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Estimating Voluntary Activation of the Elbow and Wrist Muscles in Chronic Hemiparetic Stroke Using Twitch Interpolation Methodology

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Abstract

One of the cardinal motor deficits that occurs after stroke is paresis, a decrease in the voluntary activation of muscles. Paresis leads to a decrease in voluntary joint strength, impacting stroke survivors' ability to perform activities of daily living (ADLs). Quantifying this decrease in voluntary activation is important when designing rehabilitation interventions to address movement impairments and restore the ability to perform ADLs. Twitch interpolation is an experimental technique developed to quantify muscle voluntary activation[1]. This method has been used widely across pathologies but often limited to assessment of the voluntary activation of the plantar flexors, given the ease of activating these muscles through stimulation of the tibial nerve [2]. The complex innervation of elbow and wrist musculature imposes practical difficulties when applying the twitch interpolation technique to these joints[1]. Therefore, only a few studies have used this technique to examine the pathological[3]–[5] upper extremity, with little quantitative data documenting the degree of paresis present in the upper limb after stroke. The goal of this study is to evaluate the feasibility of applying twitch interpolation to quantify voluntary activation of the elbow and wrist flexors and extensors in chronic stroke survivors.

I. Introduction

Stroke is the leading cause of serious long-term disability in the United States [6]. Approximately 50–70% of stroke survivors experience long-term upper-extremity functional impairments [7]. The three primary motor deficits that lead to these functional impairments are paresis, spasticity and loss of independent joint control [8], [9]. Paresis, a decrease in the voluntary activation of muscles, causes weakness, which makes it difficult for stroke survivors to complete ADLs. The amount of paresis that occurs at specific joints in the upper extremity has not been quantified, in part because directly assessing changes in neural firing is difficult. This paper will describe the feasibility and methodology of a technique to quantify the amount of paresis post stroke.

Twitch interpolation is an experimental method developed to indirectly measure motoneuron drive [1]. Voluntary activation is estimated based on measurement of the muscle twitch evoked by an electrical stimulus superimposed on volitional joint torque [10]. This method

has been used successfully to show differences in voluntary activation between muscles [11], at different joint angles [12] and in a variety of pathologies [2], [13].

There are two main methods used to calculate voluntary activation through twitch interpolation, the ratio and the linear prediction methods. Both methods rely on the principle that there is an inverse relationship between the amplitude of a twitch evoked by a stimulus and the voluntary force output during stimulation [1]. In the ratio method, voluntary activation is estimated by comparing the amplitude of the twitch elicited by the electrical stimulus applied during rest to the twitch elicited by stimulation during a maximum voluntary contraction. In contrast, in the linear prediction method, voluntary activation is equivalent to the maximum voluntary torque normalized by the theoretical maximum joint torque. The theoretical maximum joint torque is the x-intercept of the linear regression between the voluntary torque and the amplitude of the superimposed twitch (where electrical stimulation would no longer elicit a twitch).

The goal of this study was to evaluate the feasibility of using twitch interpolation to quantify voluntary activation of the paretic elbow and wrist flexors and extensors. Voluntary activation in the paretic limb was compared to the non-paretic limb and the dominant limb in an able bodied subject. A secondary goal was to compare the two quantification methods, ratio and linear prediction, in estimating voluntary activation during elbow flexion and extension.

II. Methods

A. Participants

Voluntary activation of the elbow and wrist flexors and extensors was assessed in the paretic and non-paretic limbs of one individual with chronic hemiparetic stroke and in the dominant limb of a control participant. The individual with chronic stroke was 60 years old, 8 years post-stroke and scored a 24/66 on the upper-extremity portion of the Fugl-Meyer. The research protocol was approved by the Institutional Review Board of Northwestern University and participants provided written informed consent.

B. Isometric Torque Measurement

Participants were seated in a Biodex chair (Biodex, Shirley, NY) with their trunk secured via shoulder and lap belts and the tested arm rigidly attached to an isometric setup to measure elbow and wrist joint torques. A 6 degree-of-freedom load cell (JR3, Woodland, CA) was used to measure elbow flexion and elbow extension torque [8] while a single axis torque sensor (Futek, Irvine, CA) mounted at the wrist was used to measure wrist torque. The subject was positioned with 15° shoulder flexion, 20° shoulder abduction, 90° elbow flexion and in neutral with respect to pronation/supination and wrist and finger posture.

C. Twitch Interpolation Setup

A standard twitch interpolation protocol [3], [14], [15] was used with the following specifications and modifications to optimize measurement of the paretic upper extremity. Using the locations listed in Table I as starting points, a motor point pen (Compex,

Guildford, UK) was used to determine the specific location of each motor point for each muscle by finding the point where the lowest amplitude of stimulation triggered the largest visible muscle contraction [16]–[18]. Two self-adhesive electrodes (Dura-Stick, Hanover, Germany) were placed on each muscle group, one over the muscle specific motor point (cathode) and the other distal to the motor point (anode) as specified in Table I.

D. Maximum Voluntary Torque Measurements

For each of the four muscle groups, participants were asked to generate at least six voluntary maximum contractions (MVC), with additional MVC trials collected if needed, to ensure that the six greatest torque values were within 10% of each other and that the last trial was not the greatest value.

E. Twitch Interpolation Measurements

The electrical stimulus consisted of a single monophasic pulse with duration of 100 μ s to maximize motor recruitment while minimizing activation of pain fibers. The maximal stimulation amplitude was set at the 1mA increment where the measured joint torque plateaued or began to decrease. This is in contrast with standard twitch interpolation protocols in the lower limb that employ 110% of the maximal stimulation amplitude [2]. Due to the reduced muscle and limb size in the arm and forearm, using supramaximal amplitudes will result in current spread to antagonist muscles, decreasing net joint torque production. Participants were asked to relax followed by a maximum voluntary contraction held for 4 seconds. A stimulus of maximal amplitude was applied after 250 ms of sustained contraction level within 10% of the target effort. A second stimulus was applied 6 s after the first stimulus, with the limb at rest (Fig. 1). This was repeated for 6 trials. Between trials, participants were asked to activate the antagonist muscle group, to eliminate residual torque from the previous trial (as seen in Fig. 1). This is an important consideration since individuals post stroke often have hypertonicity and difficulty relaxing the flexor muscles, thus the use of reciprocal inhibition is needed to minimize any potential residual torques from the previous trial.

In addition, we performed 6 twitch interpolation trials at 33% and 66% of MVC only for the elbow flexors and extensors to determine voluntary activation with the linear prediction method.

F. Data Analysis

Elbow joint torque was calculated offline from the measured forces and moments at the forearm through a Jacobian-based transformation. The wrist torque was obtained directly from the torque sensor based on its calibration equation determined previously. All joint torques were filtered using a two-sided moving average filter with a 100 ms window. For the MVC trials, the maximum joint torque was calculated as the greatest average moment maintained over 0.5 seconds.

For each of the four muscle groups, voluntary activation was estimated for each trial using the ratio method, and defined in (1):

$$\text{Voluntary Activation} = (1 - \tau_A/\tau_R) * 100\% \quad (1)$$

Where τ_a , the twitch torque, represents the torque produced by electrical stimulation during MVC and τ_r , the resting twitch torque, represents the torque produced by electrical stimulation with the limb at rest (Fig. 1) [19]. The pre-stimulus torque value was defined as the average torque produced over the 250 ms prior to the stimulus. The stimulus torque was defined as the maximal torque value occurring within 150 ms after the stimulus. Therefore, τ_a and τ_r were calculated as the difference between the stimulus torque and pre-stimulus torque.

Voluntary activation using the linear prediction method is defined in (2):

$$\text{Voluntary Activation} = (\tau_{MVC}/\tau_p) * 100\% \quad (2)$$

Where τ_{mvc} represents the torque generated during MVC trials and τ_p , predicted maximal torque, is the maximum torque that would be generated with full activation, and is extrapolated from the data. Linear regression was used to predict τ_p for the elbow flexors and extensors. The twitch torque, τ_a , was calculated for all six twitch interpolation trials performed at 100%, 66% and 33% of MVC and the resting twitch torque, τ_r , was calculated for all 18 trials. A linear regression model was created for twitch torque, τ_a versus pre-stimulus torque value (Fig. 2). Since the stimulus was applied 18 times while the limb was at rest, for equal representation, only the six trials closest to the median τ_r were included in the regression. Predicted maximal torque, τ_p is the intercept obtained from the linear regression.

III. Results

Fig. 1 shows example data from a 100% MVC elbow extension twitch interpolation trial for the paretic limb of the stroke subject. Electrical stimulation, shown in grey, has been superimposed on the elbow extension torque data, shown in black.

Fig. 2 illustrates elbow extension twitch torque vs. pre-stimulus torque and the linear regression used to extrapolate predicted maximal torque, τ_p , for the elbow extensors of the paretic limb of the stroke participant. The predicted maximal elbow extension torque was 13.41 Nm.

These preliminary results show similar voluntary activation using both methods, across muscles except for elbow flexion in controls where the voluntary activation estimate was 96% for the ratio method and 112% for the linear prediction method (Fig. 3).

The preliminary results also show decreased voluntary activation of all the muscle groups in the paretic limb, except elbow extension, compared to the non-paretic and control limbs (Fig. 4). Similarly, voluntary activation of the non-paretic and control limbs is similar across muscles, except for wrist extension (Fig. 4). The voluntary activation of the wrist extensors in the control limb was 101% while the activation in the non-paretic limb was only 80% (Fig. 4).

IV. Discussion

Preliminary results from this study show that it is feasible to measure voluntary activation of the upper extremity through the use of twitch interpolation as described above.

A. Limitations of the Twitch Interpolation Method

Twitch interpolation is a valid method to indirectly measure the degree of paresis after stroke; however, interpretation of the results needs to be constrained by the actual measurements. Twitch interpolation estimates voluntary activation based on torque measurements during voluntary contraction compared to the torques elicited during electrical stimulation. Twitch interpolation does not directly measure descending drive, motoneuron firing rate or the source of motoneuron drive [1].

Both the ratio and linear prediction methods rely on the assumption that the amplitude of the voluntary torque and the amplitude of the evoked twitch are linearly related (inverse) [1]. However, linearity is a simplification of this relationship that ignores tendon compliance, the length-tension relationship, antidromic collisions and stimulation of antagonists.

Minimizing spillover to antagonist muscles during electrical stimulation is one aspect that can be controlled by the choice of stimulation properties, electrode size and placement. Through careful review of neuromuscular anatomy and previous literature as well as methodical experimentation, we have developed a method that optimizes these variables resulting in minimal to absence of stimulation to antagonist muscle groups while optimizing stimulation of agonists.

The general agreement of the ratio and linear prediction methods at the elbow (Fig. 3) suggests that the method is reliable.

B. Voluntary Activation After Stroke

Preliminary results indicate that voluntary activation, as measured through twitch interpolation, is decreased in the paretic upper extremity. This points to a compromised ability to activate the muscles of the paretic limb. Additionally, voluntary activation of the wrist muscles is further compromised compared to the elbow, consistent with previous findings that show that distal muscles are more affected by the stroke compared to proximal muscles [20]. Finally, the results show that activation levels are similar between the non-paretic and control limbs, except at the wrist. Further measurements in a representative sample of participants with stroke are needed to determine if the non-paretic limb is also affected distally and to draw conclusions on the effect of the stroke on voluntary activation of elbow and wrist muscle flexors and extensors.

V. Conclusion

This study shows that it is feasible to quantify voluntary activation of the elbow and wrist flexors and extensors in individuals with chronic hemiparetic stroke and describes methods to do so. This study provides preliminary evidence that similar results are obtained with both the ratio and linear prediction methods. The use of the twitch interpolation method to

quantify voluntary activation in the upper extremity of stroke subjects will help us better understand the deficits of the paretic limb and in turn improve rehabilitation techniques.

Acknowledgments

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Figure 1.
Example data from 100% MVC elbow extension twitch interpolation trial for the paretic limb of the chronic stroke subject.

Figure 2. Example linear regression model used to extrapolate predicted maximum torque, τ_p for the elbow extensors of the paretic limb.

Figure 3. Comparison of activation values calculated using the ratio and linear prediction methods (mean $\pm$ 1 standard error) for the paretic, non-paretic and control elbow flexors and extensors.

Figure 4. Voluntary activation of parietic, non-parietic and control elbow and wrist flexors and extensors (mean $\pm$ 1 standard error) using the ratio method.

Electrode Location and Size

Table I.

Muscle Group	Approximate Motor Point Location (Cathode)	Distal Electrode Location (Anode)	Electrode Size
Elbow flexors	4 Finger breadths distal to axilla, 1 cm anterior to medial bicipital groove (short head of biceps brachii)	Over distal biceps tendon	5cm × 6cm
Elbow extensors	5 finger breadths from posterior axilla along a line from the posterior axilla to the olecranon (long head of triceps)	Over distal triceps tendon	5cm × 6cm
Wrist extensors	2 finger breadths distal to lateral epicondyle of humerus, along a line from the lateral epicondyle to the base of 2 nd metacarpal (extensor carpi radialis longus and brevis)	Bony prominences of posterior wrist	4cm × 6cm
Wrist flexors	3 finger breadths distal to medial epicondyle, along a line from the medial epicondyle of the humerus to the base of the 2 nd metacarpal (flexor carpi radialis)	2 finger breadths proximal to anterior wrist crease	4cm × 6cm