surgical transfer of the biceps brachii muscle to the insertion of the triceps (biceps-to-triceps tendon transfer) is a common rehabilitative approach to restore active elbow extension [1, 2]. Following tendon transfer of the biceps, individuals must learn to activate the muscle to extend the elbow. Outcomes after tendon transfer are variable. Previous researchers have grouped outcomes based on an individual's ability to extend the elbow against gravity [3, 4]. Corticomotor excitability of the transferred biceps may play a role in distinguishing between subjects who can and cannot extend against gravity.

Previous assessments of single joint postures suggest that corticomotor excitability tends to increase at postures placing the muscle at shorter lengths [5-8]. However, for the nonimpaired biceps, we recently found that with multi-joint changes in functionally relevant postures, changes in muscle length do not fully explain posture-dependent changes in corticomotor excitability [9]. What remains unclear is how motor pathways of the transferred biceps following SCI respond to multi-joint changes, as well as the extent to which posture-related modulation is explained by muscle length.

In this study, we (i) evaluated corticomotor excitability (ii) evaluated elbow extension strength, and (iii) estimated muscle length in functionally relevant, multi-joint arm postures in six upper limbs from four subjects with SCI and transferred biceps. Our primary aim was to determine whether corticomotor excitability of the transferred biceps is related to an individuals' ability to extend the elbow. We expected that individuals with greater elbow extension strength with the transferred biceps would also demonstrate the largest motor evoked potentials (MEPs) to transcranial magnetic stimulation (TMS) of the motor cortex as these individuals would have less impaired cortical drive. In addition, we evaluated whether posture and muscle length affects corticomotor excitability after SCI and tendon transfer similarly to the nonimpaired biceps [9].

II. METHODS

A. Subjects

Corticomotor excitability of the biceps was assessed in twelve nonimpaired arms of healthy subjects (described previously [9]) and six arms of individuals with complete or incomplete injury at the C5 or C6 level who had undergone biceps-to-triceps transfer (Table 1). Healthy subjects had no neurological impairment or injury to the upper limb. Tendon transfer subjects were recruited from the MetroHealth Medical Center and the Shriners Hospitals for Children, Chicago. Eight individuals with tendon transfer were screened for participation; four males qualified (Table 1). Tendon transfer subjects were at least one year post-operative and were excluded from the study if they had

---

This research was supported by the Rehabilitation Research & Development Service of the Dept. of Veterans Affairs (Grant B7515R).

C. L. Peterson, L. M. Rogers, E. J. Perreault, and W. M. Murray are with the Rehabilitation Institute of Chicago, Chicago, IL 60611 USA (phone: 312-238-1618; e-mail: cpeterson@ric.org).

J. P. M. Mogk is with Autodesk Research, Toronto, ON, CA M5A 1J7.

M.S. Bednar is with the Shriners Hospitals for Children-Chicago, Chicago, IL USA 60707.

A.M. Bryden and M.W. Keith are with the MetroHealth Medical Center, Cleveland, OH USA 44109.

L.M. Rogers, E.J. Perreault, and W.M Murray are with Northwestern University, Dept. of Biomedical Engineering, Evanston, IL 60208 USA.

C.L. Peterson, M.S. Bednar, E. J. Perreault and W. M. Murray are with the Edward Hines, Jr. VA Hospital, Hines IL 60141 USA.

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

concurrent severe medical illness or used a baclofen pump. All subjects were free of contraindications for TMS and provided informed consent. The experimental protocol was approved by the Edward Hines, Jr. VA Hospital Institutional Review Board.

TABLE I. CHARACTERISTICS OF BICEPS-TO-TRICEPS PARTICIPANTS

Subject	***Transferred Arm***	***Biceps function grade***[a]	***Age (yrs)***	***Years since injury***	***Years since surgery***
BT1	R and L	R - 5 L – 4.5	19	3.8	R - 1.9 L - 2.3
BT2	R and L	R - 3 L - 3	27	6.1	R - 2.2 L – 4.0
BT3	R	0	41	7.4	1.3
BT4	R	5	22	9	3.3

a. Elbow extension motor score per the American Spinal Injury Association International Standards for Neurological Classification of Spinal Cord Injury

B. Transcranial Magnetic Stimulation

Single-pulse TMS was delivered to the motor cortex contralateral to the target arm using a Magstim 200 stimulator (Magstim, Dyfed, Wales, UK) via either a 70 mm figure-of-eight (nonimpaired subjects) or custom 90 mm batwing shaped coil (SCI subjects). The custom coil was used to maximize the probability of inducing MEPs in individuals with SCI as they are often small or absent [10, 11]. A linen cap was tied snugly on the subject's head, with vertex marked at the intersection of the inion-nasion and inter-aural lines. The coil was held tangentially on the scalp, at a distance ~5cm from vertex, with the coil center rotated to induce a posterior-to-anterior cortical current across the central sulcus. The location was identified evoking the largest peak-to-peak amplitude MEP in the biceps using the lowest stimulation intensity. All subsequent stimulation was applied at this location. Resting threshold (rTH) was determined in the horizontal plane with the forearm in neutral, defined as the lowest stimulus intensity that induced MEPs of $\geq 50\ \mu V$ in at least 5 of 10 consecutive stimuli. The stimulus intensity for experimental trials was set at 120% rTH. During experimental trials, the stimulator was triggered to deliver 10-20 stimuli at a rate of 0.2 Hz.

C. Electromyography

Surface electromyography (EMG) was used to monitor muscle activity prior to each stimulus event and to record the TMS-induced responses in the biceps. The skin was lightly abraded and cleaned with alcohol, and disposable dual Ag-AgCl electrodes (Noraxon U.S.A. Inc., Scottsdale, AZ) were positioned over the belly of the biceps brachii. The reference electrode was placed over the acromion process. EMG signals were amplified (1000×) and bandpass-filtered (10 – 500 Hz) using an AMT-8 amplifier (Bortec Biomedical, Calgary, Alberta, Canada), prior to analog to digital conversion (CED Micro 1401 MkII, Cambridge Electronic Design, Cambridge, UK). All EMG data were sampled at 2 kHz using Spike2 software (Cambridge Electronic Design, Cambridge, UK).

D. Experimental Protocol

Subjects were seated in an armless chair (nonimpaired) or in their own wheelchair (SCI) with their dominant or transferred arm positioned and supported. The upper limb was supported in each of three functional postures: overhead reach (120° arm abduction, 70° shoulder flexion, 130° elbow flexion), weight relief (45° abduction, 50° shoulder extension, 90° elbow flexion), and the horizontal plane (90° abduction, 45° shoulder flexion, 90° elbow flexion). These postures incorporated changes in both shoulder and elbow posture, and mimicked positions required for tasks important for functional independence following cervical SCI [12]. While positioned in each of the three functional postures, the forearm was rotated into two different static orientations (neutral, and full supination), resulting in a total of six postures (3 functional postures x 2 forearm orientations).

To maintain a given posture during testing, the upper limb rested on a custom-built padded support, which was secured to a platform of adjustable height to support the weight of the arm. The upper arm was supported at the level of the elbow via a contoured pad mounted on a lockable pivoting frame (to adjust pad orientation), and attached to a metal stem (to adjust pad height). The forearm and hand were supported by a padded cast that could be moved relative to the elbow support to accommodate forearms of different length. Shoulder and elbow postures were confirmed using a manual goniometer prior to stimulation.

For each subject, trials were captured in a blocked-random order by main functional posture. All measures were made with the arm at rest, as confirmed using surface EMG. All tendon transfer subjects completed an upper level ASIA assessment in addition to the test session.

E. Assessment of Isometric Elbow Extension Strength

In a separate test session, maximum isometric elbow extensor moments were recorded from participants with SCI in each of the three functional postures. An elbow moment transducer [13] was supported and attached to the transferred arm to record elbow moments. Subjects held each maximum voluntary contraction for approximately 5-7 seconds and were allowed two minutes rest between contractions. Three trials were recorded in each posture.

F. Estimating Transferred Biceps Length

The muscle fiber length of the transferred biceps in each functional posture was estimated by adapting a biomechanical model of the upper extremity [14]. The biceps-to-triceps transfer was modeled by altering the musculotendon path of the biceps based on illustrations and descriptions of the surgical procedure [1, 2]. The long and short heads of the biceps were routed medially around the humerus and merged with the insertion path of the triceps. We assumed that: 1) the moment arm of the transferred biceps equaled that of the triceps, and 2) the moment arm of the transferred biceps in elbow extension did not change with forearm orientation. Each functional posture was replicated using the model to obtain muscle fiber length.

G. Data and Statistical Analysis

Purpose-written Matlab code (The MathWorks, Inc., Natick, MA) to assess: the root mean square (RMS) amplitude of the pre-stimulus background EMG (20 ms interval immediately preceding the stimulus), the RMS amplitude of the evoked response, and the peak-to-peak MEP amplitude. Stimulus events where the pre-stimulus

RMS amplitude was larger than the evoked response, or where voluntary activity was detected prior to the MEP, were discarded to ensure similar levels of background activity across postures. MEP amplitudes recorded in each of the six test postures were normalized by responses in the horizontal plane posture with the forearm in neutral. For the assessments of isometric elbow extension strength, the maximum elbow extension moment was computed for each trial as the highest average moment maintained for 0.5 seconds. Maximum elbow extension moments for each trial were averaged within each arm and posture condition.

Separate one-way analysis of variance and post-hoc comparisons were performed to confirm that the mean RMS amplitude of pre-stimulus EMG did not differ between postures. Given the small number of eligible SCI subjects for this study (4 individuals with 6 total transferred arms) standard ANOVAs to compare within- or between-group differences would be inappropriate. Instead, Fisher's exact test was used to compare the proportions of transferred biceps that shared the same most excitable posture as the nonimpaired biceps.

III. RESULTS

A. Transferred biceps more excitable in arms generating the largest elbow extensor moments

Within individual arms across postures, there was no relationship between maximum isometric elbow extensor moment and MEP amplitude of the transferred biceps (Fig. 1). However, the individuals who generated the largest elbow extensor moments (Fig.1; BT1 and BT4) had larger MEP amplitudes than the individuals who generated small elbow extensor moments (Fig. 1; BT2 and BT3).

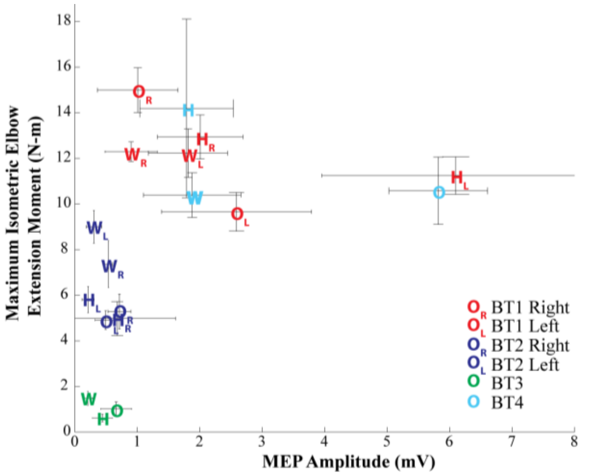

Figure 1. Average MEP amplitude and isometric elbow extensor moments for each transferred arm in each functional posture (W = weight relief, H = horizontal plane, O = overhead reach; subscripts R and L denote right or left arms, respectively). Error bars are ± one standard deviation.

B. Changes in corticomotor excitability with arm posture

In nonimpaired subjects, the horizontal, supinated posture resulted in the largest biceps MEPs in all arms tested (12/12 arms). The proportion of transferred biceps where the largest MEPs occurred in this same posture differed (p = 0.017). The largest MEPs from the transferred biceps were observed either when the limb was positioned in the overhead reach, neutral posture (3/6 arms), overhead reach, supinated posture (1/6) or in the horizontal, supinated posture (2/6 arms). Therefore, we identified two distinct groups of transferred arms: a group with the same most excitable posture as the nonimpaired arms and a group with a different most excitable posture. MEP amplitudes averaged across nonimpaired arms and the two transferred arm groups are shown in Fig. 2.

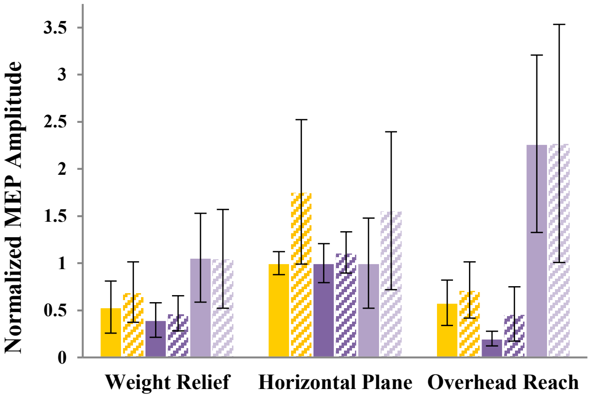

Figure 2. Average MEPs from nonimpaired (yellow) and transferred (purple) biceps in each posture, with the forearm either in neutral (solid) or supinated (dashed fill). Transferred arms exhibited two distinct groups: where the biceps was most excitable in the horizontal plane (dark purple) and where overhead reach was the most excitable posture (light purple). Error bars are ± one standard deviation.

C. Arms with least excitable transferred biceps demonstrate relationship between corticomotor excitability and muscle length

Across all transferred arms, there was no relationship between MEP amplitude and relative muscle fiber length of the transferred biceps (Fig. 3). However, the arms in which the smallest MEP amplitudes were recorded demonstrated a trend of increasing MEP amplitude at shorter muscle lengths (Fig. 3; BT2 and BT3).

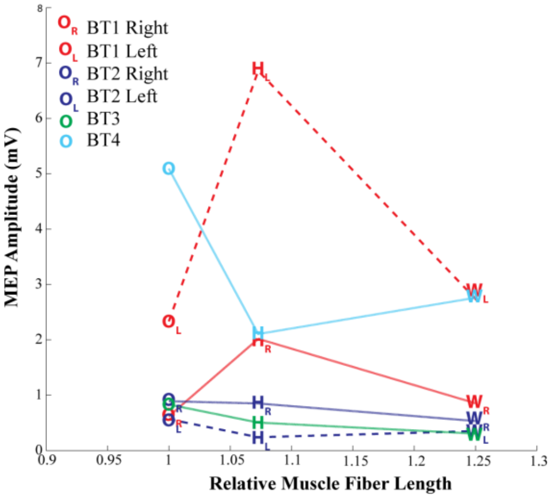

Figure 3. Average MEP amplitudes as a function of modeled fiber length . Each data point corresponds to a transferred arm in each functional posture (W = weight relief, H = horizontal plane, O = overhead reach; subscripts R and L denote right or left arms, respectively). Transferred biceps fiber length is expressed relative to the overhead reach posture (shortest length).

IV. DISCUSSION

The current study was performed to investigate the relationship between corticomotor excitability and strength of the transferred biceps muscle in individuals following cervical SCI and tendon transfer. Also, we investigated the effects of multi-joint upper limb posture on the excitability of the transferred biceps. Posture-dependent changes in TMS-evoked responses were taken as evidence of posture-related modulation of overall corticomotor excitability, and the posture-dependent pattern was compared between nonimpaired and transferred arms. Also, a musculoskeletal model was used to evaluate posture-mediated changes in excitability as a function of the muscle length of the transferred biceps.

In agreement with our expectation, MEP amplitudes were greater in the individuals that generated larger elbow extensor moments relative to weaker transferred arms. This was expected because stronger biceps are likely to have more motor units accessible to cortical drive, and a larger motor pool. Indeed, previous work has shown that within nonimpaired subjects, MEP amplitudes increase with biceps strengthening [15]. Although comparisons of non-normalized MEP amplitudes across subjects in the current study is limited by factors affecting the EMG signal (e.g., adipose tissue, EMG placement), we observed large differences in MEP amplitudes between the weak and strong transferred arms. For the transferred arms in which small MEPs were recorded, either biceps excitability was low prior to transfer (i.e., result of SCI) or as a result of transfer. If biceps excitability is decreased prior to transfer, this would suggest excitability should be assessed prior to transfer, in addition to the standard assessments, to better ensure the transfer will result in gained elbow extension strength. Alternatively, if biceps excitability is decreased as a result of transfer, rehabilitative strategies to increase excitability, (e.g., repetitive TMS) may be beneficial.

Limb posture consistently modulated nonimpaired biceps corticomotor excitability such that TMS responses were maximal in the horizontal reach posture with the forearm supinated for 100% of the arms tested (12/12). In contrast, for the transferred biceps, the position of maximal excitability differed between arms such that response patterns could be classified in two distinct groups. In 2/6 transferred arms, the limb posture of maximal excitability was the same horizontal reach, supinated posture as the control arms. However in 4/6 arms, the transferred biceps was maximally excitable in the overhead reach posture. These results suggest that posture-dependent corticomotor excitability is altered in some individuals following SCI and tendon transfer. Therefore, initial training of the transferred muscle in postures that correspond to increased corticomotor excitability in nonimpaired arms may not be beneficial. Rather training should be tailored based on the most excitable posture for each individual. A limitation of this study is that MEP amplitudes were not assessed prior to transfer or during the rehabilitative period following transfer. Thus, it is not known whether the posture in which the biceps was most excitable was altered from the nonimpaired group as a result of SCI or tendon transfer.

Estimates of muscle fiber length based on a musculoskeletal model of the nonimpaired [9] and transferred biceps suggest that the biceps is shortest in the overhead reach posture. Although this posture was the most excitable in 4/6 transferred arms, a trend of increasing excitability at shorter muscle lengths was not consistent across the three postures for most of the SCI subjects. Therefore, our results largely agree with previous work demonstrating strong central modulation of corticomotor excitability with changes in posture [8, 9]. The only evidence of a relationship between corticomotor excitability and muscle length in the current study was observed in the transferred arms in which the smallest MEPs were recorded. Although more data are needed to determine whether this relationship is significant, it is possible that peripheral input (e.g. muscle length) modulating excitability of motorneurons in the spinal cord has a larger effect on the MEP when cortical drive to the muscle is low.

ACKNOWLEDGMENT

We thank Vikram Darbhe and Heidi Roth for their assistance with the data collection.

REFERENCES

[1] S. H. Kozin, "Biceps-to-triceps transfer for restoration of elbow extension in tetraplegia," *Tech Hand Up Extrem Surg,* vol. 7, pp. 43-51, Jun 2003.

[2] M. Revol, *et al.*, "Biceps-to-triceps transfer in tetraplegia. The medial route," *J Hand Surg Br,* vol. 24, pp. 235-7, Apr 1999.

[3] K. D. Mohammed, *et al.*, "Upper-limb surgery for tetraplegia," *J Bone Joint Surg Br,* vol. 74, pp. 873-9, Nov 1992.

[4] M. J. Mulcahey, *et al.*, "Prospective evaluation of biceps to triceps and deltoid to triceps for elbow extension in tetraplegia," *J Hand Surg Am,* vol. 28, pp. 964-71, Nov 2003.

[5] E. Lackner and H. Hummelsheim, "Motor-evoked potentials are facilitated during perceptual identification of hand position in healthy subjects and stroke patients," *Clin Rehabil,* vol. 17, pp. 648-55, Sep 2003.

[6] G. N. Lewis, *et al.*, "Phasic modulation of corticomotor excitability during passive movement of the upper limb: effects of movement frequency and muscle specificity," *Brain Res,* vol. 900, pp. 282-94, May 11 2001.

[7] K. Mitsuhashi, *et al.*, "Modulation of excitability in the cerebral cortex projecting to upper extremity muscles by rotational positioning of the forearm," *Tohoku J Exp Med,* vol. 212, pp. 221-8, Jul 2007.

[8] C. I. Renner, *et al.*, "Central compensation at short muscle range is differentially affected in cortical versus subcortical strokes," *Stroke,* vol. 37, pp. 2076-80, Aug 2006.

[9] J. P. Mogk, *et al.*, "Corticomotor excitability of arm muscles modulates according to static position and orientation of the upper limb," *Clinical Neurophysiology,* 2014.

[10] B. Brouwer and D. H. Hopkins-Rosseel, "Motor cortical mapping of proximal upper extremity muscles following spinal cord injury," *Spinal Cord,* vol. 35, pp. 205-12, Apr 1997.

[11] F. D. Roy, *et al.*, "Afferent regulation of leg motor cortex excitability after incomplete spinal cord injury," *J Neurophysiol,* vol. 103, pp. 2222-33, Apr 2010.

[12] D. J. Magermans, *et al.*, "Requirements for upper extremity motions during activities of daily living," *Clin Biomech (Bristol, Avon),* vol. 20, pp. 591-9, Jul 2005.

[13] W. D. Memberg, *et al.*, "A transducer to measure isometric elbow moments," *Clin Biomech (Bristol, Avon),* vol. 16, pp. 918-20, Dec 2001.

[14] K. R. Holzbaur, *et al.*, "A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control," *Ann Biomed Eng,* vol. 33, pp. 829-40, Jun 2005.

[15] D. J. Kidgell, *et al.*, "Neurophysiological responses after short-term strength training of the biceps brachii muscle," *J Strength Cond Res,* vol. 24, pp. 3123-32, Nov 2010.