PREDICTING THE MAXIMUM FORCE GENERATING ABILITY OF THE ANKLE PLANTARFLEXOR MUSCLES USING SUBMAXIMAL CONTRACTIONS

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Honors Bachelor of Science in Exercise Science with Distinction.

Fall 2009

Predicting The Maximum Force Generating Ability of the Ankle Plantarflexor Muscles using Submaximal Contractions

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ACKNOWLEDGMENTS

I would like to acknowledge my adviser, Dr. Stuart Binder-Macleod for helping me to develop and write this thesis. I would also like to thank Trisha Kesar, PhD, Ramu Perumal, PhD, Brian Knarr, and Erin Helm for their help in this process.

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ABSTRACT

This study attempted to find an accurate method of measuring volitional activation and predicting maximum force generating ability (MFGA) that could be used with a neurologically impaired population. Deficits in muscle strength in individuals with neurological disorders are either muscular or neurological in origin. Electrical stimulation is often superimposed over a subject's maximal volitional contraction to determine the extent of strength deficit that can be attributed to neurological impairment. This study tested the Burst Superimposition Test, the Twitch Interpolation Technique, the Doublet Interpolation Technique, and the Twitch to Tetanus Ratio Method on the ankle plantarflexor muscles of 13 healthy subjects contracting at submaximal volitional efforts (25%, 50%, and 75% of the muscle's maximum force generating ability, MFGA) to represent the decreased volitional activation of those with neurological impairments. The predicted MFGA's from the tests at submaximal volitional efforts were compared to the Burst Superimposition Test at maximal effort, which is considered to be the gold standard in measuring volitional activation and MFGA. The results suggest that the Burst Superimposition Test was the most accurate method at submaximal volitional efforts when predicted MFGA was adjusted by a correction equation. The Twitch to Tetanus Ratio also showed promising results at the 25% volitional effort level.

Chapter 1

INTRODUCTION

Muscle weakness, defined as decreased force generating ability, is a major concern for stroke survivors (13, 18, 27). Over 795,000 people experience a stroke or recurrence of a stroke each year, and there are already 6.5 million stroke survivors in the United States (7). Because individuals who have had a stroke can demonstrate weakness due to atrophy of their muscles secondary to disuse or decreased activation of their muscles due to their neurological impairment, it is difficult to determine the proportion of muscle weakness that can be attributed to either of these areas. The ability to determine the cause and degree of muscle weakness in this and other neurologically impaired populations is critical for tracking the progression of and recovery from diseases involving upper motor neuron lesions (27), deciding the rehabilitation program of a patient (20). It will also influence future research, such as measuring changes in volitional activation throughout the progression of a neurological disorder and responses due to treatments (13). However, no method currently exists for determining the extent of weakness attributed to atrophy or neurological causes in individuals with neurological impairments.

Decreased muscle strength due to damaged neural connections between the brain and muscle (4, 29) may result in the brain not recruiting all available motor neurons or some neurons may fire subtetanically. This causes fewer motor units (group of muscle fibers innervated by one motor neuron) to be recruited than are available or the motor units to fire at a lower rate (22, 27). The resulting "muscle inactivation" is the force deficit between the force the muscle produces voluntarily (maximal voluntary contraction, MVC) and the force the muscle is capable of producing (maximum force generating ability, MFGA) (1, 27). "Volitional Activation" describes the proportion of muscle force created by the MVC compared to the muscle's maximum force generating ability (26). Motivational factors (6) and fatigue (4) can also influence this force deficit. If an electric pulse stimulates the muscle to contract with more force than it could without stimulation, the muscle weakness may be due to neurological factors (8, 27).

It is crucial to understand the source of their strength deficit to better aid the recovery of poststroke individuals (10). This can be accomplished by measuring volitional activation (10). Knowing the degree of muscle inactivation present in poststroke adults would allow clinicians to classify individuals with respect to their neural deficit and execute rehabilitation programs accordingly. For example, volitional activation could be divided into 20% activation levels. Subjects with severe neurological impairment may only be able to activate up to 20% of their muscle, subjects with moderate neurological impairment may be able to activate up to 40% of their muscle, and subjects with low impairment might activate 80-100% of their muscle. Strength training may be sufficient to increase strength in those individuals with low impairment, but individuals with high neurological impairment may require programs that also involve electrical stimulation and biofeedback (25). When strength gains are accomplished, measuring volitional activation would differentiate between gains accomplished through increased neural drive and physical changes to the muscle (23).

The Burst Superimposition Test is considered to be the current gold standard for measuring the maximum force generating ability of a skeletal muscle (14). This technique superimposes stimulation with a train of maximal electric pulses over a maximum voluntary contraction (MVC). The force generated by both the voluntary maximum contraction and the electrical stimulation is considered the maximum force generating ability of the muscle (MFGA) (15). A ratio of the force created voluntarily to the force created with the aid of stimulation determines the degree of volitional activation. A ratio of 1 indicates full activation (15). This technique has been used successfully to measure and predict maximum force generating ability in healthy (14), ACL injured (3), multiple sclerosis (19), cerebral palsy (21), chronic fatigue syndrome (11), and osteoarthritic subjects (15). However, no studies have been published that have used the Burst Superimposition Test on patients who have sustained a stroke.

In addition to testing the maximal efforts of subjects, the Burst Superimposition Test has also been used to predict muscle activation at submaximal volitional efforts in healthy (22) and older adults (23). While this method tends to over-estimate the activation of a muscle, an equation that corrected these predictions has been used on the quadriceps (22). This submaximal method is reflective of performing a Burst Superimposition Test on those in the stroke population who have lower volitional activation. Unfortunately, the test requires a 10-pulse train of supramaximal stimulation, which is less comfortable for subjects than methods that require fewer stimulation pulses (10, 22).

The Twitch Interpolation Technique delivers a supramaximal single pulse to the resting muscle and then superimposes a supramaximal pulse on a volitional muscle contraction (1, 15). The ratio between the resting twitch force and the superimposed twitch force is used to calculate muscle activation (1), and predict the maximum force generating ability of the muscle (8). As the volitional force increases towards 100% of the muscle's maximum force generating ability, the superimposed twitch moves towards creating no additional force (8, 14). The use of a single twitch is more comfortable for subjects than the train of stimulation used in the Burst Superimposition Test (10), but this method has been said to overestimate muscle activation (1), especially at higher activation levels (22).

A similar approach, the Doublet Interpolation Technique, delivers two closely spaced supramaximal pulses (doublet) on the resting muscle and the volitional muscle contraction in the same manner as the Twitch Interpolation Technique. Using multiple twitches or doublets to assess muscle activation has been shown to be more sensitive in measuring decreased activation in the elderly than using a single twitch interpolation (16). This may be due to the summation of force created by increased frequency of stimulation before the muscle fiber is given time to relax (29). The two pulses of stimulation may make impairments with rate coding more apparent using this test than the Twitch Interpolation Technique. The Burst Superimposition Test has been shown to be more sensitive in measuring volitional activation than both the twitch interpolation and doublet interpolation techniques (10).

A fourth method, the Twitch to Tetanus Ratio Method, requires no voluntary effort by subject. This method uses the forces created by a supramaximal single pulse, submaximal single pulse, and submaximal tetanic train of pulses applied to a resting muscle to calculate the maximal tetanic force of which the muscle is capable (13). The validity of using the

Twitch Interpolation technique and Twitch to Tetanus Ratio Method to calculate the maximum force generating ability of muscle is yet to be proven with either able-bodied or neurologically impaired individuals (13). The Twitch to Tetanus Ratio Method is especially important in this study because it has not been proven valid against the gold standard, the Burst Superimposition test, and results from the test have not yet been published. The test uses a less intense and more comfortable stimulation compared to the Burst Superimposition test, and also requires no voluntary force production from the subject. If this test proves to be an accurate measure of the maximum force generating ability of a muscle, it could be used in cases of extreme weakness. This method would be a useful tool in tracking volitional activation in populations with neurological disorders.

To determine whether the methods of assessing volitional activation would be accurate and consistent when testing clinical populations, the method must be able to characterize the degree of activation accurately during submaximal efforts of healthy adults that mimic the reduced activation and strength (13, 18, 24) of poststroke adults. A study testing single motor units of the tibialis anterior in hemiparetic poststroke adults discovered that just over half of the available motor units were active during volitional contractions and walking, and that these motor units fired at only about two thirds the normal rate (9). This reduced firing rate could potentially result in decreased muscle efficiency, and increased effort, fatigue, and weakness in an individual (5). Patients with amyotrophic lateral sclerosis, a disease involving dysfunction of the upper motor neuron, were similarly found to have lower volitional activation when compared to healthy adults using the Burst Superimposition Test (10), but healthy adults were not tested at submaximal contractions to determine whether this method was accurately reporting low activation levels. In the present study, four methods will be compared that have the potential to predict volitional activation at low intensities (MVC of only 25-75% of the MFGA).

The purpose of this study was to determine the most accurate method for maximum force generating ability with the greatest potential for use on neurological populations. This was accomplished by comparing the estimated maximum force generating ability of the ankle plantarflexor muscles of able-bodied individuals as predicted by the Burst Superimposition Test (the gold standard) at 100% volitional effort to the maximum force generating ability predicted by the Twitch Interpolation Technique, the Doublet Interpolation Technique, and the Burst Superimposition Technique using submaximal volitional efforts of 25%, 50%, and 75% of the MFGA, and the Twitch to Tetanus Ratio Method using submaximal twitch forces that produced 25% and 50% of the maximum twitch force**.** We hypothesized that overall, the Burst Superimposition test using submaximal volitional contractions would be the best predictor of maximum force generating ability.

Chapter 2

METHODS

2. 1 Subjects

Data were collected from 13 able-bodied subjects (9 males and 4 females) between the ages of 18 and 30 (Mean age 21.9 +/- 1.9) from the University of Delaware Community. Subjects reported no history of lower extremity orthopedic, neurological, vascular, or cardiac problems, or neoplasms, serious injuries (muscle tears, or sprains, or fractures) involving the leg to be tested. Subjects did not have blood vessel disease involving either arteries or veins of the leg, such as, but not limited to, blood clots, or blockage of the blood vessels. Neither did they report imposed limitations in activity due to heart disease or uncontrolled high blood pressure, cancer, known neurological disorders, or muscle diseases (such as, but not limited to multiple sclerosis, nerve injury, polio, muscular dystrophy or myotonia). Each subject signed an informed consent form that was approved by the University of Delaware Human Subjects Review Committee.

Subjects were terminated from the study if they were unable to voluntarily generate ≥95% of their muscle's maximal force generating ability from their ankle plantarflexor muscles during the Burst Superimposition Technique in 3 attempts. Subjects were also terminated from the study if they requested to be excluded from the study.

2.2 Apparatus

For each testing, the subjects lay supine on a KIN-COM III dynamometer (Chattecx Corp, Chattanooga, Tennessee) with their ankle in neutral position. Three Velcro straps held the foot firmly against the foot platform, one Velcro strap was fastened around the proximal shank, and seatbelts attached to the bench at hip-level were fastened around the subjects' shoulders to reduce body movement during muscle contractions. All electrical pulses were delivered via two 3-by-5 inch self-adhesive surface electrodes attached to the skin overlying the bulk of the ankle plantar-flexor muscles. Electrical pulses were delivered using a Grass S8800 stimulator and customized software (LabView 5.1, National Instruments, Austin, Texas).

2.3 Experimental Protocol

2.3.1 Set Up

Two surface electrodes were first placed over the motor point of the ankle plantar-flexors of the leg being tested. Subjects were asked to stand on their toes in order to locate the bulk of the plantarflexor muscle. Placement was tested by delivering a train (30 Hz 300 ms 600µs pulse duration) of low voltage. The voltage was slowly increased until the subject felt familiar with the stimulation, and visual plantarflexion of the ankle was observed. The subject then lay supine on the bench of the force dynamometer and their foot was positioned in the foot platform with their ankle in a neutral position. The subjects were strapped to prevent movement and a wedge and pillow were used to support their heads.

After set-up was complete, 3 groups of tests were administered (the Submaximal Burst Superimposition Test, the Twitch and Doublet Interpolation Techniques, and the Twitch to Tetanus Ratio Method) (fig.1). The tests were performed in a random order. Subjects were unstrapped between each test and given time to rest. At the start of each test, a Burst Superimposition Test at maximal effort was administered. Once this was complete, the rest of the testing followed within 2 minutes.

Chart Showing Experimental Protocol

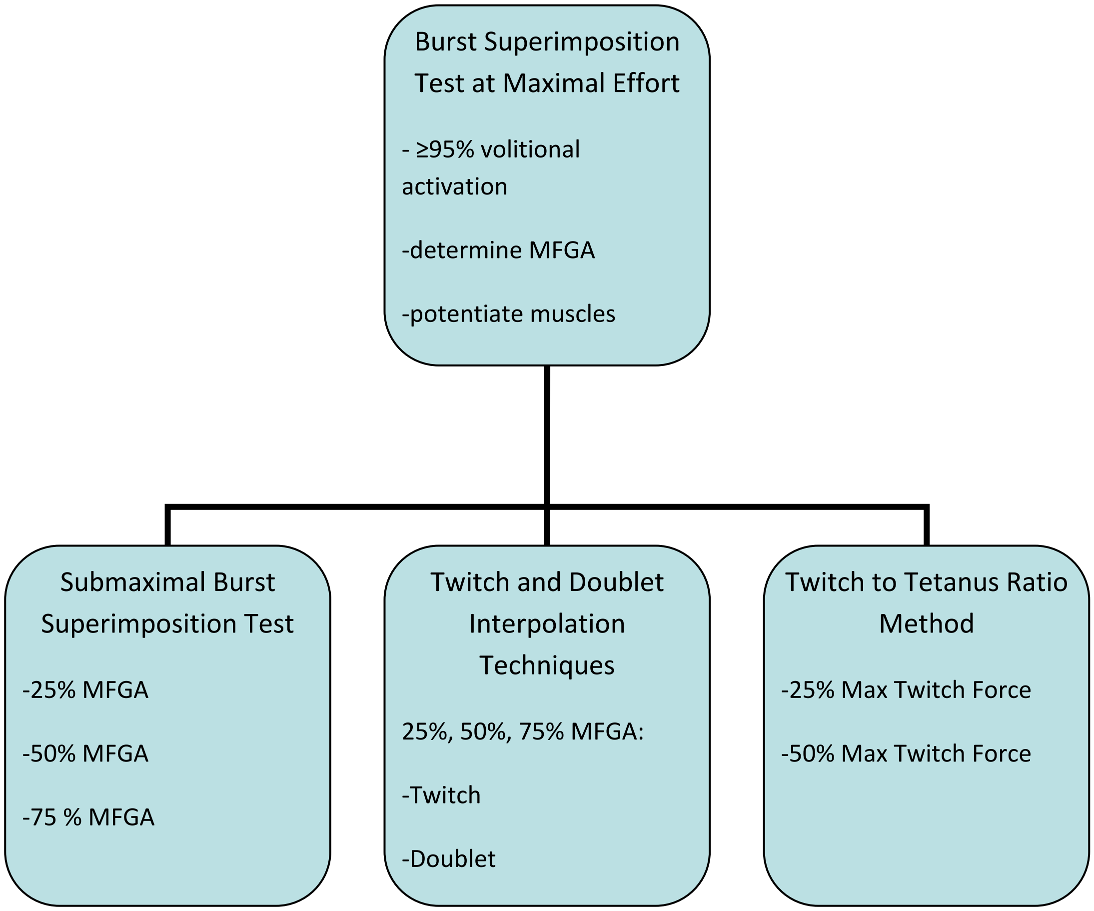

Figure 1. The layout of experimental testing. A Burst Superimposition Test at maximal Effort was performed three times, once before each of the 3 methods being tested. The order of the 3 methods (the Submaximal Burst Superimposition Test, the Twitch and Doublet Interpolation Techniques, and the Twitch to Tetanus Ratio Method) was randomized.

2.3.2 Burst Superimposition Test at Maximal Effort:

This test required the subject to contract their muscle maximally for four seconds. Two seconds into their maximal contraction, a maximal electrical stimulation burst (600 µs pulse duration, 100 ms train duration, 135 V, 100 Hz train) was superimposed over their contraction. If the subject was not able to contract their muscle with 95% volitional activation or greater in three attempts, the testing was not continued and the subject was asked to return on another day. If the subject could not reach 95% volitional activation after trying for 2 days, they were discontinued from the study. If at least 95% volitional activation was achieved, the testing continued. The maximum force recorded during the Burst Superimposition Test prior to the test being administered was used as the subject's Maximum Force Generating Ability (MFGA) value, and sub-maximal volitional contractions will be calculated using this value. This Burst Superimposition Test was also used to potentiate the muscle for the test that followed (i.e., Submaximal Burst Superimposition Test, Twitch and Doublet Interpolation Technique, Twitch to Tetanus Ratio Method).

2.3.3 Test 1. Submaximal Burst Superimposition Test:

First a maximal single pulse (600 µs, 135 V) was delivered to the resting muscle to initiate the start of the test for timing purposes. The subject then produced a ~4 second-long sub-maximal contraction that produced either 25%, 50%, or 75% of the subject's MFGA (force of the contraction with aid from the stimulation) found by the Burst Superimposition test at maximal effort performed prior to this test. The order of the volitional forces tested was randomized. The subject accomplished the force goal by matching the set target force using visual feedback of the dynamometer. About 2 seconds into the sub-maximal contraction (5 seconds after the initial single pulse), a maximal train (600 µs pulse duration, 100 ms train duration, 135 V, 100 Hz train) was superimposed over the contraction.

2.3.4 Test 2. Twitch and Doublet Interpolation Techniques:

The Twitch and Doublet Interpolation Techniques were each performed with a volitional force of 25%, 50%, and 75% the subject's MFGA determined immediately prior to this test. Each of these combinations (twitch or doublet, and value of volitional force) was randomized to determine the order of testing.

2.3.4.1 Twitch Interpolation

First a maximal single pulse (600 µs, 135 V) was delivered to the resting muscle. Then, the subject produced a ~4-second long sub-maximal contraction that produced 25%, 50%, or 75% of the subject's MFGA. They accomplished this by attempting to produce the set target force on the feedback screen of the dynamometer. About 2 seconds into the sub-maximal contraction, a second single maximal pulse was administered (600 µs, 135 V).

2.3.4.2 Doublet Interpolation

Two maximal pulses (600 µs, 135 Volts) with an interpulse interval (ipi) of 5 milliseconds were initially delivered to the resting muscle. Then, the subject produced a ~4-second long sub-maximal contraction that produced 25%, 50%, or 75% of the subject's MFGA force. They accomplished this by attempting to produce the set target force on the feedback screen of the dynamometer. About 2 seconds into the sub-maximal contraction, two more maximal pulses were administered (600 µs, 135 V, 5 ms ipi).

2.3.5 Test 3. Twitch to Tetanus Ratio Method (TTR)

Eight single pulses (135 volts) were administered to the resting muscle with ~5 seconds rest between each pulse. The pulses began at a pulse duration of 20 microseconds and increased until the eighth pulse was delivered at 600 microseconds. The resulting forces of these pulses were recorded and used to plot the pulse duration versus force production curve of the muscle. The following 2 tests were administered in a random order with ~ 30-60 seconds rest in between.

2.3.5.1 25% Twitch and Train

Using the data from the pulse duration versus force curve, the pulse duration that would produce 25% of the maximum twitch force was determined. A pulse of this duration and 135 Volts was administered to the resting muscle, followed ~5 seconds later by a train of the same pulse duration (135 V, 100 Hz, 500 ms train duration).

2.3.5.2 50% Twitch and Train

The pulse duration that would produce a force equal to 50% of the maximum twitch force was also determined. A pulse of this duration and an amplitude 135 Volts was administered to the resting muscle, followed ~5 seconds later, by a train of the same pulse duration (135 V, 100 Hz, 500 ms Train Duration).

2.4 Corrected Predicted Central Activation Ratio (CAR)

Preliminary analysis of the data showed that the Submaximal Burst Superimposition Test consistently overestimated volitional activation and underestimated MFGA for all volitional levels (Fig 2A, 3). There was not a consistent trend of over or under estimating MFGA with any of the other methods (fig. 2 B,C,D). Because of this consistent error, the data had the potential to be corrected and result in a more accurate estimate of MFGA. A Corrected Predicted CAR has been successfully calculated for the Submaximal Burst Superimposition Test in the quadriceps muscles of healthy (20), ACL injured (3), and elderly adults (25). The Corrected Predicted CAR value found more accurate results than the uncorrected method in elderly adults (25), but was not more accurate when studying ACL injured patients (3). However, Corrected Predicted CAR values calculated using all presented equations in the 2000 Stackhouse study were not sufficient to accurately correct the plantarflexor data of this study. Thus, the data from the first six subjects recruited into the study were used to determine the proper correction factor for the human plantarflexor muscles. For the first 6 subjects who completed the Submaximal Burst Superimposition Test, their Predicted CAR was plotted against the Actual % MFGA. The best fit curve was calculated for the relationship. The best fit equation was then used to correct the Predicted CAR data from the final 7 subjects to complete the Submaximal Burst Superimposition Test. The Predicted CAR was substituted as Y, and the best fit equation was solved for X (the Corrected CAR).

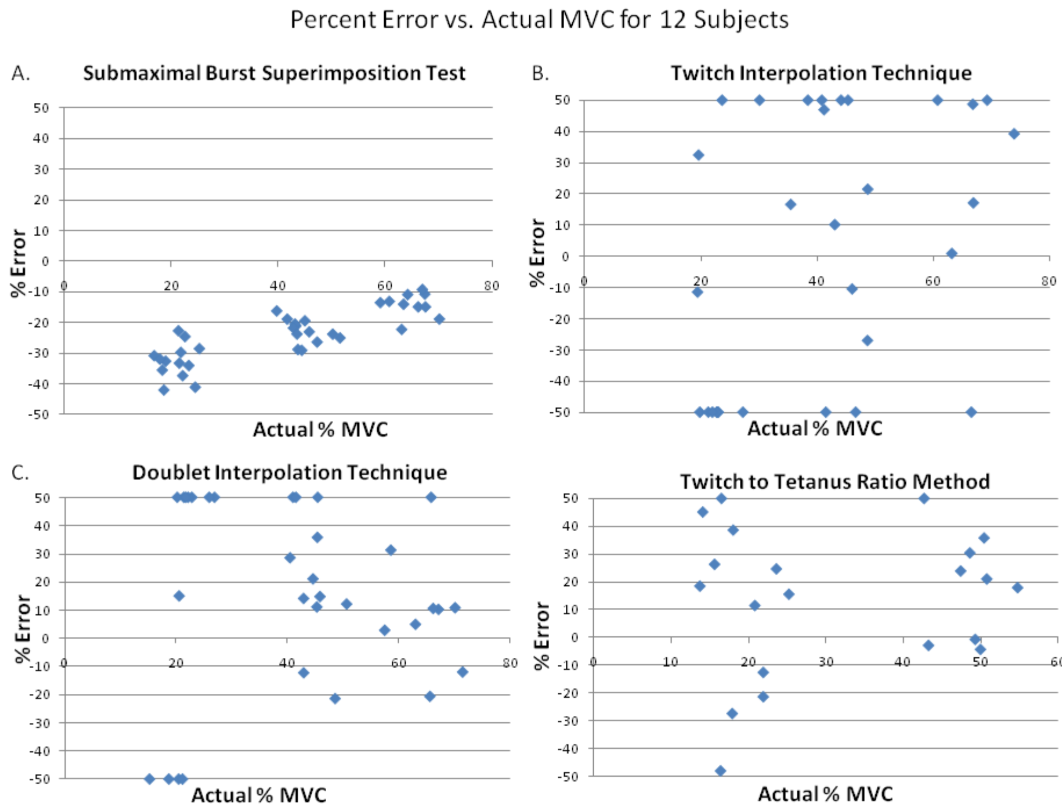

Figure 2. Graphs plotting the resulting Percent Error of Predicted Maximum Force Generating Ability (MFGA) compared to the Actual MFGA against the Actual Volitional Activation for 12 subjects from the Submaximal Burst Superimposition Test (A), the Twitch Interpolation Technique (B), the Doublet Interpolation Technique(C), and the Twitch to Tetanus Ratio Method (D). Data points with error greater than 50% are represented as 50% Error on the graphs.

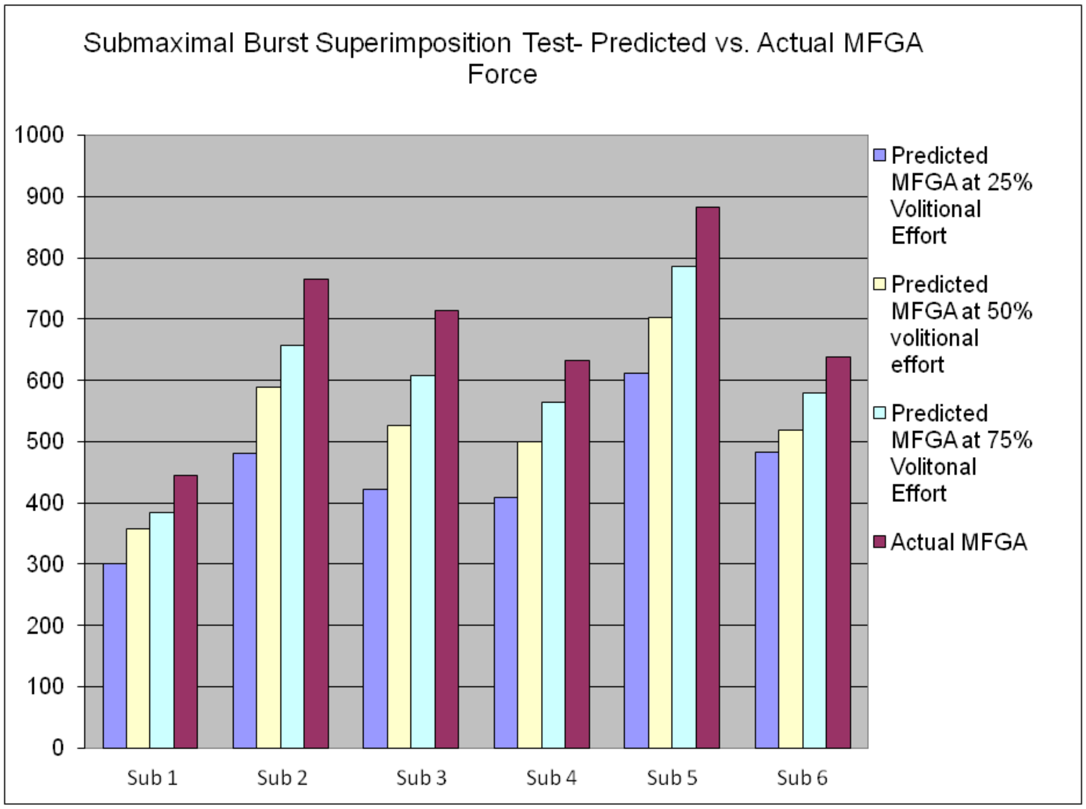

Figure 3. The 25%, 50%, and 75% Submaximal Burst Superimposition Tests consistently underestimated Maximum Force Generating Ability (MFGA) when compared to the Actual MFGA of the first 6 subjects.

2.5 Data Management

Data were analyzed with custom-written software (LabView 5.1, National Instruments, Austin, Texas) (Fig. 4). All baseline force values were taken just before the volitional contraction began. If this baseline force was seemingly higher than the baseline force before and after stimulation occurred, the baseline force before initial stimulation was used. For the Burst Superimposition Tests at maximal effort, the Central Activation Ratio

(CAR) was calculated by dividing the peak force, before 6000 milliseconds (the MVC) by the peak force overall (the Actual MFGA).

The volitional force produced during the for the Submaximal Burst Superimposition, the Twitch Interpolation, and the Doublet Interpolation tests were determined by taking the average force between 5900 and 6000 milliseconds (just before the stimulation was delivered) and subtracting the baseline force value. The Actual Volitional Activation was calculated by dividing the volitional force by the MFGA found in the previous Burst Superimposition Test at maximal effort. The percent error was calculated using this predicted MFGA from the test and the Actual MFGA from the Burst Test at Maximal Effort.

The predicted Central Activation Ratio (CAR) for the Submaximal Burst Superimposition Test was calculated by dividing volitional force during the test by the peak force overall during the submaximal test. The predicted MFGA value was determined by dividing the average volitional force of the submaximal test by the predicted CAR from the submaximal test.

Data processing for the Twitch Interpolation and Doublet Interpolation Techniques were the same. The force from the initial stimulation of the resting muscle was taken relative to the baseline force value just before stimulation. The force of the stimulation superimposed over the volitional contraction was determined by subtracting the volitional force from the peak force overall. Predicted Volitional Activation was calculated by dividing the force of the superimposed stimulation by the force of the stimulation on the resting muscle and subtracting this value from 1. The predicted MFGA was determined to be the volitional force divided by the Predicted Volitional Activation.

For the Twitch to Tetanus Ration Method, the peak forces of the twitches and tetanic contractions relative to the baseline force just before stimulation were used. The Maximum Twitch Force was the force value of the last twitch (600 microseconds, 135 Volt) of the initial 8-twitch series. The Twitch to Tetanus Ratio (TTR) was the force of the submaximal twitch divided by the force of the submaximal tetanic contraction. The Predicted MFGA was calculated by dividing the Max Twitch Force by the TTR.

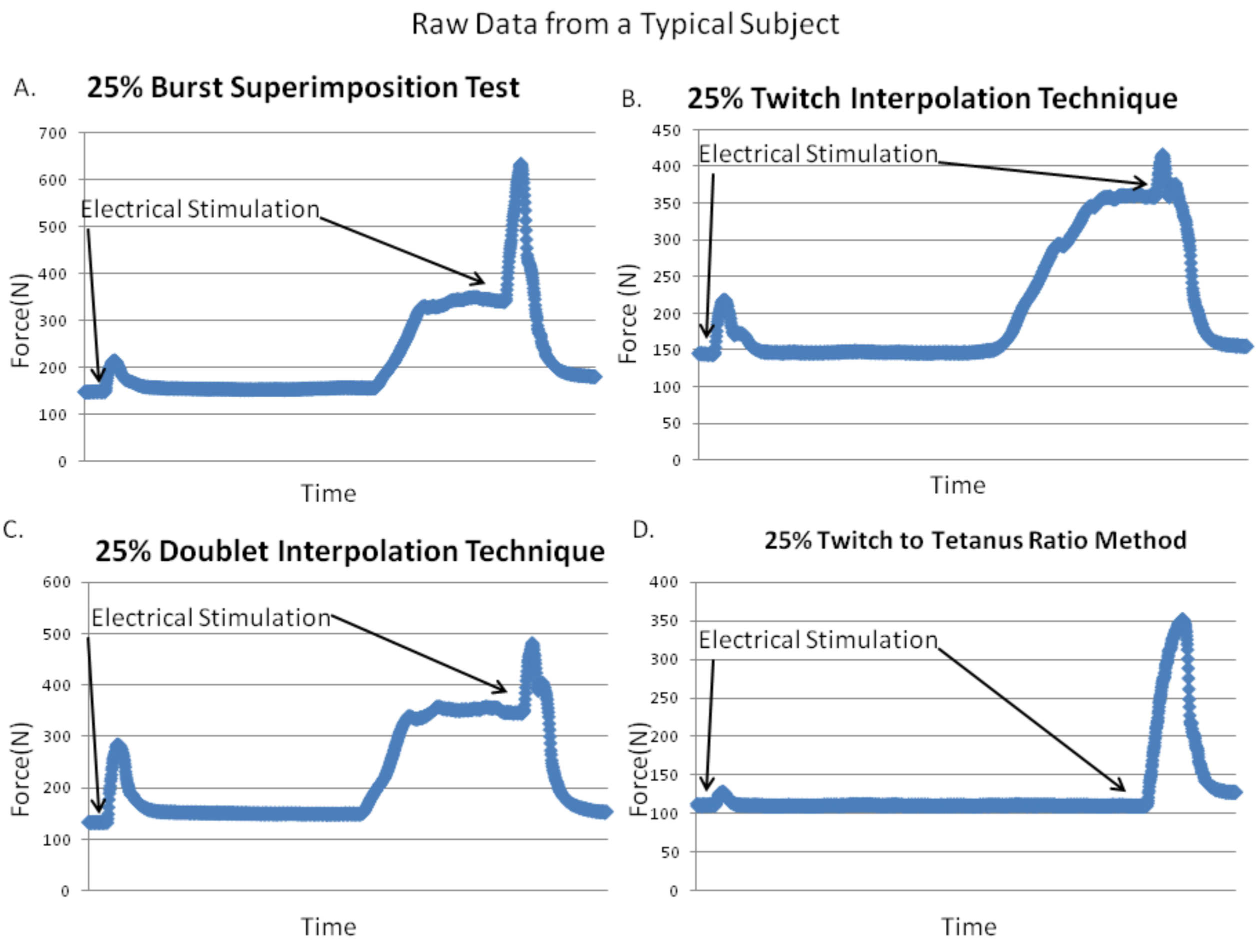

Figure 4. Data from the 25% Submaximal Burst Test (A), 25% Twitch Interpolation Technique (B), 25% Doublet Interpolation Technique (C), and 25% Twitch to Tetanus Ratio Method (25% of maximal single pulse followed by tetanic stimulation) (D) from a typical subject.

Equations

Submaximal Burst Superimposition Test:

A. $$\text{Predicted CAR} = \frac{\text{Vol. Submax Force}}{\text{Peak Submax Force}}$$

B. $$\text{Predicted MFGA} = \frac{\text{Vol. Submax Force}}{\text{Predicted CAR}}$$

Twitch and Doublet Interpolation Techniques:

C. $$\text{Volitional Activation} = 1 - \left(\frac{\text{Superimposed Force}}{\text{Resting Force}} \right)$$

D. $$\text{Predicted MFGA} = \frac{\text{Vol. Submax Force}}{\text{Volitional Activation}}$$

Twitch to Tetanus Ratio Method:

E. $$\text{TTR} = \frac{\text{Submax Twitch Force}}{\text{Submax Tetanic Train Force}}$$

F. $$\text{Predicted MFGA} = \frac{\text{Maximal Twitch Force}}{\text{TTR}}$$

Figure 5. Equations used to compute Predicted Central Activation Ratio (CAR) (A) and Predicted Maximum Force Generating Ability (MFGA) (B) from the Submaximal Burst Superimposition Test, Volitional Activation (C) and Predicted MFGA (D) from the Twitch and Doublet Interpolation Techniques, and the Twitch to Tetanus Ratio (TTR) (E) and Predicted MFGA (F) from the Twitch to Tetanus Ratio Method.

2.6 Data Analysis

Percent Error was calculated by subtraction the Predicted MFGA from the Actual MFGA, and dividing this number by the Actual MFGA. Within each method, Paired T-Tests were performed on the percent errors between Predicted MFGA and Actual MFGA from each of the volitional efforts (i.e., 25% vs. 50%, 25% vs. 75%, and 50% vs. 75% MFGA). A one-way repeated measures analysis of variance (ANOVA) was performed on the percent errors of the 50% volitional effort tests from each method, followed by a Bonferroni post-hoc test. The 50% Volitional Effort Tests were compared due to the fact that poststroke individuals have been found to recruit just over half of the available motor units in their tibialis anterior during walking and volitional contraction (9). A one-way repeated measure analysis of variance (ANOVA) was also performed using the percent errors of the 50% volitional effort tests from the last 7 subjects from each method along with the Corrected Predicted CAR values.

Chapter 3

RESULTS

3.1 Group Data

The Root Means Squared Error (RMSE) was calculated by squaring the percent error between Predicted and Actual MFGA. The square root of the sum of these squared percent errors were divided by the number of subjects to yield the Root Means Squared Error (RMSE). The RMSE and range of the percent errors of the Submaximal Burst Superimposition Test data (13 subjects) for 25%, 50%, and 75% MFGA were 33.0 (19.2), 23.2 (12.8), 15.5 (12.9), respectively (Table 1). The 75% Submaximal Burst Superimposition test showed the lowest RMSE out of all test results at all volitional levels of activation (excluding the Corrected Burst Superimposition Test), followed by the Submaximal Burst Superimposition Test at 50%. The Submaximal Burst Superimposition tests at 75% and 50% volitional levels also had the 2 lowest ranges of percent error out of all test and all volitional levels of activation.

The RMSE of the Twitch to Tetanus Ratio Method (12 subjects) at 25% and 50% were both lower than the 25% Submaximal Burst Superimposition Test, with the 50% TTR Method having the lowest RMSE for the volitional levels of the Twitch to Tetanus Ratio Method. The ranges for both the 50% and 25% Twitch to Tetanus Methods were larger than any of the volitional levels of the Submaximal Burst Tests and were the 4^{th} and 5^{th} smallest values overall for uncorrected methods.

The largest RSME values (from highest to lowest) resulted from the 75%, 50%, and 25% Twitch Interpolation Technique (12 subjects). The Twitch Interpolation Tests also resulted in the 3 largest range values of all uncorrected methods and all volitional levels. The 75%, 50%, and 25% Doublet Interpolation Method (12 subjects) had the 6^{th}, 7^{th}, and 8^{th} highest RSME values and corresponding ranges for uncorrected data, respectively.

3.2 Correction Equation

The equation of best fit (shown in figure 6), derived from the relationship between Predicted CAR and Actual % MVC for 6 subjects who completed the Submaximal Burst Superimposition Test, resulted in a coefficient of determination of .9915 (fig. 6). The Corrected Predicted CAR values for the 25%, 50%, and 75% Submaximal Burst Superimposition Test (7 subjects) resulted in RSME (and Range) values of 9.4 (27.9), 8.2 (21.9), 7.0 (16.1), respectively (Table 1). This Corrected Submaximal Burst Superimposition Method resulted in the lowest overall RSME values.

Table 1. The Root Means Squared Error (RMSE) and Range for data on all subjects in each volitional level (25%, 50%, 75%) and Method and for the Corrected Submaximal Superimposition Test Results for 7 subjects.

Method		Volitional Level		
		25%	50%	75%
Submaximal Burst Superimposition	RMSE	33.0	23.2	15.5
	Range	19.2	12.8	12.9
Twitch Interpolation	RMSE	1164.8	1307.0	5611.1
	Range	4696.3	4693.5	19845.6
Doublet Interpolation	RMSE	790.9	117.9	53.0
	Range	2360.8	409.8	197.9
Twitch to Tetanus Ratio Method	RMSE	31.4	25.8	N/A
	Range	99.5	72.6	N/A
Corrected Submaximal Burst (final 7)	RMSE	9.4	8.2	7.0
	Range	27.9	21.9	16.1

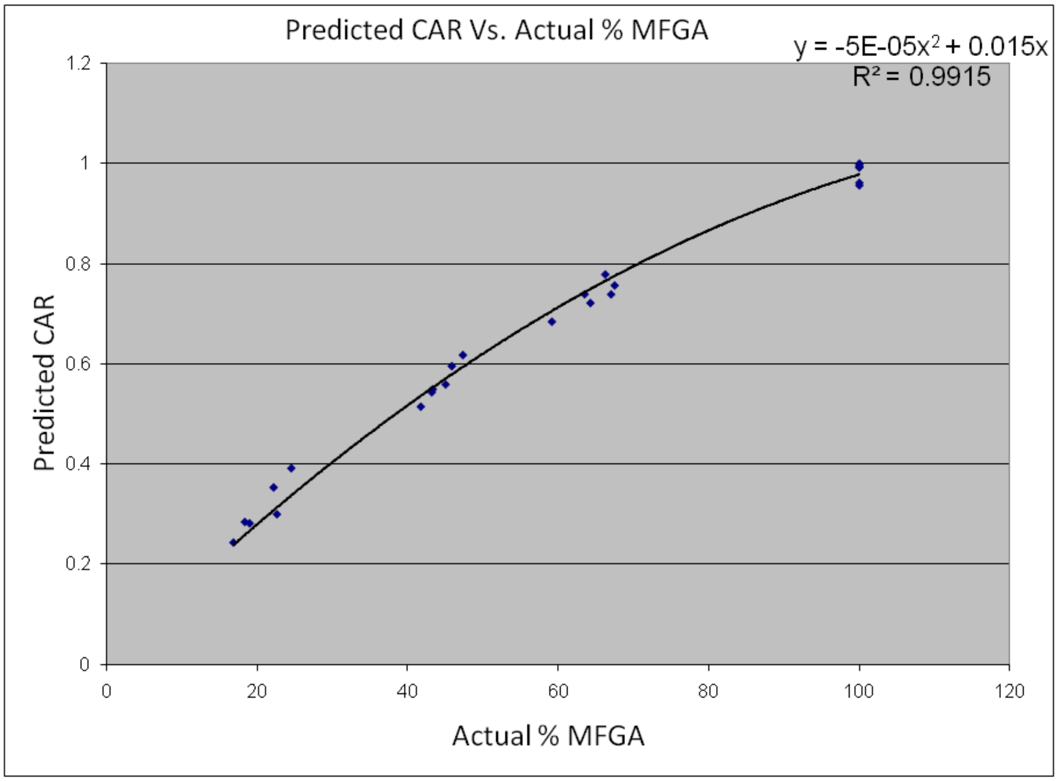

Figure 6. A best fit curve and coefficient of determination were calculated for the first 6 (out of 13) subjects to complete the Submaximal Burst Superimposition Test by plotting Predicted Central Activation (CAR) against Actual Percent Maximum Force Generating Ability (MFGA). This equation was then used to calculate a Corrected Predicted CAR value for the remaining 7 subjects by substituting the Predicted CAR as Y and solving for X.

3.3 Statistical Results

One of the 13 subjects did not entirely complete the testing session. This subject's data was used for equation-modeling purposes, but not included in statistical analysis. Significant differences were found between the % Error of the volitional levels of the Submaximal Burst Superimposition Test (P=.05). All other methods showed no significant differences between the tests of 25%, 50%, and 75% volitional efforts. No significant differences were found between methods (including Corrected Predicted CAR values) at 50% volitional efforts. However, these results may be due to the large standard deviation of methods with inconsistent results (fig. 7, 8).

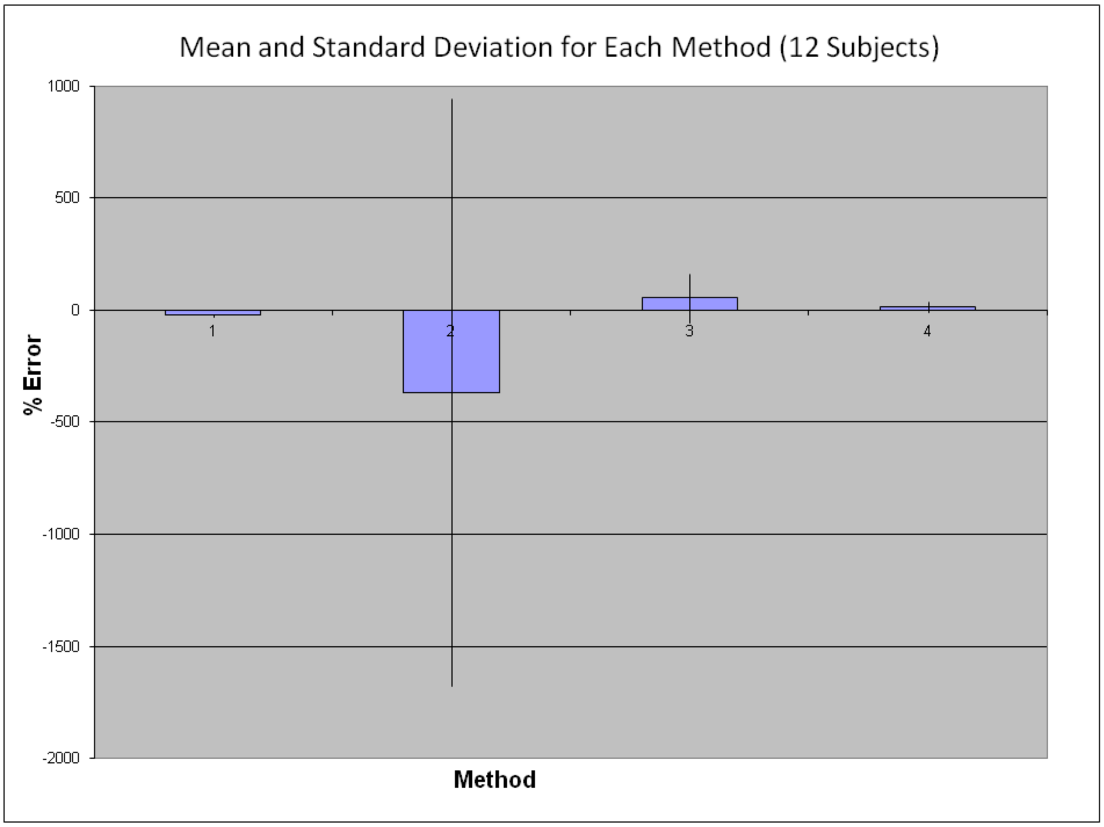

Figure 7. The mean and Standard Deviation of the Percent Error from the Submaximal Burst Superimposition Test (1), the Twitch Interpolation Technique (2), the Doublet Interpolation Technique (3) and the Twitch to Tetanus Ratio Method (4) for 12 subjects.

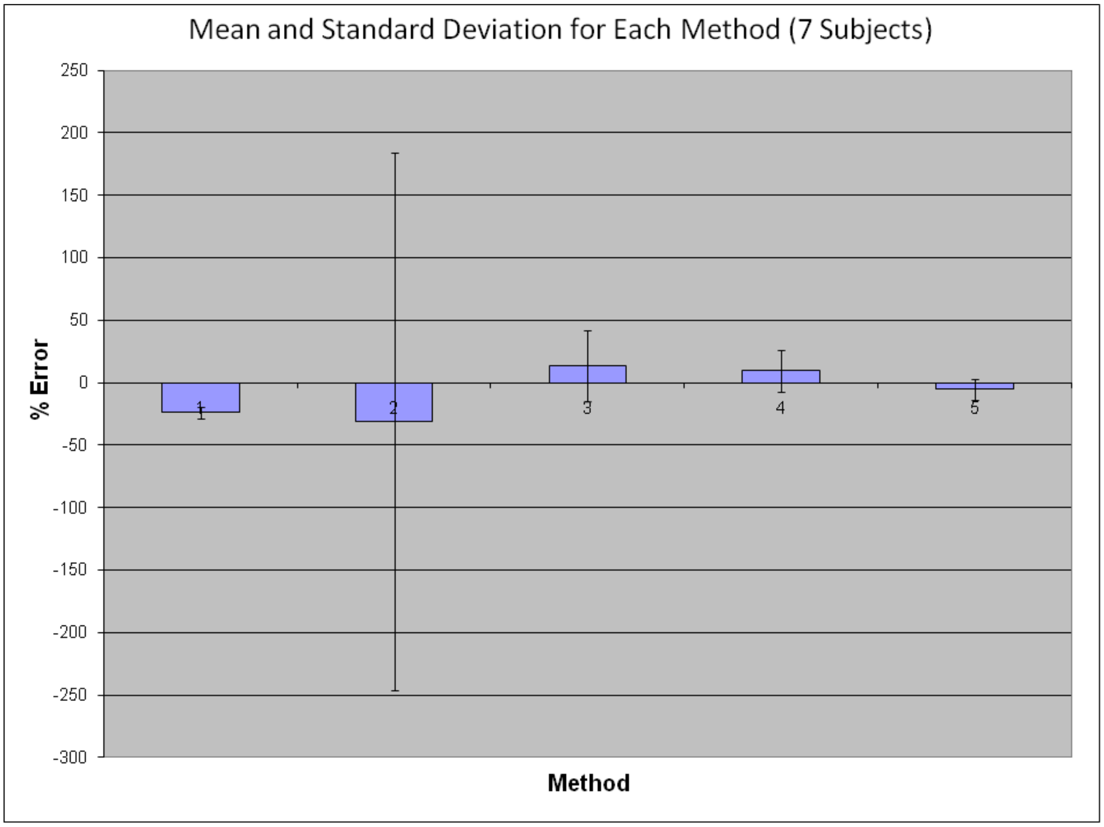

Figure 8. The mean and Standard Deviation of the Percent Error from the Submaximal Burst Superimposition Test (1), the Twitch Interpolation Technique (2), the Doublet Interpolation Technique (3), the Twitch to Tetanus Ratio Method (4), and the Corrected Submaximal Burst Superimposition Test (5) for the final 7 subjects to complete the study.

Chapter 4

DISCUSSION

Studies that have used multiple twitches or doublets to assess muscle activation have been more sensitive in measuring decreased activation in the elderly than those that have used single twitch interpolation (16, 10). Between all uncorrected methods in the present study, the Submaximal Burst Superimposition Test at 50% and 75% had the lowest RMSE and range. While the Twitch Interpolation Technique found no activation difference between young and elderly adults (2, 28), one study that used the Doublet Interpolation Technique did find a difference (17), as did studies using the Burst Superimposition Technique (10, 22, 24, 30). Kent-Braun and colleagues also concluded the Burst Superimposition Test to be more sensitive than the Twitch or Doublet Interpolation Techniques when measuring volitional activation of the healthy nonfatigued subjects, healthy fatigued subjects, and subjects with amyotrophic lateral sclerosis (10). These findings illustrate the increased sensitivity of Burst Superimposition Test to detect muscle inactivation compared to either the Twitch and/or Doublet Interpolation Methods (10).

The increased accuracy of methods that use a tetanic stimulation when compared to a single or double pulse may be due to the summation of force created by increased frequency of stimulation before the muscle fiber is given time to relax (29). The Burst Superimposition test delivers a tetanic stimulation over the volitional contraction that may allow for a greater summation of force compared to either the Twitch or Doublet Interpolation Methods (10).

Negative volitional activation values were predicted by the Twitch Interpolation Technique and the 25% Doublet Interpolation Method (See Appendix A). Behm and colleagues also found the Twitch Interpolation Technique predicted negative volitional activations (1). A negative volitional activation occurs because the force of the superimposed twitch is greater than the force of the twitch on the resting muscle. Behm suggested that the difference in sensitivity between the Burst Superimposition Test and the Twitch to Tetanus Ratio method may be due to which forces the methods compare in order to calculate volitional activation (1). While the subject is actively contracting their target muscle, stabilizing muscles are also active. This could increase the target muscle's efficiency and increase force output. While the Burst Superimposition test compares a superimposed stimulation force to the force of a voluntary contraction, the Interpolation Methods compare the superimposed force to the force produced by stimulation on a resting muscle (1). A pulse delivered to the resting muscle may work to initiate contraction of the muscle, but some force is used in taking up slack in these components. The pulse delivered during the voluntary contraction is able to produce a greater force because the subject has voluntarily stretched the elastic components of the tendons and muscle.

Consistent with the findings of this study, the Submaximal Burst Superimposition Test has previously been shown to overestimate volitional activation because the superimposed burst does not create a force equal to the force elicited during a maximal effort Burst Superimposition Test (22). It is thought that a train that is longer in duration would show a higher and more accurate superimposed force, but this would greatly increase subject discomfort (22). This consistent error in predicting the Actual MFGA allowed for the creation of an equation that uses the Predicted CAR to calculate the Corrected Predicted CAR for the Submaximal Burst Test. No correction equation could be created for the other methods in this study because they did not consistently under- or over-estimate the MFGA.

The results of this study indicate that the Burst Superimposition Test may be an accurate tool in measuring volitional activation on those with neurological impairments if modified by the correction equation. Studies have shown that there is a 15% physiological variability in the force output of a muscle (12), and that individuals with stroke show increased variability (12). Therefore, a method that predicts the muscle's MFGA within 15 percent error is as accurate as possible due to the muscle's fluctuations in force output. Unfortunately, the more comfortable methods, which required less stimulation (10) were not able to produce this degree of accuracy.

If no correction is used, the Twitch to Tetanus Ratio Method is almost as accurate as the uncorrected Submaximal Burst Superimposition Test when looking at the RMSE. However, it is not as consistent in its predictions, and does not always over- or under-estimate MFGA. At the 25% volitional levels, the Twitch to Tetanus Ratio Method has a somewhat smaller RMSE than that Submaximal Burst Superimposition Test, but a greater range of values. This method needs to be refined in order to produce greater consistency in its predictions.

Chapter 5

CONCLUSION

The use of the Burst Superimposition Test gives the most accurate prediction of submaximal volitional activation of the ankle plantarflexor muscles of healthy adults. The test overestimates volitional activation, but accurate within the limitations set by a muscles physiological variability (+/- 15 %) when corrected by the equation presented in this study (12). The Twitch Interpolation Technique and the Doublet Interpolation Technique, which required less stimulation than the Burst Superimposition Test did not accurately predict the volitional activation. The Twitch to Tetanus Ratio Method, which required no voluntary effort from the subjects, showed promising results at low volitional levels.

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APPENDIX A

Percent Errors between predicted MFGA and Actual MFGA

	Burst Superimposition Test				Twitch Interpolation Technique		
Vol. Level	25%	50%	75%		25%	50%	75%
Sub 1	-32.506626	-19.414276	-13.5451208		N/A	N/A	N/A
Sub 2	-37.187304	-22.988113	-14.0602077		-1041.1337	121.35822	103.66241
Sub 3	-40.928905	-26.301274	-14.9086167		-919.06294	-4492.7719	413.68084
Sub 4	-35.396722	-21.110714	-10.7931911		-164.05633	46.947852	16.585712
Sub 5	-30.716572	-20.478243	-10.9210802		-208.17833	83.2701	-19431.931
Sub 6	-24.528467	-18.86757	-9.27672488		630.49531	68.44441	17.083211
Sub 7	-33.152637	-28.710619	-22.2100895		32.435582	-486.74953	0.8699422
Sub 8	-22.650595	-16.215856	-13.1273656		2582.4869	21.468709	39.232722
Sub 9	-28.431325	-23.746942	-18.8453673		-1295.1966	-10.505389	48.710233
Sub 10	-29.648561	-21.776331	-14.9073566		-11.494802	10.118294	29.031816
Sub 11	-41.846223	-28.970758	-19.7426361		-360.71404	-27.039424	30.550079
Sub 12	-33.905934	-24.971303	-17.5254732		-2113.8243	200.70735	24.587698
Sub15	-31.848998	-23.719201	-16.0361236		968.11847	75.503944	137.92841
	Doublet Interpolation Technique				TTR		
Vol. Level	25%	50%	75%		25%	50%	
Sub 1	N/A	N/A	N/A		N/A	N/A	
Sub 2	-2041.5044	35.78093	31.25707157		24.672007	-4.2761388	
Sub 3	-1669.2148	388.32556	177.2805984		-21.300253	-0.6917952	
Sub 4	319.27398	11.085308	-20.6565762		45.112843	23.91564	
Sub 5	-373.11492	28.534929	4.923041019		11.509909	61.805179	
Sub 6	264.01053	87.218035	10.22846245		15.558209	35.799623	
Sub 7	-224.8004	67.153782	10.80561908		-27.338371	-2.8388614	
Sub 8	211.09544	14.092879	2.814564872		-12.563908	17.929351	
Sub 9	66.343601	-21.438801	-12.0214966		51.557411	30.413838	
Sub 10	53.711159	21.0525	10.54387432		38.636938	21.042167	
Sub 11	15.008076	-12.28556	-12.5447659		-47.974649	-10.748905	
Sub 12	226.92116	12.135069	-5.65058522		26.312683	-8.7496496	
Sub15	295.70647	14.771209	15.08649084		18.484715	20.453785	

HUMAN SUBJECTS PROTOCOL
University of Delaware

Protocol Title: Predicting Maximum Force Generating Ability of Skeletal Muscle using Submaximal Contractions

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Type of Review: Exempt Expedited ✓Full Board

Exemption Category: 1 2 3 4 5 6

Minimal Risk: ✓ yes ______ no

Submission Date: May 4, 2009

HSRB Approval Signature	Approval Date 6/1/09
HS Number HS09-672	Approval Next Expires 5/31/10

Investigator Assurance:
By submitting this protocol, I acknowledge that this project will be conducted in strict accordance with the procedures described. I will not make any modifications to this protocol without prior approval by the HSRB. Should any unanticipated problems involving risk to subjects, including breaches of guaranteed confidentiality occur during this project, I will report such events to the Chair, Human Subjects Review Board immediately.

Signature of Principal Investigator: ______________________________

Date: ______________________________

Signature of Faculty Advisor: ______________________________

Date: ______________________________