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Comparison of Techniques to Determine Human Skeletal Muscle Voluntary Activation

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1. Introduction

Muscle force production depends on the interaction of both central and peripheral nervous systems in which any decrease in intended maximal force production results from disrupted transmission processes along the central or peripheral pathways [Gandevia, 2001; Kent-Braun & Le Blanc, 1996]. When the muscle weakness is of central origin, it is defined as volitional activation (VA) failure and indicates either incomplete motor unit recruitment or suboptimal discharge rates of those units [Gandevia, 2001]. VA failure has been reported in older adults and in individuals with knee pathologies or neurological disorders [Farquhar et al, 2005; Flynn et al, 2012; Stackhouse et al 2003]. The identification of the VA failure may assist in developing effective rehabilitation protocols that include electrical stimulation or biofeedback to maximize strength gains in these populations.

Two techniques have been traditionally used to identify VA failure: *interpolation* and *superimposition*. Both of these techniques are based on the principle that the amplitude of the response to electrical stimulation of a muscle is inversely related to the level of voluntary activation of that muscle at the time of stimulation [Taylor et al., 2009]. The interpolation technique (IT) quantifies VA deficits by subtracting the ratio of the superimposed to the

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Conflict of Interest

The authors report no conflicts of interest.

resting twitch force from 1.0. To identify small VA deficits, however, high resolution measurement is needed for using the IT method [Shield & Zhou, 2004]. One way to improve the sensitivity of the IT is to increase the number of the superimposed stimuli to elicit a maximal force and improve the signal- to- noise ratio since a twitch may not be efficient in generating a force response in maximum contractions [Miller et al, 1999]. Lexell & Miller [2009] suggested employing a train of pulses with a greater frequency than the mean motor unit firing rate for detecting VA failure. In particular, high-frequency bursts compared to single pulses have been used to increase the stimulated force amplitude during maximal isometric knee extensions [Miller et al, 1999] even though antidromic collisions and reflex effects might negatively influence the amplitude of the produced force [Herbert & Gandevia, 1999]. A doublet stimulus, as another alternative, has been suggested to allow for increased and less variable stimulated force of knee extensors compared to a single pulse [Folland & Williams, 2007]. Systematic simultaneous study of twitch, doublet and a high-frequency train of pulses has yet to specify which stimuli provides the most accurate results when using the IT for VA testing.

During the superimposition technique, which is widely known as the central activation ratio (CAR) technique [Kent-Braun & Le Blanc, 1996], a train of supramaximal electrical pulses is delivered to the contracting muscle. VA is calculated by dividing the volitional force achieved before the delivery of a supramaximal stimulus and the combined supramaximal stimulus and volitional force responses, which represents the theoretical maximum force generating ability of the muscle (i.e., volitional force plus any force increment from the superimposed stimulus). A value of 1.0 corresponds to complete activation, whereas anything less indicates VA failure or inhibition [Kent-Braun & Le Blanc, 1996; Stackhouse et al., 2000, 2003]. It has been found, however, that the CAR overestimates VA levels and may be insensitive at high voluntary efforts [Stackhouse et al., 2000, 2003]. Additionally, Krishnan & Williams [2010] found that when the maximum volitional force was used as a reference (regardless when it occurred) for calculating VA, the CAR technique yielded inaccurate VA findings. Therefore, a curvilinear equation [Stackhouse et al., 2000, 2003], a correction factor [Flynn et al., 2012] and using the voluntary force just prior to stimulus as the reference force for calculating VA [Krishna & Williams, 2010] have been recommended to correct the VA ratio value.

Past studies have compared the ability of both activation techniques to detect VA failure [Bampouras et al., 2006; Behm et al., 2001; Flynn et al., 2012; Grindstaff & Threlkeld, 2014; Krishna & Williams, 2010] concluding that the CAR provides artificially higher VA ratios than the IT because the CAR calculation precludes normalization of the superimposed force to the resting electrically induced force [Krishna & Williams, 2010]. In contrast, the burst and adjusted burst CARs (a correction equation is used to adjust for the associated CAR error) estimated more accurately VA compared to the IT (twitch and doublet stimulus) during submaximal isometric contractions of the plantarflexor muscles [Flynn et al., 2012]. Consideration should also be given to the force that is used as a reference for VA computations, since such detailed methodological information is usually omitted, and it might be a contributing factor in the variability of the VA reported values [Miller et al, 2006]. In particular, transitory peaks during the initiation of a strong volitional contraction may not necessarily be maintained during the stable plateau phase and therefore using the

peak force prior to stimulation (F_{peak}) instead of the force at the instantaneous delivery of stimulation ($F_{\text{@stim}}$) can potentially result in the overestimation of VA. Both IT and CAR techniques have been widely described in the literature, however, the decision of which VA evaluation method to use primarily rests on the evaluator's preference, thus making comparisons of the literature challenging. Usually, CAR is the preferred method in clinical settings and used in orthopedic and neurological populations [Farquhar et al., 2005; Mizner et al., 2003; Kent-Braun & Le Blanc, 1996; Stackhouse et al, 2003, 2005] since it only requires the participants' stimulation during a volitional contraction compared to the IT; thus minimizing discomfort levels associated with the stimulation. Recently, strong correlations between the two different methods have been reported ($r=0.85$ to 0.99) when a doublet or burst stimulus were superimposed on voluntary contractions and an equation to correct VA ratios was used [Grindstaff & Threlkeld, 2014; Krishna & Williams, 2010]. Nevertheless, VA estimates using these two methods were significantly different from each other even when similar stimulation parameters were employed [Grindstaff & Threlkeld, 2014].

Both methods have some limitation in calculating VA, however, they are the only available clinical tools to determine the extent of VA and identify VA changes following interventions or comparisons between control and pathological groups, especially when involving submaximal levels of VA [Taylor, 2009]. Therefore, the purpose of this study was to determine the most accurate method to quantify VA of the quadriceps femoris muscle. Specifically, we compared: 1) the IT versus CAR methods when using the F_{peak} and the $F_{\text{@stim}}$ as reference forces (i.e. IT with F_{peak} vs. CAR with F_{peak} vs. IT with $F_{\text{@stim}}$ vs. CAR with $F_{\text{@stim}}$) to determine the most accurate method, and 2) the VA values obtained by the most accurate method when three different types of stimuli (burst, doublet, and twitch) were used. Finally, to validate our findings, we modeled the relationship between VA ratio (VAR) and percent of maximum volitional isometric contraction (MVIC) for all the investigated stimuli, calculated the predicted MVIC ($\text{MVIC}_{\text{predicted}}$) of healthy individuals from submaximal contractions, and then compared the $\text{MVIC}_{\text{predicted}}$ with the MVIC. These submaximal contraction levels were used to demonstrate the decreased activation levels of individuals with orthopedic and neurological deficits.

2. Methods

Twenty-eight subjects (16 men; age 26 ± 4.7 yr.) with intact sensation, and no known orthopedic, neuromuscular, or vascular problems affecting their tested lower extremity volunteered, read and signed informed consent forms approved by Temple University (for Shriners Hospitals for Children), the University of Delaware and Arcadia University.

2.1. Experimental Set up

Subjects were seated on a computerized controlled dynamometer (KinCom II, Chattecx Corporation, Chattanooga, Tennessee) with their knees flexed to 90° and the lateral femoral condyle aligned with the axis of the dynamometer. The tibia and thigh of the leg tested, pelvis and trunk were stabilized by the force transducer pad, thigh strap, seat belt, and straps crisscrossing the torso. Electrical stimulation was delivered by a Grass S88 stimulator equipped with a Grass model SIU8T stimulus isolation unit (Grass Instruments, West

Warwick, Rhode Island). Two self-adhesive surface electrodes (7.6×12.7 cm; Conmed, Utica, New York) were placed in the usual manner (proximal electrode placed over the rectus femoris and distal electrode over the vastus medialis portions) to allow stimulation of the quadriceps femoris muscle [Stackhouse et al., 2000]. The stimulator was driven by a computer using customized software (Labview 4.0.1, National Instruments, Austin, Texas) to control the timing parameters of each stimulation pattern. Forces were recorded at a sampling rate of 200 Hz.

2.2. Experimental Sessions

All subjects participated in three randomly assigned testing sessions separated by at least two days. Subjects were advised to avoid any type of arduous exercise for a 24 hours prior to each trial. Before proceeding each day's data collection, the CAR was used to screen each individual to verify their ability to produce a VAR_{CAR} of 0.95 by using the following equation:

$$VAR_{CAR} = MVIC / (MVIC + \text{Force of superimposed stimulation})$$

A *supramaximal* burst (a 13-pulse, 600 μ s pulse duration, 100Hz train, 135 V) was delivered during a 3–5 s MVIC, during which visual force feedback and verbal encouragement were provided, followed by a second burst when the muscle was relaxed. These burst stimulation characteristics have been used in different clinical studies [Farquhar et al, 2005; Flynn et al., 2012; Stackhouse et al, 2000, 2003] and elicit a maximal force response from quadriceps [Stackhouse et al, 2003]. If required, subjects were given a maximum of three trials-separated by 5 min rest- to reach a VAR_{CAR} 95%. If unable to achieve a ratio of 95% within the three trials, the subject was given an additional opportunity to repeat the experiment at a later date. If still unable to achieve a VAR_{CAR} 95%, the subject was withdrawn from the study.

During testing, a different stimulation pattern- 1) a burst: a 13-pulse, 600 μ s pulse duration, 100Hz train [Farquhar et al., 2005; Flynn et al., 2012; Stackhouse et al, 2000, 2003], 2) a doublet: 2 pulses with a 10ms interpulse interval [Bampouras et al, 2006; Folland & Williams 2007], and 3) a twitch: single pulse, 2ms pulse duration- was randomly selected (without replacement) and used for that session. Using a twitch stimulus decreases the potential risk of antidromic collisions, while increasing the pulse duration –in this case to 2ms- may enhance motor unit recruitment and therefore allow for greater force increment [Gregory et al, 2007]. For each subject, the stimulation intensity for the selected stimulation pattern was determined by progressively increasing the voltage until maximal force was achieved from the resting quadriceps muscle. The intensity was initially set to 60-volts and increased in 5-volt increments until a force plateau was achieved. This *maximum intensity* was recorded for each individual and subsequently used within the testing session.

Following a 5-min rest, the subject's MVIC was used to set the visual feedback force targets, corresponding to 25, 50, 75, and 100% of each individual's MVIC. With 5-min rests between contractions, and starting at 25% MVIC, subjects produced forces at the specified target level. When subjects reached a stable force plateau, the electrical stimulus was

delivered to the muscle during the voluntary effort and then again during rest (Figure 1.A). This procedure was repeated for each successive higher target. The final target was set at 100% of the initial MVIC. This trial was used to determine whether subjects fatigued during the test. The data were discarded if the force level produced by the final MVIC was not within 10% of the original MVIC.

2.3 Data Analysis

The VAR was calculated for IT and CAR methods by using the F_{peak} and $F_{\text{@stim}}$ as the reference force based on the equations presented in Figure 1.B. The $F_{\text{@stim}}$ was calculated as a percentage of the MVIC(%MVIC):

$$\%MVIC = (F_{\text{@stim}} / MVIC) * 100$$

The obtained VARs were plotted against the %MVIC. To identify which of the two VA techniques predicts better the actual volitional effort, a unity line was plotted and the residuals (difference between the observed and the “perfect” ratio with respect of the %MVIC) were calculated. The unity line corresponded to the ideal linear relationship between %MVIC and VAR (i.e. 25% and 100% of MVIC represent 0.25 and 1.0 of VAR respectively). A mixed model repeated measures analysis of variance (ANOVA) was used to compare the residuals (between-subjects factor: gender & within-subject factor: VA method) and Tukey’s post-hoc analysis with Bonferroni correction was used to identify the most accurate technique.

Once the most accurate technique was defined, the VAR values for the three different types of stimuli (burst, doublet, twitch) were calculated and then plotted against %MVIC. Linear and curvilinear polynomial equations were used to determine the line of best fit for these data and to derive r^2 values. Separate repeated measures ANOVAs were used to compare: 1) the VAR achieved using the most accurate technique when a burst, doublet and twitch stimulus were used, 2) the recorded % MVIC for each type of stimulus, and 3) the electrical stimulation intensities for the three different stimuli. If significant main effects were present, Tukey’s post-hoc comparisons with Bonferroni adjustments, were performed between the means.

To validate the VAR-%MVIC relationships, we performed the analysis used by Stackhouse and colleagues [2003]; by removing a subject’s data from VAR-%MVIC relationship and recalculating the equation for the particular individual. The VAR obtained from 25%, 50%, and 75% of MVIC and for each different stimulus were used to solve the linear and curvilinear equations for the modeled %MVIC. To predict the MVIC force from submaximal contraction levels the following equation was applied:

$$MVIC_{\text{predicted}} = (F_{\text{@stim}} / \text{Modeled \%MVIC}) * 100$$

Finally, both identity plots and intraclass correlation coefficients (ICC (2,1)) were used to investigate the agreement between the MVIC and $MVIC_{\text{predicted}}$ values for each contraction level and stimulus type [Farquhar et al, 2005; Stackhouse et al, 2003]. Throughout the

analysis, the significance level was set at $p < 0.05$. The abbreviations used in this study are listed in Table 1.

3. Results

Twenty of 28 participants (11 males & 9 females) satisfied the criterion of achieving a $VAR_{CAR} \leq 95\%$ and completed the study. The range of the MVIC forces reported in this study was 1453.28 N (Mean $\pm$ 95% CI: 971.6 ± 94.86). Additionally, the mean ($\pm$ 95% CI) VARs for the IT and CAR methods with F_{peak} and $F_{@stim}$ references are presented in Table 2. Scatter plots of the two VA methods with the two different volitional force reference points were plotted against %MVIC and the residuals between each data point and the unity line were computed, with smaller values indicating better accuracy. There were no significant interactions for VA method by gender ($p = 0.4$, $\eta_p^2 = 0.03$). Similarly, the residuals did not differ significantly by gender ($p = .76$, $\eta_p^2 = 0.001$). Significant differences among the residuals of the IT and CAR methods with the two reference forces were found ($F_{(2.04, 610.1)} = 258.93$, $p < 0.0005$), with a partial eta squared (η_p^2) of 0.46 indicating a large effect size. Post-hoc comparisons indicated that the CAR method with the F_{peak} as a reference ($M = 0.17$, 95% CI [0.15, 0.19]) significantly overestimated the value of VA. No significant differences were observed between the CAR with the $F_{@stim}$ ($M = 0.11$, 95% CI [0.09, 0.13]) and the IT with the F_{peak} as a reference ($M = 0.1$, 95% CI [0.08, 0.12]). Finally, the IT method with the $F_{@stim}$ as a reference ($M = 0.00$, 95% CI [-0.01, 0.02]) was significantly more accurate in predicting VA (Figure 2).

When we compared the VAR values using the IT with $F_{@stim}$ method and the three different types of stimuli, no significant difference was found except for 25% of MVIC (Table 3). Likewise, there was no significant difference among %MVIC in each target contraction level across burst, doublet, and twitch stimulation. The mean stimulation intensities, however, for the three different types of stimuli were significantly heterogeneous ($F_{2, 38} = 45.7$, $p < 0.0005$, $\eta_p^2 = 0.7$). Particularly, the necessary intensity for the twitch to produce the maximum force contraction was statistically higher when compared with doublet and burst stimulus (mean $\pm$ 95% CI/ burst: 111.75 ± 8.04 , doublet: 135 ± 7.85 , twitch: 148 ± 2.33 V). When VARs were plotted against %MVIC, a curvilinear relationship was found to better describe the data than a straight line for all three types of stimuli (Figure 3). Only burst stimulus r^2 values for the linear and curvilinear regressions were similar (Figure 3, C & D).

3.1 MVIC versus $MVIC_{predicted}$

To validate our findings, the VAR-%MVIC relationship for each stimulus type were used to calculate $MVIC_{predicted}$. Then, identity plots of MVIC vs. $MVIC_{predicted}$ were plotted (Figure 4) and ICCs between MVIC and $MVIC_{predicted}$ were calculated (Table 4).

Twitch stimulus (Figure 4, panel A)—Predictions made at the 25% force level were close to the identity line, except for two data points that represented a significant overestimation of MVIC. At the 50% contraction level, the predicted force was greater than MVIC. Moreover, predictions based on 75% of MVIC appeared to be accurate. ICC values obtained by the comparison between MVIC and $MVIC_{predicted}$ were 0.43, 0.81, and 0.92 for 25%, 50%, and 75% levels respectively.

Doublet stimulus (Figure 4, panel B)—The attained ICC values were respectively 0.56, 0.74, and 0.79 for 25%, 50%, and 75% of MVIC. Predictions made from the 25% and 50% contraction levels significantly overrated MVIC. The MVIC force was underestimated when the curvilinear force relationship was used at the 75% contraction level to calculate $MVIC_{predicted}$.

Burst stimulus (Figure 4, panel C & D)—At 25%, an overestimation of the MVIC was detected when both the burst linear and curvilinear VAR-%MVIC relationships were used. The MVIC was slightly overestimated using the curvilinear model at the 50% contraction level, whereas at 75% was slightly underestimated. The degree of over/under estimation obtained when the burst stimulus was used, however, was smaller compared to the results derived by the other two stimuli. ICC values from 25%, 50%, and 75% contraction levels by using the curvilinear VAR-%MVIC relationship were 0.54, 0.92, and 0.93 respectively. When the burst linear force relationship was applied to 50% and 75% contraction levels, $MVIC_{predicted}$ results were similar to the MVIC values and ICCs were 0.95 and 0.97, respectively.

4. Discussion

The aim of this study was to identify the most accurate method to evaluate VA of quadriceps femoris muscle. Specifically, we compared the IT and CAR methods when two different reference forces - F_{peak} versus $F_{@stim}$ —were used. The residuals between the two different techniques with the two references indicated that the IT with $F_{@stim}$ technique was more accurate in calculating overall the VA (Figure 2). Previous results demonstrated similar findings [Bampouras et al., 2006; Behm et al., 2001; Grindstaff & Threlkeld, 2014; Krishna & Williams, 2010], in which VAR values with the IT were lower compared to those derived from the CAR. This can be attributed to normalizing the superimposed force by the resting force (i.e., the amount of force produced by the same proportion of muscle activated by the electrical stimulus applied during the MVIC to that produced in the relaxed state) for the IT method. The CAR with both reference forces overestimated the VA of quadriceps femoris at submaximal contraction levels, because the superimposed and volitional force was lower than the MVIC as previously reported [Stackhouse et al., 2000; Figure 2]. Moreover, for both techniques, when $F_{@stim}$ was used as the reference, the degree of overestimation decreased, a finding consistent with previous research [Krishna & Williams, 2010].

When a burst, doublet, and twitch stimulus were used with the IT with $F_{@stim}$ (the most accurate technique), the range of VAR values during maximum contractions were 0.90–0.93. Krishnan & Williams [2010] found 0.93 when they measured quadriceps muscle activation at 60° of knee flexion with IT using a 10-pulse train. Generally, previous studies have also shown VAR values between 0.70–0.90 suggesting reduced quadriceps femoris activation in healthy adults [Bampouras et al., 2006; Grindstaff & Threlkeld, 2014]. Other conditions where volitional activation failure is present include: fatigue [Stackhouse et al., 2001, 2010], older age [Kent-Braun & Le Blanc, 1996; Stackhouse et al., 2003], postsurgical conditions [Mizner et al., 2003] and diseases with upper motor neuron function involvement [Kent-Braun & Le Blanc, 1996; Stackhouse et al., 2005]. Comparisons between the obtained VARs for the three different stimuli at each target level indicated insignificant differences, except

25% of MVIC. A possible explanation is that the superimposed force, although proportional to the stimuli number, was normalized to the force of the resting stimulus. As a result the differences between burst, doublet, and twitch were eliminated and VAR data were analogous for all tested stimuli.

A curvilinear regression model better described the relationship between VAR and %MVIC for IT with $F_{@stim}$ for all the investigated stimuli. A similar relationship has been previously reported for the IT method between the ratio of the superimposed to the resting forces and the volitional force [Behm et al., 1996; Folland & Williams, 2007]. For all submaximal targeted force levels, the VARs obtained by using doublet and twitch stimuli overestimated %MVIC, whereas burst stimulus did not. This finding indicated that using burst stimulus with the IT with $F_{@stim}$ was the most accurate method. It has been suggested that the application of multiple pulses instead of single pulses decreases the variability of the electrically evoked force response and consequently improves the accuracy of the IT [Lexell & Miller, 2009; Taylor, 2009] and the signal-to-noise ratio [Bampouras et al., 2006]. Furthermore, the coefficient of determination for the burst illustrated a stronger curvilinear VAR and %MVIC relationship ($r^2 = 0.9$) compared to doublet and twitch stimuli. Although our r^2 values are slightly lower compared to Behm and colleagues, [2001] they still demonstrated a strong VAR-%MVIC relationship. Small differences may be due to the use of different stimulus types and intensities that produced *maximal* electrical force responses rather than using *supramaximal* intensities.

When the burst stimulus was used with the IT with $F_{@stim}$, a linear function was also a good fit for the VAR- %MVIC relationship ($r^2 = 0.89$). Moreover, the line was visually superimposed over the unity line; suggesting that approximately 25%, 50% and 75% of volitional activation corresponded to 25%, 50% and 75% of MVIC. A linear relationship between VAR and %MVIC has been previously reported when a 100-Hz 1,000-ms train was employed in one volunteer and the VAR values were calculated based on the CAR [Stackhouse et al., 2000]. Applying long supramaximal tetanic bursts, however, is extremely uncomfortable and may be intolerable for routine use [Bampouras et al., 2006; Stackhouse et al., 2000]. Folland and Williams [2007] also reported a linear relationship between the normalized superimposed and volitional force for contraction levels above 40% of maximum volitional force when twitch stimulus was used with IT.

To validate the VAR-%MVIC relationships, the maximum force generating ability of the quadriceps was predicted from submaximal contractions. At the 25% of MVIC the curvilinear models overestimated the actual force (ICC's: 0.54, 0.56, & 0.43 for burst, doublet, & twitch respectively). When the linear burst VAR-%MVIC was used, the attained ICC value was considered poor despite increasing from 0.54 to 0.63. As previously suggested, at 25% of MVIC, a 120-ms train length may be insufficient to produce a force increment at the same level as the one achieved with higher contraction levels [Stackhouse et al., 2003; Figure 1]. Using contraction forces of <40% of maximum contraction to predict the maximum generated force resulted in an error of 33.3% when the IT was applied [Behm et al., 1996]. The ICCs attained by the use of the curvilinear VAR-%MVIC model at 50% and 75% of MVIC were >0.80 for burst and twitch stimuli, but surprisingly not for the doublet stimulus. Using the burst stimulus led to greater ICCs and therefore better

predictions of the maximum capacity of quadriceps femoris. To estimate the maximal force ability, only submaximal contractions greater than 50% of MVIC can be used to extrapolate the linear and curvilinear burst VAR-%MVIC relationships.

Interestingly, the $MVIC_{\text{predicted}}$ values, when a twitch was used, were similar to the observed MVIC at contraction levels >50% of MVIC (ICC's: 0.81 at 50% and 0.92 at 75% of MVIC). In particular, the obtained ICCs were stronger for all the investigated contraction levels for twitch versus doublet stimulus, even though their VAR values did not differ statistically. These findings contradict research [Lexell & Miller, 2009; Suter & Herzog, 2001] suggesting that applying a doublet could lead to increased reliability of IT because a twitch stimulus would not produce enough force increment. One potential reason may be that a doublet stimulus, although brief, produces a much greater rapid rise of force [Binder-Macleod & Lee, 1996] than the twitch or burst and may be perceived as being more uncomfortable than the other stimuli and thus, individuals may not be as likely to sustain their force effort during its delivery. Another possible explanation is that our 2ms pulse duration allowed enough time for membranes to build up charge to meet the threshold for action potential generation resulting to increased muscle fibers recruitment and therefore increased twitch force production [Duchateau, 2009; Gregory et al, 2007]. The clinical importance of this outcome is that the application of a twitch stimulus can provide accurate quadriceps VA values in individuals who cannot tolerate a burst stimulus. Quantification of VA may have significant implications for clinical practice in rehabilitation [Farquhar et al., 2005; Klein et al., 2010; Mizner et al., 2003]. In particular, determination of VA may be used to investigate the efficacy of strength training and the relative contributions of the underlying mechanisms for strength gains (i.e., neural adaptations vs. muscle hypertrophy). Conversely, knowing the extent VA deficits contribute to weakness can drive the design of effective rehabilitation programs based on the nature of the individual's strength deficits.

In conclusion, our findings showed that IT with $F_{\text{@stim}}$ was the most accurate method to calculate VA, when a burst stimulus was applied to quadriceps femoris. Our results were validated by good agreement between MVIC and $MVIC_{\text{predicted}}$ forces when extrapolating the linear burst VAR-%MVIC force relationships for contraction levels above 50% of MVIC. Finally, we suggest that a twitch stimulus with 2ms pulse duration instead of a burst can serve as an acceptable alternative when special populations like children and pain-sensitive individuals are tested.

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Biographies

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Dr. Samuel CK Lee is an Associate Professor at the University of Delaware and a Research Scientist at the Shriners Hospital for Children, Philadelphia. He holds a Bachelor of Biomedical Engineering degree from the Boston University, a Master's degree in Physical Therapy and a PhD in Biomechanics and Movement Science from the University of Delaware. His research focuses on improving the function of individuals with central nervous system injury through the application of electrical stimulation to activate paralyzed or weakened muscles. Particularly, he is interested in the use of electrical stimulation: 1) as a tool to study the physiologic characteristics of muscle and the central and peripheral nervous systems; 2) as a rehabilitative or training method to improve muscle function, strength and fitness and; 3) as a method to produce functional movement (FES) of impaired muscles (neuroprosthetic effects) and to promote carryover to function (neurotherapeutic effects).

B. Volitional Activation Equations

Method	F_{peak}	$F_{\text{@stim}}$
IT	$1 - \frac{(a - b)}{e}$	$1 - \frac{d}{e}$
CAR	$\frac{b}{a}$	$\frac{c}{a}$

Figure 1.

A: Schematic illustration of a typical analysis curve at 75% of MVIC. A burst is delivered when subjects maintain force at 75% of MVIC and when at rest. a: Volitional force+superimposed force, b: Volitional peak force prior stimulation (F_{peak}), c: Volitional force at the instantaneous delivery of stimulation ($F_{\text{@stim}}$), d: Superimposed force increment, and e: Maximal resting stimulated force. B: VA equations for IT and CAR methods with F_{peak} and $F_{\text{@stim}}$ as reference forces.

Figure 2.

Mean residuals for IT and ST techniques with F_{peak} and $F_{@stim}$ as reference forces. The error bars represent 95% confidence intervals. * Significant difference from ST with MVIC ($p < 0.0005$). † Significant difference from IT with $F_{@stim}$ ($p < 0.0005$).

Figure 3.

VAR values for the three different types of stimuli plotted against %MVIC. All investigated stimuli was described by curvilinear VAR-%MVIC relationships (A–C). A linear VAR-%MVIC relationship for burst is presented (D).

Figure 4.

Identity Plots of MVIC versus MVIC_{predicted} forces for all three types of stimuli at 25%, 50%, 75% of the MVIC. MVIC_{predicted} force values were derived by using the curvilinear VAR-%MVIC force relationship for burst, doublet, twitch stimulus and the linear VAR-%MVIC force relationship for the burst stimulus. The black line represents equality between MVIC and MVIC_{predicted} values ($y=x$) and not the regression line. Data points lying near the line indicate the agreement between the two measurements. Data points falling above the identity line overestimated the MVIC and underestimated it when falling below.

Table 1

Abbreviations used in this study.

Abbreviation	Explanation
VA(R)	Volitional Activation (Ratio)
MVIC	Maximum Volitional Isometric Contraction
IT	Interpolation Technique
CAR	Central Activation Ratio Technique
F_{peak}	Peak force prior the delivery of stimulation
F_{@stim}	Force at the instantaneous delivery of stimulation
%MVIC	F _{@stim} was calculated as a percentage of the MVIC
ANOVA	One-way measures analysis of variance
ICC	Intraclass Correlation Coefficients

Table 2
The mean ($\pm 95\%$ CI) ratios for both VA techniques with F_{peak} and $F_{\text{@stim}}$ as reference forces.

Interpolation technique (IT)		Central Activation Ratio (CAR)			
Reference point:	F_{peak}	$F_{\text{@stim}}$	F_{peak}	$F_{\text{@stim}}$	
Initial	MVIC	0.96 ± 0.02	0.91 ± 0.02	0.98 ± 0.01	0.95 ± 0.01
25%	MVIC	0.43 ± 0.05	0.30 ± 0.03	0.59 ± 0.04	0.50 ± 0.03
50%	MVIC	0.71 ± 0.04	0.58 ± 0.03	0.83 ± 0.03	0.76 ± 0.02
75%	MVIC	0.91 ± 0.03	0.79 ± 0.02	0.95 ± 0.01	0.89 ± 0.01
Final	MVIC	0.97 ± 0.02	0.92 ± 0.02	0.99 ± 0.01	0.94 ± 0.01

Table 3

The mean VAR ($\pm$ 95% CI) for IT with $F_{@stim}$ are presented in the table.

		BURST	DOUBLET	TWITCH
Initial	MVIC	0.92 ± 0.04	0.90 ± 0.04	0.92 ± 0.04
25%	MVIC	$0.26 \pm 0.05^*$	0.31 ± 0.05	$0.34 \pm 0.05^*$
50%	MVIC	0.55 ± 0.04	0.59 ± 0.06	0.61 ± 0.1
75%	MVIC	0.78 ± 0.04	0.80 ± 0.05	0.79 ± 0.03
Final	MVIC	0.91 ± 0.04	0.90 ± 0.04	0.93 ± 0.03

Asterisks indicate significant difference between the VAR values when a twitch and burst stimulus were used for the 25% MVIC contraction level ($p < 0.05$). No significant differences among VARs in the remaining of target contraction level were found.

Table 4

ICC (2,1) values between the $MVIC_{predicted}$ and $MVIC$ for each submaximal contraction level and stimulus type. Higher values reflect better agreement. $MVIC_{predicted}$ were calculated by using the curvilinear VAR-%MVIC relationships for burst, doublet, and twitch. MVIC predictions were also made by using the linear VAR-%MVIC relationship for burst stimulus.

		Curvilinear			Linear		
		BURST	DOUBLET	TWITCH	BURST	BURST	BURST
25%	MVIC	0.54	0.56	0.43	0.63		
50%	MVIC	0.92	0.74	0.81	0.95		
75%	MVIC	0.93	0.79	0.92	0.97		