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USING SUBMAXIMAL CONTRACTIONS TO PREDICT THE MAXIMUM FORCE GENERATING ABILITY OF MUSCLES

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Abstract

Introduction—Muscle weakness can be caused by decreases in either the maximum force generating ability of a muscle (MFGA) or neural drive from the nervous system (e.g., following a stroke). Presently, there is no agreed upon practical method for calculating the MFGA in individuals with central nervous system pathology. The purpose of this study was to identify the best method of determining the MFGA.

Methods—The predicted and estimated MFGA of the muscles of 23 non-neurologically impaired subjects (13M, 21.9 +/- 1.9 years) were compared using the burst superimposition, twitch interpolation, doublet interpolation, twitch-to-tetanus ratio, and adjusted burst superimposition methods.

Results—The adjusted burst superimposition test was the most accurate predictor of MFGA.

Discussion—Further testing is needed to validate the use of the adjusted burst superimposition test in a neurologically impaired population.

Keywords

Maximum force generating ability; Volitional activation ratio; Burst superimposition; Twitch interpolation; Doublet interpolation

Introduction

Individuals with upper motor neuron pathologies such as stroke can demonstrate weakness due either to muscle atrophy secondary to disuse or decreased voluntary muscle activation caused by the neurological impairment (1-8). Determining specific causes of the muscle weakness in neurologically impaired populations may be important for choosing appropriate rehabilitation programs for each patient (5-7, 9). For example, strength training may be sufficient to increase strength in individuals who have considerable muscle atrophy and minimal neurological impairment. In contrast, individuals with high degrees of neurological impairment due to impaired central activation may require rehabilitation programs that involve electrical stimulation or biofeedback to better activate their muscles and therefore achieve greater strength gains (6, 7, 9). Unfortunately, no clinical method currently exists for determining the extent of neurologically-caused weakness in individuals with central nervous system impairment.

The volitional activation ratio (VAR) is a measure of the volitional muscle activation at any level of effort. In contrast, the maximum force generating ability (MFGA) of the muscle represents the force the muscle is capable of generating with full muscle activation (1). Thus,

$$VAR = \frac{F_{vol}}{MFGA} \quad (1)$$

where F_{vol} is the volitional force (2, 5-7, 9, 10). A VAR of 1 means the muscle is fully activated by the volitional effort (2, 5-7). A $VAR < 1$ means the individual is not fully activating the muscle (5-7). F_{vol} is typically measured isometrically and can be directly measured using a force dynamometer (2, 5-7, 10). In contrast to the F_{vol} , there are no known methods that have been shown to accurately and reliably estimate the MFGA or VAR in neurologically impaired individuals. However, if we can determine the MFGA, we can use equation (1) to calculate the VAR for any level of force (2, 5-7, 10). Likewise, by determining VAR we can calculate MFGA for any level of force (1).

Previous studies have used the burst superimposition technique to estimate the MFGA in individuals with no neurological impairment (2, 5, 7, 9, 11). During the burst superimposition technique, a train of maximal electric pulses is delivered to the subject during a maximal voluntary isometric contraction. The MFGA of the muscle is the total force produced by the volitional contraction and the stimulation. This technique has been used at maximal (7, 9, 10-15) and submaximal volitional effort levels (5, 6, 16) to predict the VAR in several populations. It tends to over-estimate the activation of a muscle at submaximal volitional levels (5, 6) and may be an insensitive estimate of activation at high volitional effort (7, 9). An equation that corrects the predicted VAR has been tested for evaluating the quadriceps femoris muscles (5, 6, 9, 11) of healthy adults (5), those with ACL injury (11), and older adults (6, 9). The accuracy of the predicted VAR has not been determined in individuals with nervous system pathologies (15, 17) and the equation used to correct the burst superimposition technique for the quadriceps femoris muscles has not been validated for use in any other muscle group.

The twitch interpolation (1-3, 8, 10, 18-25) and doublet interpolation (2, 16, 26-31) techniques have also been used to estimate the VAR of a muscle. These interpolation techniques deliver either a single (twitch) or two closely spaced supramaximal pulses (doublet) to the resting muscle and also during a volitional muscle contraction (2, 8, 10, 16, 18, 19). The VAR is determined by calculating the ratio of the force produced by stimulation on the contracting muscle to the force produced by stimulation of the resting muscle, and subtracting this number from 1 (2, 7, 8, 18, 19, 24). Both the twitch and doublet interpolation techniques have been reported to overestimate muscle activation (2, 16, 30).

A novel method, the twitch-to-tetanus ratio, directly assesses the MFGA of the muscle. This method involves stimulating a resting muscle with a supramaximal single pulse, a submaximal single pulse, and submaximal stimulation train. The twitch-to-tetanus ratio at submaximal intensities is assumed to be equal to those at supramaximal intensities. Thus, the ratio of the submaximal twitch force to the submaximal train force is set equivalent to the ratio of the maximal twitch force to the unknown maximal train force. Solving for the unknown maximal train force gives an estimate of the MFGA of the muscle. Our preliminary study using the twitch-to-tetanus ratio method in post-stroke individuals showed promising results (32).

The purpose of this study was to determine which of the four methods, the burst superimposition, the twitch interpolation, the doublet interpolation, or the twitch-to-tetanus ratio, most accurately estimates MFGA. We compared the predicted MFGA of the ankle

plantarflexor muscles of able-bodied individuals as calculated by these four methods at submaximal targeted forces. These forces were designed to represent the reduced activation (1, 2, 6, 7) of individuals with neurological impairment. In addition, a modified version of the burst superimposition test introduced and evaluated.

Materials and Methods

Data were collected from 23 able-bodied, non-obese subjects (13 males and 10 females) between the ages of 18 and 30 (Mean age 21.9 $\pm$ 1.9, all BMIs <30) from the University of Delaware community. Each subject signed informed consent forms approved by the University of Delaware Human Subjects Review Board.

Electrical pulses were delivered using a Grass S8800 stimulator (Grass Technologies, Warwick, RI) with a SIU8T stimulus isolation unit and two self-adhesive surface electrodes (Versa-Stim 3" $\times$ 5", CONMED Corp., New York, USA). A personal computer using customized software (LabView 5.1, National Instruments, Austin, Texas) was used to control the timing of all electrical pulses delivered to the subjects. The cathode was placed over the proximal area of the ankle plantar flexors, and the anode was placed on the distal portion of the muscle belly of the calf being tested (33).

During testing, subjects lay supine on a KIN-COM III dynamometer (Chattecx Corp, Chattanooga, Tennessee) with the knee extended and the ankle in neutral position. Three inelastic straps with Velcro closures held the foot firmly against the foot platform. One inelastic strap with a Velcro closure was fastened around the proximal shank. Two inelastic straps with buckle closures were anchored to the bench at hip-level and used as trunk restraints which wrapped around the contralateral shoulder to reduce body displacement away from the foot platform during muscle contractions. This ensured that all forces generated by the plantar flexor muscles were captured by the force transducer and were not channeled into body movements.

Experimental Procedure

The estimated MFGA of the muscles was measured by having subjects produce a maximal volitional contraction using stimulation (600- μ s pulse duration, 100-ms train duration, 135 V, 100-Hz train) to determine if maximal force was generated (5-7). The voltage was set at 135V, the maximum voltage the stimulator is capable of producing. Previous experience in our laboratory showed that 135V was well tolerated by most subjects and was capable of producing maximal or near maximal muscle forces from the quadriceps femoris muscle, which is much larger than the plantar flexor muscles studied here (5-7). If a subject was unable to volitionally produce 95% of the total force, the trial was not considered a true estimation of the muscle's MFGA, and the test was repeated. If the subject was unable to volitionally produce 95% of the total force in three attempts, the session was terminated, and the subject was asked to return on another day. If the subject was unsuccessful in producing 95% of the total force on the second day, the subject was dropped from the study (5-7, 10). Immediately after the subject reached 95% of total force, testing proceeded to the next bout of tests within two minutes to ensure the muscles were potentiated but not fatigued (34). For the purposes of this study, MFGA was operationally defined as the peak force during a maximal volitional contraction with electrical stimulation superimposed over the contraction. The peak force was assumed to be approaching the MFGA in able-bodied individuals and was used as the subject's estimated MFGA. We appreciate that this peak force may not be the actual MFGA of the subject. The estimated MFGA was used to calculate the targeted submaximal targeted forces for each subject to be used during the bout of tests that followed immediately.

The four tests were administered in three bouts (Fig.1). The estimated MFGA for each subject was reassessed at the start of each bout of testing. One bout included the submaximal burst superimposition test. Another bout tested the twitch and doublet interpolation techniques. A third tested the twitch-to-tetanus ratio method. The testing order of the three bouts was selected randomly for each session. Within the three bouts, the order of testing of the targeted force levels tested was randomized (25%, 50%, and 75% of estimated MFGA). Within the twitch and doublet interpolation test group, all six trials were randomized (3 force levels, 2 stimulation types). Subjects were allowed to stand up and ambulate between bouts of testing.

Data were analyzed using custom-written software (LabView 5.1, National Instruments, Austin, Texas) (Fig. 2). Baseline force values were subtracted from all measurements.

The volitional force (F_{vol}) produced for the burst superimposition, the Twitch interpolation, and the doublet interpolation tests was determined by taking the average force in a 100-ms window just before the stimulation was delivered. Estimated VAR was calculated by dividing the F_{vol} by the estimated MFGA.

Submaximal burst superimposition test

The submaximal burst superimposition first delivered a maximal single pulse (600 μ s, 135 V) to the resting muscles. Two seconds after the initial pulse, subjects were instructed to contract their muscles and maintain volitional force production through the delivery of stimulation. For submaximal targeted force levels, subjects attempted to match their volitional forces to the targeted force level as shown on the visual feedback screen of the dynamometer. The subjects' forces were monitored throughout the trial and were stored on a personal computer for later analysis. The superimposed stimulation burst stimulation burst (600- μ s pulse duration, 100-ms train duration, 135 V, 100-Hz train) was delivered to the volitionally contracted muscles 5 seconds after the first pulse (3 seconds following the initiation of the volitional contraction).

Predicted MFGA using the burst superimposition test ($MFGA_{burst}$) was calculated using the following equation:

$$MFGA_{burst} = F_{vol} + F_{stim} \quad (2)$$

where F_{stim} is the force produced by the stimulation.

Twitch and doublet interpolation method

The twitch interpolation method first delivered a maximal single pulse (600 μ s, 135 V) to the resting muscles, while the doublet interpolation method delivered two maximal pulses separated by 5 milliseconds to the resting muscles. Two seconds after the initial pulse, subjects were instructed to contract their muscles and maintain volitional force production through the delivery of stimulation. For submaximal targeted force levels, subjects attempted to match their volitional forces to the targeted force level as shown on the visual feedback screen of the dynamometer. The subjects' forces were monitored throughout the trial and stored on a personal computer for later analysis. The superimposed stimulation was delivered to the volitionally contracted muscles 5 seconds after the first pulse (3 seconds following the initiation of the volitional contraction). The twitch interpolation delivered a maximal single pulse, and the doublet interpolation delivered two maximal pulses separated by 5 milliseconds.

Predicted VAR using the twitch interpolation technique (VAR_{twitch}) was calculated as:

$$VAR_{twitch} = 1 - \left(\frac{F_{sup-twitch}}{F_{rest-twitch}} \right) \quad (3)$$

where $F_{sup-twitch}$ is the force when a supramaximal pulse of stimulation was delivered during the volitional contraction, and $F_{rest-twitch}$ is the force produced when the stimulation was delivered to the resting muscles.

Predicted MFGA using the twitch interpolation technique ($MFGA_{twitch}$) was then given by:

$$MFGA_{twitch} = \frac{F_{vol}}{VAR_{twitch}} \quad (4)$$

Predicted VAR using the doublet interpolation method ($VAR_{doublet}$) was given by the following equation:

$$VAR_{doublet} = 1 - \left(\frac{F_{sup-doublet}}{F_{rest-doublet}} \right) \quad (5)$$

where $F_{sup-doublet}$ is the force of the doublet delivered to the voluntary contraction and $F_{rest-doublet}$ is the force of the doublet on the resting muscles.

The predicted MFGA using the doublet interpolation technique was calculated as:

$$MFGA_{doublet} = \frac{F_{vol}}{VAR_{doublet}} \quad (6)$$

Twitch-to-tetanus Ratio Method

The procedure for testing the twitch-to-tetanus ratio method differed from other methods in that it involved no volitional contraction by the subject. First, eight single pulses (135 volts) were administered to the resting muscles 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 (maximum twitch). The resulting forces of these pulses were recorded and used to plot the pulse duration versus force production curve of the muscles. Using the data from the pulse duration versus force curve, the pulse durations that produced 25% and 50% of the maximum twitch force were determined. One of the two selected pulse durations was administered at 135 Volts to the resting muscles followed ~5 seconds later by a train of the same pulse duration (135 V, 100 Hz, 500 ms train duration). Before the pulse duration was varied for the second trial, ~ 30-60 seconds rest was given.

The twitch-to-tetanus ratio (TTR) was given by:

$$TTR = \frac{F_{subtw}}{F_{subtr}} \quad (7)$$

where F_{subtw} is the force of the submaximal twitch, and F_{subtr} is the force of the submaximal train.

The Predicted MFGA using the twitch-to-tetanus ratio method ($MFGA_{TTR}$) was calculated by the equation:

$$MFGA_{TTR} = \frac{F_{\max tw}}{TTR} \quad (8)$$

where $F_{\max tw}$ is the maximum twitch force produced by the last twitch (600-us, 135 Volt) of the initial 8-twitch series.

Adjusted burst superimposition Technique

Preliminary analysis of the data showed that the submaximal burst superimposition tests consistently over-predicted volitional activation and under-predicted the estimated MFGA for all volitional levels (See Fig. 3A). There was not a consistent trend of over or under predicting MFGA with any of the other methods (See Fig. 3B, C, D). Because there were consistent errors, we posited that the submaximal burst superimposition data had the potential to be corrected and result in a more accurate prediction of the MFGA. A curvilinear relationship between CAR and percent maximal volitional effort has previously been found when using the burst superimposition test at submaximal volitional effort to predict muscle activation in the quadriceps muscles of healthy (5), ACL injured (11), and elderly adults (6, 9). However, the curvilinear equation previously determined for the stimulation train analogous to the train used in the present study did not fit the current data. Upon visual inspection, it appeared that the data could be fit with a cubic equation. To confirm this cubic relationship, additional submaximal data were collected on 4 of the subjects. The additional submaximal data required the burst superimposition test to be administered at submaximal targeted force levels of 5% and 10% of estimated MFGA. Thus, the data from all 13 subjects plus additional submaximal data (at 5% and 10% MFGA) from 4 of these subjects (seen in Fig.3A) were used to determine the proper correction factor for the human plantar flexor muscles, resulting in the equation:

$$\%Error = .000105(\%VAR_{burst})^3 - .0157(\%VAR_{burst})^2 + 1.03(\%VAR_{burst}) - 52.0752 \quad (9)$$

To calculate the adjusted MFGA ($MFGA_{adj}$), the observed MFGA was multiplied by the correction factor, C , which is derived from equation 9:

$$MFGA_{adj} = MFGA_{burst} \times C \quad (10)$$

where,

$$C = \frac{1}{1 + \left(\frac{\%Error}{100} \right)} \quad (11)$$

To test the validity of the cubic adjustment, the adjusted burst superimposition method was used to make MFGA predictions for 8 additional able-bodied subjects (3 males, 5 females) at target force levels of 25%, 50%, and 75% of their MFGA force. The MFGAs of the validation subjects were predicted using the correction equation and previously determined parameters to validate the adjusted burst superimposition test.

Data Analysis

Including the adjusted burst superimposition method, a total of five methods were analyzed at the submaximal volitional levels. Percent error between predicted and estimated MFGA for each of the five methods was calculated by subtracting the estimated MFGA from the predicted MFGA and dividing this number by the estimated MFGA. The Kolmogorov-Smirnov test was used to test for the normal distribution of the magnitude of percent error at

each of the targeted force levels for each method. Because of the non-normality of magnitude of percent errors from the twitch interpolation method at 25% ($p=.007$), 50% ($p=.000$), and 75% ($p=.001$) targeted force levels and to reduce the influence of outliers, the interquartile range of percent error was calculated to assess the ranges of percent error and MFGA predictions (Fig. 4) (35). Nonparametric statistical analyses were performed on the absolute value of percent error to detect significant differences between methods. Friedman tests were performed across all methods for each targeted force level (25%, 50%, and 75%). The Wilcoxon Signed Rank test and Bonferroni correction were used to compare the adjusted burst superimposition test to each of the other methods if the Friedman test showed an overall difference. Pairwise comparison was made only between the adjusted burst superimposition test and each of the other methods, because this was the comparison of interest based on the *a priori* hypothesis that the adjusted burst superimposition test would most accurately predict MFGA. The magnitude of the percent errors for the adjusted burst superimposition test was normally distributed at all targeted force levels. A one-way repeated measure ANOVA compared the magnitude of percent error across targeted force levels (25%, 50%, and 75%) for the adjusted burst superimposition test for all subjects, including the validation subjects. Mean and standard deviation of percent errors for the adjusted burst superimposition test were also calculated to describe the data. A one-sample *t*-test was used to compare the percent errors from the MFGA predictions from the adjusted burst superimposition test to a data set with a mean percent error of 0.

Results

Twenty three subjects participated in this study. Complete data sets were collected from 12 of the 15 subjects originally recruited. Due to discomfort, one subject requested to be terminated from the study after the first bout of testing (submaximal burst superimposition test), and two subjects requested to be terminated after initially measuring their MFGA. Of the 8 subjects (3 males, 5 females) used to validate the adjusted burst superimposition method, complete data sets were collected for 7 (3 males, 4 females) of these subjects. One validation subject did not meet the requirement of producing 95% VAR and was excluded from the study.

The twitch interpolation technique resulted in an interquartile range (IQR) of predicted MFGA of 463.87 N, and 2 of the 12 MFGA predictions were negative (See Fig. 4), resulting from negative VAR predictions. The doublet interpolation had an interquartile range of predicted MFGA of 473.05 N and resulted in 1 negative prediction of MFGA (See Fig. 4). The twitch-to-tetanus ratio (IQR of $\text{MFGA}_{\text{pred}}=284.41$ N), burst superimposition (IQR of $\text{MFGA}_{\text{pred}}=185.76$ N), and adjusted burst superimposition (IQR of $\text{MFGA}_{\text{pred}}=264.63$ N) methods did not result in any negative predictions of MFGA.

The adjusted burst superimposition and burst superimposition tests resulted in similar interquartile ranges of percent error, which were also the smallest compared to all other methods (11.40% and 12.44%, respectively). The errors for the adjusted burst superimposition test centered around zero (Fig. 4, 5B), while the burst superimposition consistently underestimated MFGA (negative errors) (Fig. 3A, 5). The twitch-to-tetanus ratio method (IQR of % Error=32.73%), the doublet interpolation technique (IQR of % Error=54.97%), and the twitch interpolation technique (IQR of % Error=49.04%) all resulted in larger interquartile ranges that both over- and under-estimated MFGA (Fig. 3).

The means and standard deviations of percent error for the first 12 subjects for the adjusted burst superimposition test at the 25% ($1.76 \pm 9.39\%$), 50% ($0.78 \pm 7.06\%$), 75% ($0.28 \pm 7.49\%$) targeted force levels were small. The individual subject percent errors ranged from -17.32 to 14.72. The interquartile range of percent error of the data at 5% and 10% targeted

force levels were also small (IQR of % Error=14.43%), though the adjusted burst superimposition technique under-predicted MFGA in 6 out of the 8 trials (Fig. 5).

Validation data from 7 subjects for the adjusted burst superimposition test had slightly larger means and standard deviations of the percent error at the 25% ($-5.73 \pm 11.62\%$), 50% ($-3.75 \pm 10.95\%$), and 75% ($-7.86 \pm 11.04\%$) targeted force levels compared to the original data. The errors from the validation subjects ranged from -25.82% to 10.57% and had a mean and standard deviation of $-2.18 \pm 9.31\%$. When the percent error was averaged between the three targeted force levels for each subject, the range of percent error was 35.67%.

The Friedman test found an overall significant difference in absolute percent errors between the five methods at each of the 3 targeted force levels ($p < .001$). Pair-wise comparison found that the adjusted burst superimposition test had a significantly lower mean rank compared to each of the other methods ($p < .05$) except the twitch-to-tetanus ratio method at the 50% targeted force level ($p = .112$).

A one-way repeated measures ANOVA found no significant difference in magnitude of percent errors between the three targeted force levels (25%, 50%, and 75%) of the adjusted burst superimposition test for all subjects, including the validation subjects ($p = .452$). The one-sample *t*-test found no difference between the percent errors of the adjusted burst superimposition test and a sample with a mean percent error of 0 for all predictions, including the validation subjects (all $p > 0.1$).

Discussion and Conclusion

Our study showed that the adjusted burst superimposition test was overall the best predictor of MFGA at each of the targeted force levels as shown by its lower magnitude of percent error and its narrow interquartile range of percent error (11.40%). The twitch interpolation, doublet interpolation, and twitch-to-tetanus ratio techniques had considerably high interquartile ranges of percent error (49.04%, 54.97%, and 32.73%, respectively) and were therefore not found to be reliable predictors of MFGA.

This study was the first to report the twitch-to-tetanus ratio method as a predictor of MFGA. The assumption of the twitch-to-tetanus ratio method was that the twitch-to-tetanus ratio will remain constant with changing stimulation intensities. While no significant difference in absolute percent errors was found when compared with the adjusted burst superimposition test at the 50% targeted force level, the interquartile range of percent error for the twitch-to-tetanus ratio method (32.73%) was higher when compared to that of the Adjusted burst superimposition test (11.40%). The twitch-to-tetanus ratio method resulted in a large range of error and tended to both over- and under-predict MFGA. Because the error was not consistently positive or negative, these data could not be corrected in a manner similar to what was used for the submaximal burst superimposition test (Fig. 3D).

Kent-Braun and colleagues have shown that the burst superimposition test was more sensitive than the twitch or doublet interpolation techniques when measuring volitional activation of healthy nonfatigued subjects, healthy fatigued subjects, and subjects with amyotrophic lateral sclerosis (2). However, their study did not test at submaximal efforts, estimate MFGA, or attempt to adjust the predictions of the burst superimposition test as we did in this study. In contrast, Allen and colleagues found no difference between a superimposed twitch, doublet, or train of stimulation when estimating the voluntary drive to the elbow flexors at a volitional level of greater than 85% MVC (19). However, differences may have been found if the testing included lower submaximal volitional forces (19). Also, the train used by Allen and colleagues only contained 4 pulses compared to a 10-pulse train used in our study and the study by Kent-Braun (2, 19).

The interpolation techniques do not give a reliable quantification of neural drive (36). Herbert and Gandevia reported that the twitch interpolation technique may not distinguish between contractions from 60% to 100% of maximal motor neuronal excitation (1). They proposed that there is a sigmoidal relationship between motor neuron excitation and the interpolated twitch amplitude, where 60% of maximal volitional excitation produced a near-maximal force (1). Thus, the large increase in volitional excitation of the motor neuron pool from 60% to 100% only stimulated a small number of additional high threshold motor units responsible for near-maximal force generation (1). This force increase is too small to result in changes to the interpolated twitch (1). The large error of MFGA predictions from the interpolation techniques in our study was due to the method's inaccurate VAR predictions (Table 1). In our study, the interpolation methods appeared to inaccurately predict VAR values even at low force levels. Similar to the results for the twitch-to-tetanus ratio technique, it was not possible to adjust predictions from the interpolation methods in our study because there were both positive and negative predictions of MFGA from the Interpolation techniques (Fig.3B,C).

Similar to this study, the interpolation methods have previously been found to predict negative values of volitional activation (16, 20), which occurs because the force of the superimposed doublet on the volitionally active muscles is greater than the force of the doublet on the resting muscles. The tendency for the superimposed twitch or doublet to be greater when delivered to the contracting muscles compared to the resting muscles has been attributed to the series elastic component of the muscles (16, 31). At rest, the force produced by the superimposed twitch or doublet was used to take up the slack in the tendons of the muscles. This is important to note because both the twitch and doublet interpolation methods rely on the measurement of a resting twitch or doublet force to calculate VAR at any volitional force level. This resting twitch or doublet force is lessened due to increased slack in the series elastic components. When the muscles were volitionally contracted, more of the superimposed twitch or doublet force contributed to the actual force generation measured by the force transducer. Consistent with this theory, the mean predicted VAR values increased with larger volitionally targeted force levels (See Table 1). In our study, the series elastic component likely played the largest role at the lowest submaximal volitional forces (~25% MVC) when the least shortening of the muscle occurred.

Allen and colleagues, when studying the elbow flexor muscle group, reported high reliability in measuring volitional activation using the twitch interpolation method and did not reported negative predictions (18). The reliability in that study may be due to the fact that only maximal volitional force levels were tested (18). Todd and colleagues also found low variability of volitional activation predictions by the twitch interpolation technique and did not report any negative predictions (8). Additionally, Klein and colleagues did not report any negative predictions of volitional activation using the twitch interpolation technique with subjects post-stroke, although original data were not presented (3). In our study, some submaximal target levels resulted in negative and unreliable measurements of VAR. This could be due to the differences between the apparatus used to contain the leg and measure force. In their studies, Todd and Klein measured plantar flexor force with the knee flexed to 90 degrees, putting less stretch on the gastrocnemius muscle compared to this study where the knee was extended during testing. Testing with the knee flexed to 90° may isolate the soleus muscle, while testing with the knee extended may cause some measured plantar flexion force to be lost in subtle knee flexion moments.

The inaccuracy of the interpolation techniques could also be compounded by the muscle group being tested in our study. Taylor noted that the interpolation technique measures descending drive to the muscle best when testing muscles with short tendons and no synergists to aid joint motion (36). There are many synergist muscles involved during ankle

plantar flexion. Also, the major plantar flexor muscle, the gastrocnemius, uses the long Achilles tendon to reach the posterior calcaneus. Another possible limitation to any method of predicting MFGA that involves stimulation is activation of antagonist muscles, which could diminish the force produced by the stimulation. Klein and colleagues did not find significant coactivation of the contralesional limb compared to the ipsilesional limb when using the twitch interpolation method on the plantar flexors of individuals post-stroke (3).

The burst superimposition test consistently over-estimated volitional activation at submaximal levels (5, 6). This observation encouraged us to increase the accuracy of the burst superimposition test by adjusting its predictions. As in the study by Stackhouse and colleagues, the stimulation train superimposed on the submaximal contraction did not increase the overall force up to the level reached by the superimposed train on the maximal contraction (5) (Fig. 2A, 3A, 4). Thus, the purpose of the correction equation for the adjusted burst superimposition technique was to quantify the error associated with the burst superimposition technique and adjust MFGA predictions accordingly. A second order polynomial has been used to correct the predicted VAR in the quadriceps of healthy adults (5), ACL injured (11), and older adults (6, 9). The second order polynomial previously developed for the quadriceps femoris muscles did not fit the data for the plantar flexor muscles studied presently; we also compared different variables than previous studies. A cubic equation more closely fit the data from the present study. The Stackhouse and colleagues studies (5, 6, 7, 9) plotted CAR against percent maximal volitional effort (%MVE). However, in this study, we wanted to adjust MFGA predictions for individuals with an unknown true MFGA, which is similar to how this technique will be used in clinical situations. Thus, we plotted the %Error as a function of %VAR (analogous to CAR). Using the equation presented in this study, the %VAR from the burst superimposition test was able to determine the percent error between the predicted and estimated MFGA. This percent error was used to make a more accurate prediction of MFGA and thus VAR of the muscles. The equation for the adjusted burst superimposition test had a Y intercept of -52%. Thus, we predict that if the plantarflexor muscles were stimulated with a maximal burst of stimulation at rest, the total force produced should equal 48% of the MFGA.

When using the burst superimposition test, it is recommended that a maximal volitional contraction be used to decrease error when predicting MFGA (Fig. 3A). Because we used %Error to predict MFGA, accurate predictions of MFGA using the adjusted burst superimposition test only required a measurement of the volitional force of the muscles (F_{vol}) during the burst superimposition test. The voluntary forces did not have to be at a maximal effort to make an accurate prediction of MFGA. The adjusted burst superimposition test showed no difference in percent error when predicting MFGA using the 25%, 50%, or 75% target force level. Also, the adjusted burst superimposition test was used to predict MFGA from very low force trials (targeted force level of 5% and 10%) (Fig 5A,B). Thus, the adjusted burst superimposition technique produces comparable results when predicting MFGA at all levels of submaximal volitional forces, including the lower force levels that may be present in the neurologically impaired population (1, 2, 6, 7).

In conclusion, the results of this study showed that of the five methods compared, the adjusted burst superimposition test was the most accurate method for predicting volitional activation and MFGA using submaximal levels of contraction. Knowing the degree of volitional activation in a patient allows clinicians and researchers to determine whether the sources of strength deficits are neurological or muscular (1-3, 5-8). Furthermore, changes in volitional activation can be used as a measure of physiological adaption to training programs involving electrical stimulation, biofeedback, strength training, or other methods of rehabilitation (6, 7, 9). While the adjusted burst superimposition method may have been the most accurate predictor of MFGA in this study, it may not be an accurate method when

predicting the MFGA of a muscle group other than the plantar flexors. Before the adjusted burst superimposition test can be used clinically, it must be validated for use with neurologically impaired individuals.

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Acronyms and Equations

VAR- volitional activation ratio, is a measure of the volitional muscle activation at any level of effort.

MFGA- maximum force generating ability, represents the force the muscle is capable of generating with full muscle activation

F_{vol} = force of the volitional contraction

Estimated MFGA- peak force of the able-bodied subject contracting with maximal effort with electrical stimulation superimposed on the contraction.

Pred- predicted value (either MFGA or VAR) by either the Burst superimposition, Adjusted burst Superimposition, Twitch interpolation, Doublet interpolation, or Twitch-to-tetanus ratio tests.

The subscript denotes the test used to make the prediction.

Burst- Burst superimposition test

TI- Twitch interpolation test

$F_{sup-twitch}$ - the force when a supramaximal pulse of stimulation was delivered during the volitional contraction

$F_{rest-twitch}$ - the force produced when the stimulation was delivered to the resting muscles.

DI- Doublet interpolation test

$F_{sup-doublet}$ - the force of the doublet delivered to the voluntary contraction

$F_{rest-doublet}$ - the force of the doublet on the resting muscles.

TTR- Twitch-to-tetanus Ratio test

F_{subtw} -the force of the submaximal twitch and F_{subtr} is the force of the submaximal train

$F_{max tw}$ - the Maximum Twitch Force produced by the last twitch (600-us, 135 Volt) of the initial 8-twitch series.

Adj Burst- Adjusted burst superimposition test

VAR_{burst} = the VAR calculated using the Burst superimposition test

Figure 1.

A flowchart outlining the experimental testing. A burst superimposition test at maximal effort was performed three times, once before each of the three methods being tested. The order of the three groups of tests (the submaximal burst superimposition test, the twitch and doublet interpolation techniques, and the twitch-to-tetanus ratio method) was randomized along with the order of volitional effort levels and whether a twitch or doublet would be received in the interpolation techniques.

Figure 2.

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 able-bodied subject. Vertical lines along the time (ms) axis represent the delivery of electrical stimulation. For the burst superimposition test, the block represents a maximal stimulation train (600- μ s pulse duration, 100-ms train duration, 135 V, 100-Hz train). For the twitch-to-tetanus ratio method the block represents a 500ms, 100 Hz train of submaximal intensity. Estimated maximum force generating ability (MFGE_{est}), predicted MFGE (MFGE_{pred}), and volitional activation ratio (VAR) for each trial are given. The predicted MFGE from the adjusted burst superimposition test is given for the burst superimposition trial.

Figure 3.

Graphs plotting the resulting percent error of predicted MFGA of each targeted voluntary force level during submaximal burst superimposition testing (A), the twitch interpolation technique testing (B), the doublet interpolation technique testing (C), and testing of the twitch-to-tetanus ratio method (D). Data points with errors greater than $\pm 100\%$ are represented as $\pm 100\%$ Error on the graphs and are labeled with the actual values. (A) includes additional data collected at 5 and 10% targeted voluntary force levels. See Methods for details regarding calculation of % error.

Figure 4.

A box and whisker plot showing the interquartile range of the predictions of the MFGA for the burst superimposition (Burst), twitch interpolation (TI), doublet interpolation (DI), twitch-totetanus Ratio (TTR), and adjusted burst superimposition (Adj Burst) tests. The boxes outline the first and third quartile, and the whiskers represent the minimum and maximum values. When the minimum or maximum values fell outside the graph window, the values were labeled.

Figure 5.

A) Data from the submaximal burst superimposition test of the original 13 subjects (diamonds) were plotted and a line of best fit was calculated. This equation can be used to adjust MFGA predictions determined by the submaximal burst superimposition test. Data from the validation subjects (squares) were also plotted. B) The percent error of predicted MFGA determined by the adjusted burst superimposition technique compared to the estimated MFGA for the original 13 subjects (diamonds) and 7 validation subjects (squares).

Comparisons of All Methods Using Means

Table 1

	VAR _{est}	VAR _{pred}	MFGA[%Error]	VAR _{est}	VAR _{pred}	MFGA[%Error]
Target Force	Burst			Adj Burst		
25%	.23±.03	.34±.05	33% ± 6%	.23±.04		7% ± 6%
50%	.48±.03	.62±.06	23% ± 4%	.48±.06		6% ± 4%
75%	.69±.04	.82±.06	15% ± 4%	.70±.08		6% ± 4%
	DI					
	TI					
25%	.25±.03	.15±.16	131% ± 184%	.23±.03	.13±.09	244% ± 535%
50%	.47±.03	.53±.20	45% ± 83%	.48±.03	.5±.13	21% ± 21%
75%	.68±.10	.78±.22	24% ± 17%	.69±.04	.79±.14	17% ± 10%
	TTR					
25%	N/A	N/A	28% ± 14%			
50%	N/A	N/A	20% ± 17%			
75%	N/A	N/A	N/A			