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Percent voluntary inactivation and peak force predictions with the interpolated twitch technique in individuals with high ability of voluntary activation

Trent J Herda[1], Ashley A Walter[5], Pablo B Costa[3], Eric D Ryan[4], Katherine M Hoge[5], Jeffrey R Stout[5] and Joel T Cramer[2,6]

[1] Department of Health, Sport, and Exercise Sciences, Biomechanics Laboratory, University of Kansas, Lawrence, KS, USA
[2] Department of Health and Human Performance, Applied Musculoskeletal and Human Physiology Research Laboratory, Oklahoma State University, Stillwater, OK, USA
[3] Department of Kinesiology, Human Performance Laboratory, California State University–San Bernardino, San Bernardino, CA, USA
[4] Department of Exercise and Sport Science, University of North Carolina–Chapel Hill, Chapel Hill, NC, USA
[5] Department of Health and Exercise Science, University of Oklahoma, Norman, OK, USA

E-mail: joel.cramer@okstate.edu

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Abstract

The purpose of this study was to examine the sensitivity and peak force prediction capability of the interpolated twitch technique (ITT) performed during submaximal and maximal voluntary contractions (MVCs) in subjects with the ability to maximally activate their plantar flexors. Twelve subjects performed two MVCs and nine submaximal contractions with the ITT method to calculate percent voluntary inactivation (%VI). Additionally, two MVCs were performed without the ITT. Polynomial models (linear, quadratic and cubic) were applied to the 10–90% VI and 40–90% VI versus force relationships to predict force. Peak force from the ITT MVC was 6.7% less than peak force from the MVC without the ITT. Fifty-eight percent of the 10–90% VI versus force relationships were best fit with nonlinear models; however, all 40–90% VI versus force relationships were best fit with linear models. Regardless of the polynomial model or the contraction intensities used to predict force, all models underestimated the actual force from 22% to 28%. There was low sensitivity of the ITT method at high contraction intensities and the predicted force from polynomial models significantly underestimated the actual

[6] Author to whom any correspondence should be addressed.

force. Caution is warranted when interpreting the % VI at high contraction intensities and predicted peak force from submaximal contractions.

Keywords: voluntary activation, muscle activation, MVC, ITT, plantar flexors

1. Introduction

The interpolated twitch technique (ITT) has been defined as a quantitative assessment of neural function (Folland and Williams 2007), and has been used as an experimental measurement of muscle activation (Behm *et al* 1996, 2001b, Shield and Zhou 2003). The ITT model involves an evoked stimulus to the peripheral nerve during a voluntary contraction, called the *superimposed* or *interpolated* twitch (Belanger and McComas 1981, Merton 1954). The evoked twitch during a voluntary contraction will activate all motor units by superimposing a compound muscle action potential in motor units that are already voluntarily activated as well as those that are inactive (Belanger and McComas 1981, Merton 1954). In theory, if any individual motor units are not recruited or firing fast enough to produce maximal force, then the superimposed action potential will evoke a subsequent and transient increase in force (Herbert and Gandevia 1999). Then using the interpolated twitch force, compared to the potentiated twitch force, the 'percent voluntary activation' (Behm *et al* 2001b) or 'percent voluntary inactivation' (Behm *et al* 2001b) (% VI) can be calculated (equations are presented in section 2.2).

The ITT model has recently been scrutinized and heavily debated as to whether the technique is useful for assessing voluntary activation and predicting peak force capabilities of a muscle (Taylor *et al* 2009). Numerous studies have used the ITT method during a maximal voluntary contraction (MVC) to detect changes in motoneuron excitability after an experimental treatment or intervention (Behm *et al* 2001a, de Ruiter *et al* 2003, Fowles *et al* 2000, Ryan *et al* 2008). The principle of the ITT method is supported by the inverse relationship between the size of the superimposed twitch force and voluntary force (Herbert and Gandevia 1999). That is, as voluntary force increases, the size of the interpolated twitch force decreases and may become undetectable at high voluntary forces in subjects with maximal activation capabilities. Nevertheless, this model assumes that this relationship is linear, which theoretically allows the calculation of the % VI using only the interpolated twitch evoked during the MVC. However, most studies have reported that this inverse relationship is actually nonlinear (Behm *et al* 1996, Belanger and McComas 1981, Bulow *et al* 1993, De Serres and Enoka 1998, Rutherford *et al* 1986). Herbert and Gandevia (1999) showed that at high contraction intensities it would take a large increase in excitation to produce a small increment in force because of a plateau in (or elimination of) the superimposed twitch force at 80–100% MVC. This limitation may render the % VI estimation incapable of detecting experimentally induced changes in motoneuron excitability when it is performed and calculated at relatively high contraction intensities (80–100% MVC) (Herbert and Gandevia 1999, Yue *et al* 2000).

There have been a limited number of studies that have examined the use of the ITT method during submaximal contraction intensities to predict maximal force (Behm *et al* 1996, 2001a, Bulow *et al* 1993). The prediction of maximal force may be useful to diagnose certain medical conditions. For example, Norregaard *et al* (1994) reported that patients with fibromyalgia had significantly less leg extensor strength than matched healthy controls; however, the fibromyalgia patients' predicted maximal force was not significantly different than the healthy controls. Therefore, the ability to correctly predict force from such modeling

using the ITT method would greatly benefit the diagnoses of certain neuromuscular disease, such as fibromyalgia. The % VI from submaximal contraction intensities can be regressed against force and extrapolated to predict a force that the muscle could create if completely voluntarily activated (Behm *et al* 1996, Bulow *et al* 1993). Previous studies have extrapolated predicted force values from linear and nonlinear models (Behm *et al* 1996, Folland and Williams 2007, Kooistra *et al* 2007), and one study used a polynomial regression model to characterize the mean % VI versus force relationship (Behm *et al* 1996). Behm *et al* (1996) reported that the average % VI versus force relationship (collapsed across subjects) from 20%, 40%, 60%, 80% and 100% MVC was better fit with a second-order polynomial than a linear model, and eliminating the % VI data points at 20% and 40% MVCs further reduced the prediction error. However, due to the inherent inter-individual variability in % VI, these relationships may need to be examined on a subject-by-subject basis and using each subject's best fit polynomial model (linear, quadratic or cubic) may further reduce prediction error. Furthermore, to increase the resolution of these relationships, % VI may need to be examined at every 10% MVC increment. This additional information may help to further delineate the limitations of the traditional % VI values, particularly in highly activated subjects whose % VI values often diminish at higher contraction intensities (80–100% MVC). This may help determine better recommendations for the use of % VI in experimental settings.

Overall, there have been a number of studies that quantified muscle activation and predicted muscle strength from the ITT model performed during submaximal and maximal contractions and, furthermore, clinicians and researchers have interpreted the values from the ITT method in those studies and have made conclusions on the effectiveness of treatments and interventions. In this paper we hope to shed some light on the implications of using the ITT model to assess muscle activation and to predict peak force. Therefore, the purpose of this study was to examine % VI during MVCs and the relationship between % VI and force using the ITT during submaximal contractions (10–90% MVC and 40–90% MVC) to calculate predicted peak force using linear, quadratic and cubic polynomial models in subjects with the ability to maximally activate their plantar flexors (highly activated subjects). We hypothesized that peak force prediction error will be reduced using each subject's best fit model on muscle contraction intensities ranging from 40% to 90%.

2. Materials and methods

2.1. Subjects

Fourteen men and eleven women were screened for this investigation. For inclusion, subjects had to demonstrate high activation of their plantar flexors (>95% voluntary activation at 90% of MVC), which was based on Kooistra *et al* (2007). Therefore, seven men (mean ± standard deviation (SD); age = 21 ± 1 years; mass = 74 ± 8 kg) and five women (age = 21 ± 1 years; mass = 58 ± 5 kg) participated in the subsequent familiarization and experimental trials. None of them reported any current or ongoing neuromuscular diseases or musculoskeletal injuries that involved the ankle, knee or hip joints. This study was approved by the Institutional Review Board. All participants read and signed an informed consent form and completed a pre-exercise health status questionnaire.

2.2. Research design

Each participant was seated with restraining straps over the pelvis and thigh, with a knee flexion angle of 0° below the horizontal plane (full extension) on a custom-built apparatus equipped

with a high accuracy load cell (Omegadyne, model LC402, range 0–500 lbs; Stamford, CT, USA) that was designed to isolate plantar flexor force production. The load cell was attached between two cast iron plates, with the foot strapped to the cast iron plate that was anchored to the top (or compression side) of the load cell. All force measurements were attained at 90° (between foot and leg and the foot) and the distal end of the metatarsal bones (ball of the foot) was positioned over the load cell.

Each participant visited the laboratory on three occasions, twice for familiarization trials followed by one experimental trial. During the familiarization trials, participants performed multiple (2–6) 4 s isometric MVCs and several isometric step muscle actions at randomly ordered percentages of the MVC (10–90% of MVC) with transcutaneous electrical stimulation. Within 2–5 days after the second familiarization trial, participants reported back to the laboratory for the experimental trial. During each experimental trial, participants performed four isometric MVCs followed by nine randomly ordered submaximal isometric step contractions at 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% MVC. During all submaximal trials and two of the MVCs, the ITT was used to determine percent voluntary inactivation (% VI). Furthermore, strong verbal encouragement was provided during each MVC trial. Submaximal isometric step contraction percentages were calculated from the highest of the two initial MVCs that were performed without the transcutaneous electrical stimuli (MVC). Transcutaneous electrical stimuli were delivered to the tibial nerve using a high-voltage (maximal voltage = 400 V) constant-current stimulator (Digitimer DS7AH, Herthfordshire, UK). The stimuli were applied via bipolar surface electrodes that were placed in the popliteal space. Single stimuli were used to determine the optimal stimulation electrode location (20 mA) and the maximal compound muscle action potential (M-wave) with incremental amperage increases (2–100 mA). Once a plateau in the peak-to-peak M-wave and peak twitch force was determined, despite amperage increases, 20% was added to the amperage that yielded the highest peak-to-peak M-wave and peak twitch force to ensure a supramaximal stimulus. A single stimulus was a 200 μs duration square wave impulse, while a doublet consisted of two single stimuli delivered successively at 100 Hz. Doublets were administered with the supramaximal stimulus intensity during two of the MVC trials (ITT MVC) and all submaximal trials to increase the signal-to-noise ratio and minimize the series elastic effects on force production (Desbrosses *et al* 2006). In accordance with the twitch interpolation procedure, a supramaximal doublet was administered 350–500 ms following the start of the plateaus in force during the submaximal and ITT MVC (superimposed twitch) and then again 3–5 s after the submaximal and ITT MVC trial at rest (potentiated twitch). Percent voluntary activation (% VA) was calculated with the equation below (Allen *et al* 1995) and percent voluntary inactivation (% VI) was calculated by subtracting % VA from 100 (Behm *et al* 1996):

$$\%\mathrm{VA} = \left[1 - \left(\frac{\text{superimposed twitch}}{\text{potentiated twitch}}\right)\right] \times 100.$$

During the submaximal isometric step muscle actions, participants were required to track their force production on a computer monitor placed in front of them that displayed the real-time digitized force signal overlaid onto a programmed template, which consisted of horizontal lines on a computer monitor that served as target force lines for each submaximal step muscle action. The stimulation was administered once the subject consistently traced the line for 2–3 s based on the investigator's (TJH) judgment. All software programs were custom written with LabVIEW v 8.5 (National Instruments, Austin, TX). Reliability statistics were calculated for percent voluntary activation from the ITT method across the entire force spectrum (10–100% MVC) (Weir 2005). All P values were greater than 0.05, the intraclass

correlation coefficients ranged from 0.55 to 0.84, and the standard error of the measurement ranged from 4.34% to 9.31%. Therefore, the ITT procedure performed during submaximal and maximal contractions may be deemed reliable.

2.3. Electromyography

Pre-amplified, bipolar surface electromyography (EMG) electrodes (EL254S, Biopac Systems Inc., Santa Barbara, CA, USA) with a fixed center-to-center inter-electrode distance of 20 mm, built-in differential amplifier with a gain of 350 (nominal), input impedance of 100 MΩ and common mode rejection ratio of 95 dB (nominal) were taped over the soleus (SOL) and medial gastrocnemius (MG) muscles of the right leg. For the SOL, the electrodes were placed along the longitudinal axis of the tibia at 66% of the distance between the medial condyle of the femur and the medial malleolus. For the MG, the electrodes were placed on the most prominent bulge of the muscle in accordance with the recommendations of Hermens *et al* (1999). A single pre-gelled, disposable electrode (Ag–AgCl, Quinton Quick Prep, Quinton Instruments Co., Bothell, WA, USA) was placed on the spinous process of the seventh cervical vertebrae to serve as a reference electrode. To reduce inter-electrode impedance and increase the signal-to-noise ratio, local areas of the skin were shaved and cleaned with isopropyl alcohol prior to placement of the electrodes.

2.4. Signal processing

The EMG (μV) and force (N) signals were recorded simultaneously with a Biopac data acquisition system (MP150WSW, Biopac Systems, Inc., Santa Barbara, CA, USA) during each assessment. The force signal from the load cell and the EMG signals from the SOL and MG muscles were sampled at 2 kHz using a 16-bit analog-to-digital converter (DHQCard-6036E, National Instruments, Austin, TX, USA) interfaced with a laptop computer (Inspiron 8200, Dell Inc., Round Rock, TX, USA). The force value was calculated during a 0.25 s epoch immediately prior to the stimulation for all submaximal and the two MVC (ITT MVC) trials. For the two MVCs without stimulation (MVC), force was recorded from the highest consecutive 0.25 s epoch during the contraction. The duration of time (seconds) from the onset of force to the selected peak force epoch was recorded. The onset of force was determined when the force signal reached ten SD above the baseline. All signals were recorded, stored and processed off-line with custom-written software (LabVIEW v 8.5, National Instruments, Austin, TX, USA).

2.5. Statistics

In addition, a paired-samples *t*-test was used to indicate if there was a mean difference for peak force recorded from the highest MVC without stimulation (MVC) versus the peak force recorded from the highest MVC with stimulation (ITT MVC). A paired-samples *t*-test was also used to indicate if there was a mean difference between the duration of time (seconds) recorded from the onset of force production to the epoch used to calculate peak force for the ITT MVC and MVC.

Polynomial regression models were used to analyze the relationships for % VI versus force for 10–90% MVC and 40–90% MVC. The relationships were examined separately for each subject. The statistical significance ($P \leqslant 0.05$) for the increment in the proportion of the variance that would be accounted for by a higher degree polynomial (i.e. *F*-test for the R^2-change) was determined using the *F*-test described by Pedhazur (1997). Coefficients of

determination (R^2) were calculated for the polynomial models (linear, quadratic or cubic) that best fitted the % VI versus force relationships, but only if the linear model was initially found significant ($P \leqslant 0.05$). Linear, quadratic and cubic polynomial models were used for the best fit analyses of the 10–90% VI versus force relationships, whereas for the 40–90% VI versus force relationships, only linear and quadratic models were used. The cubic model was excluded from the best fit analyses for the 40–90% VI versus force relationships based off the recommendations of Herda *et al* (2009), which suggested that the limited number of data points is not appropriate to regress against three independent variables (cubic = x, x^2 and x^3). In addition, % VI versus force relationships (10–90% MVC and 40–90% MVC) were also fitted with all models (linear, quadratic and cubic) regardless of best fit to examine if one of the polynomial models would predict peak force closer to their actual peak force (obtained without stimulation) better than their best fit model. Therefore, a one-way repeated measures ANOVA (MVC versus 10–90% best fit versus 10–90% linear versus 10–90% quadratic versus 10–90% cubic versus 40–90% linear versus 40–90% quadratic versus 40–90% cubic) was used to determine if their predicted peak force from the seven models was different from their actual peak force obtained without stimulation. When appropriate, follow-up analyses were performed using paired-samples *t*-tests with Bonferroni corrections. An alpha level of $P \leqslant 0.05$ was considered statistically significant for all comparisons. SPSS version 14.0 (SPSS Inc., Chicago, IL, USA) was used for all statistical analysis.

3. Results

There was a significant difference ($P = 0.008$) between the peak force values obtained during the MVC without stimulation (mean ± SD, 452 ± 101 N) and the ITT MVC (423 ± 94 N). In addition, there was no significant difference between ($P = 0.130$) the duration of time from the onset of force to the epoch used to calculate peak force during the ITT MVC (0.99 ± 0.27 s) and MVC (1.27 ± 0.59 s).

Peak force values (N) from the MVC and ITT MVC trials and polynomial regression models (linear, quadratic and cubic) and subsequent R^2 values with predicted peak force values (N) for the 10–90% and 40–90% VI versus force relationships for each participant are presented in table 1. The one-way repeated measures ANOVA (MVC versus 10–90% best fit versus 10–90% linear versus 10–90% quadratic versus 10–90% cubic versus 40–90% linear versus 40–90% quadratic versus 40–90% cubic) indicated that there were significant differences ($P = 0.001$) among the predicted forces from the seven models and the force obtained during the MVCs. The mean peak force obtained from the MVC without stimulation was higher than the mean predicted peak forces from the 10–90% VI best fit ($P = 0.001$), quadratic ($P < 0.001$) and cubic models ($P = 0.004$) and 40–90% VI linear ($P = 0.001$), quadratic ($P = 0.018$) and cubic ($P = 0.005$) models, but was not significantly different from the 10–90% VI linear model ($P = 0.085$) (figure 1). In addition, there were no differences among the seven models' mean predicted peak forces ($P > 0.005$).

4. Discussion

4.1. ITT MVC and MVC without stimulation

One of the findings of this study was that peak force during the ITT MVC was less than peak force during the MVC without stimulation (figure 1). Also, mean (±SD) voluntary inactivation during the ITT MVC was 1.7% ± 7.9%; however, the peak force obtained during the MVC without stimulation was 6.7% higher than the peak force acquired during the ITT

Table 1. Peak force values (N) from the maximal voluntary contraction without stimulation (MVC) and the MVC with stimulation (ITT MVC) for each individual. Polynomial regression models (linear, quadratic and cubic) and the coefficients of determination (R^2) with predicted MVC (PRED MVC) values (N) for the 10–90% VI versus force relationships and 40–90% VI versus force relationships.

			10–90% VI versus force relationships						40–90% VI versus force relationships					
			Linear		Quadratic		Cubic		Linear		Quadratic		Cubic	
Subject	MVC	ITT MVC	R^2	PRED MVC	R^2	PRED MVC	R^2	PRED MVC	R^2	PRED MVC	R^2	PRED MVC	R^2	PRED MVC
1	456.0	390.7	0.975	353.3	0.991*	362.1	0.996	357.3	0.927*	361.1	0.979	470.8	0.998	380.3
2	382.6	384.3	0.968	381.1	0.988*	349.1	0.994	378.6	0.986*	364.4	0.989	354.9	0.997	364.5
3	581.5	549.4	0.985	529.0	0.986	520.5	0.994*	562.1	0.969*	519.6	0.990	561.0	0.996	513.0
4	365.8	305.7	0.975*	292.3	0.982	296.1	0.988	292.7	0.954*	293.6	0.989	292.1	0.992	284.3
5	450.8	458.7	0.975	394.1	0.975	391.2	0.996*	396.5	0.974*	390.7	0.985	422.1	0.997	441.7
6	528.9	518.2	0.980	441.4	0.997	459.2	0.999*	473.4	0.967*	454.0	0.987	473.4	1.000	486.6
7	447.7	441.7	0.964	360.2	0.971	363.4	0.995*	342.7	0.851*	362.9	0.889	355.0	0.980	349.4
8	220.6	217.9	0.983*	195.2	0.984	196.8	0.985	203.9	0.937*	199.3	0.941	196.6	0.993	200.9
9	507.6	440.1	0.988*	412.0	0.989	414.2	0.991	415.3	0.958*	412.1	0.967	415.2	0.982	410.6
10	408.1	411.7	0.977	473.2	0.977	358.7	0.995*	361.3	0.989*	358.3	0.989	366.1	0.990	357.4
11	496.4	429.2	0.982*	415.1	0.989	419.5	0.992	420.2	0.952*	422.1	0.980	420.6	0.992	422.2
12	584.0	538.2	0.969*	550.3	0.974	473.5	0.984	454.5	0.993*	471.3	0.993	460.3	0.953	426.4
Mean	452.4	423.8†		399.8		383.7**		388.2**		384.1**		399.0**		386.4**

* Indicates the significant polynomial model for that subject.

** Indicates that there was a significant difference ($P < 0.05$) between the model's predicted force and peak force from the MVC.

† Indicates a significant difference ($P < 0.05$) in mean peak force values between ITT MVC and MVC.

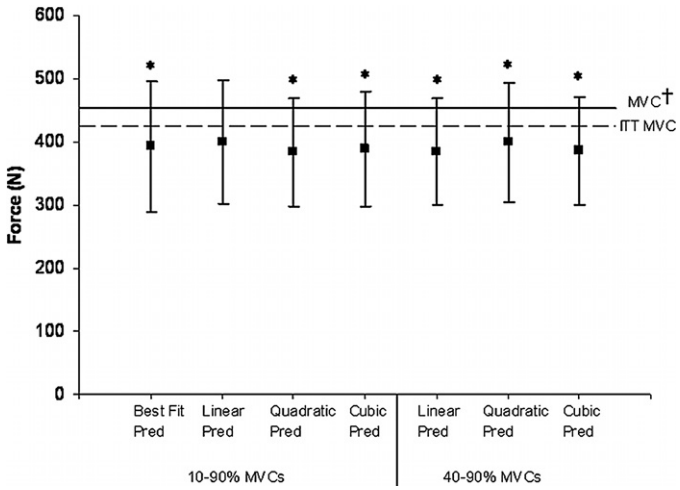

Figure 1. Mean ± SD values for predicted forces from the seven models and the mean force values from the ITT MVC (horizontal dashed line) and MVC (horizontal solid line); * indicates that there was a significant difference ($P < 0.05$) between the model's predicted force and peak force from the MVC; † indicates a significant difference ($P < 0.05$) in mean peak force values between ITT MVC and MVC.

MVC. Thus, the ITT MVC may overestimate the percent of voluntary activation. Moreover, the mean voluntary inactivations at 80% and 90% MVC were 3.8% ± 7.2% and 0.6% ± 4.5%, respectively, while the mean peak forces at 80% and 90% MVC were 17.0% and 5.5% lower than the mean ITT MVC force, respectively. Therefore, the ITT method at near maximal contraction intensities (>80% MVC) may not be sensitive enough to estimate voluntary activation in subjects with maximal activation capabilities (Herbert and Gandevia 1999). The low sensitivity at the higher contraction intensities (>80% MVC) may be the result of rate coding and the fusion of twitches achieved by highly activated subjects to increase force output after all available motor units have been recruited (Herbert and Gandevia 1999). Herbert and Gandevia (1999) reported that at higher contraction intensities, when all motor units are normally activated, it takes a very large increase in excitation ($[Ca^{2+}]_i$) to evoke small increases in force. Therefore, the doublet stimulus (such as that used in this study) may not be sufficient to elicit additional force increments during an MVC in highly activated subjects, because of their ability to fuse twitches during the voluntary process of rate coding at higher intensity contractions (>80% MVC).

Previous studies have used the peak force/torque from the ITT MVC to examine changes in force as a result of a treatment or intervention (Behm *et al* 2001a, de Ruiter *et al* 2003, Fowles *et al* 2000, Ryan *et al* 2008). However, when examining the peak force values from the ITT MVC and MVC on a subject-by-subject basis in this study there were inter-individual differences. Although this study did not test this hypothesis, it is possible that some of the subjects anticipated the stimulation during the MVC, which resulted in lower ITT MVC peak force values. These results are in accordance with Button and Behm (2008) in that subjects who expected the ITT method had significantly less peak force and muscle activation (as measured by EMG) than when the subjects performed an MVC with knowledge that they would not receive a stimulation. However, Button and Behm (2008) also reported that a group of subjects who had prior experience with the ITT method (>10 practice ITT MVC trials) did not have a significant difference between peak force from an MVC with no expectation of an interpolated twitch and an MVC with expectation of an interpolated twitch. Therefore, in

this study two familiarization sessions with up to 12 practiced ITT MVC trials may not have provided enough experience to overcome some of the subject's anticipation of the stimulus. In addition, comparing the peak force values from the ITT method to an MVC without stimulation to confirm that the ITT MVC is an accurate representation of the true peak force is another mechanism to overcome this limitation. For example, six of the subjects exhibited ITT MVC peak force values that were 5.8–19.6% less than the MVC peak force values. Yet, the remaining six subjects showed peak force values from the ITT MVC that were only 0.4–2.1% different than the MVC without stimulation. These findings suggested that the inter-individual variability may need to be monitored by comparing both voluntary and stimulated (ITT) MVC peak force values. However, results of this study indicated that the mean peak force from the ITT MVC was lower than the mean peak force from the MVC (figure 1). Therefore, caution is warranted when interpreting the changes (or lack thereof) in ITT MVC after an experimental intervention or treatment in highly activated subjects.

Another possible explanation for the difference between the ITT MVC and MVC without stimulation was the process of selecting the epochs to calculate mean peak force. During the ITT MVC, the mean peak force was calculated as an average of the 500 data points (0.25 s) that were recorded immediately prior to the stimulation. In contrast, for the MVC without stimulation, the mean peak force was calculated as the highest average force value for any 500 consecutive data points (0.25 s) recorded during the MVC. Because the interpolated twitch stimulation is supposed to be administered shortly after a plateau in force is achieved during an MVC (Allen *et al* 1995), the time epoch used to calculate mean peak force may occur earlier than the epoch used to calculate mean peak force during a normal MVC. In this study, we attempted to control for this potential influence by using the same epoch duration (500 data points; 0.25 s) to calculate mean peak force for both MVC trials. We also measured the durations of time from the onset of force development to the epoch used to calculate mean peak force for both the ITT MVC and normal MVC. There was no difference ($P > 0.05$) in the duration of time from the onset of force to the selected epoch to calculate mean peak force between the ITT MVC (1.27 ± 0.59 s) and MVC (0.99 ± 0.27 s) in this study, which suggested that the epochs were selected at the same time points during the MVCs. These findings helped to rule out simple measurement differences in how and when the mean peak force values were calculated as factors that may have otherwise influenced the differences in mean peak force values.

Studies have also utilized the ITT model to detect changes in motoneuron excitability as a result of an experimental treatment or intervention (Behm *et al* 2001a, de Ruiter *et al* 2003, Fowles *et al* 2000, Ryan *et al* 2008). However, when examining % VI versus force relationships in highly activated subjects, there may be limitations of the % VI calculated from the ITT method. In figure 2, subject 4 is fully activated at 80% MVC (289.8 N), because the % VI is near zero. However, this subject recorded a peak MVC without stimulation of 365.8 N, which was 26% higher than the force recorded at 80% MVC. Therefore, to report an increase in % VI for this subject, it would take a decrease in peak force greater than 26% due to the plateau in % VI that started at 80% MVC (figure 2). It is possible that subject 4 may have reached maximal motor unit recruitment near 80% MVC and used rate coding to increase muscle force output thereafter. In cases such as this, using the traditional ITT method to assess changes in motoneuron excitability may not be useful when the force output is at 80% MVC or higher. It is possible for individuals that do not display plateaus in % VI at high contraction intensities that the traditional ITT method may be more sensitive to assess changes in motoneuron excitability. In addition, the doublet stimulus applied during the contractions may not have been able to supply enough of a motoneuronal excitation to produce an additional significant amount of force, and, therefore, an evoked potential greater than a doublet stimulus

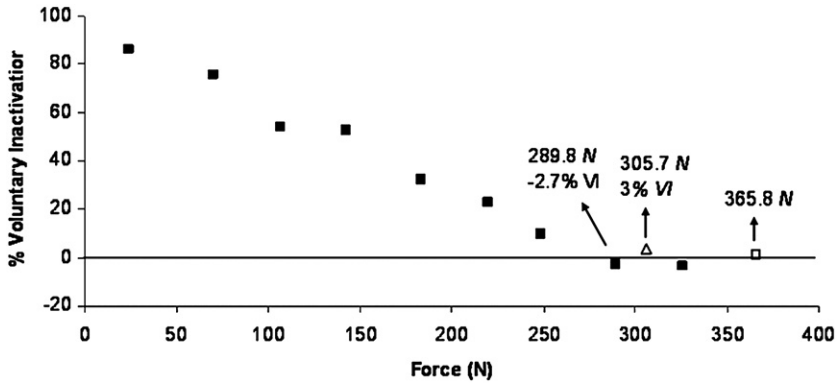

Figure 2. The plotted percent voluntary inactivation (% VI) versus force (N) relationship (black squares), the force and % VI values for 80% and the ITT MVC (white triangle), and the force value for the MVC without stimulation (white square) for one subject.

may be enough of an excitation to augment force at higher contraction intensities in the plantar flexors. Without knowing the % VI versus force relationship for each subject, perhaps using the interpolated twitch at moderate contraction intensities of approximately 40–70% MVC is most appropriate for assessing experimental motoneuron excitability changes.

4.2. VI versus force relationships and MVC prediction

For the 10–90% VI versus force relationships, the results of the polynomial regression analyses (table 1) indicated that the relationships were best fitted with linear models for 42% (5 of 12) of the subjects, quadratic for 17% (2 of 12) and cubic for 42% (5 of 12) (table 1). Thus, there were inter-individual differences in the patterns of response. Herbert and Gandevia (1999) and Behm *et al* (1996) have suggested that the traditional ITT model that uses an interpolated twitch during an MVC to predict % VI relies on a linear relationship between % VI and force. The results of this study tentatively support the hypothesis that it may not be appropriate to use one data point from the traditional ITT method to predict % VI for all subjects, because 58% (7 of 12) of the subjects were best fit with nonlinear models. In contrast, all of the 40–90% VI versus force relationships were best fitted with linear models (12 of 12) (table 1), which suggested that the removal of the lower contraction intensities (<40% MVC) increased the linearity of the pattern. In addition, the nonlinear relationships for the 10–90% VI patterns may have been due to the lower contractions and, furthermore, also indicating that there were nonlinear decreases in superimposed twitch amplitude at the lower contractions for seven (59%) of the subjects. It may be advantageous to predict an MVC using only these contraction intensities (40–90% MVC) because of the minimal inter-individual variability. Furthermore, Behm *et al* (1996) reported that there was least amount of prediction error when excluding the lower contraction intensities (<40% MVC); however, the authors applied a second-order polynomial model and not a linear model to those relationships.

For prediction of the peak force from the 10–90% VI versus force relationships, only the linear model was not significantly lower than the peak force recorded during the MVC without stimulation. However, the linear model underestimated the peak force by 22%, which would be considered too much error to accurately predict force. Overall, predicted force values from the models (best fit, linear, quadratic and cubic) for the 10–90% VI versus force relationships underestimated actual peak force from 22% to 28% (table 1). For the

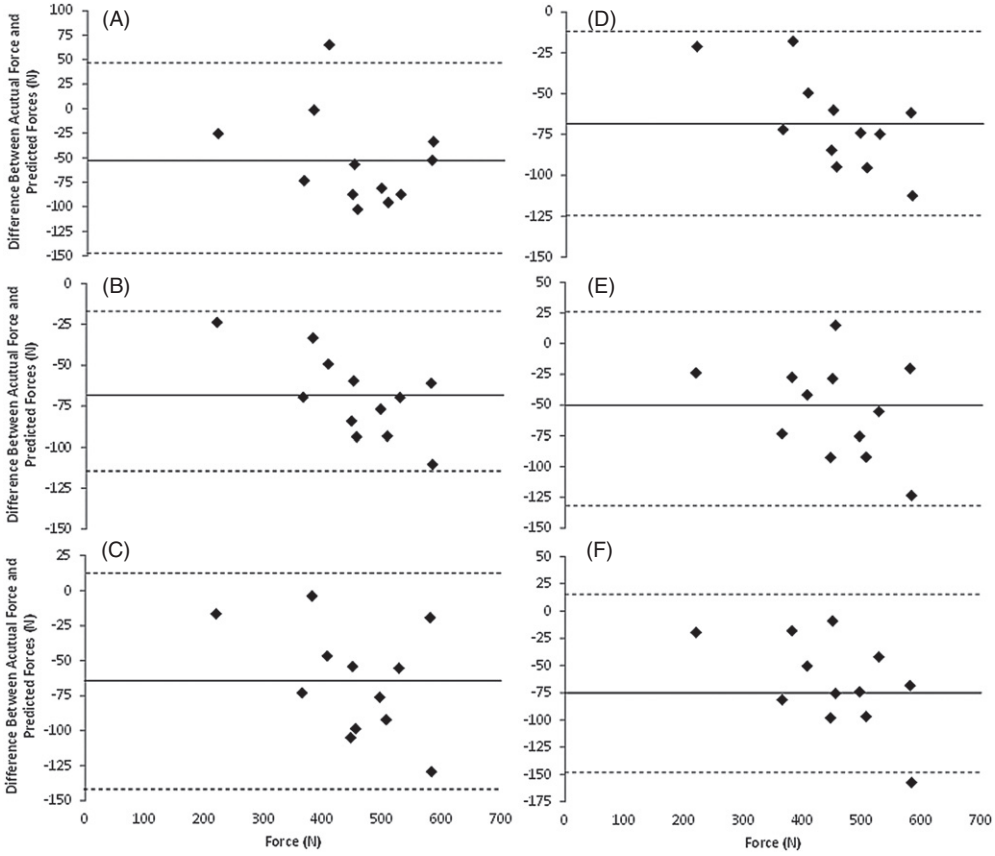

Figure 3. Bland–Altman plots for assessing agreement between the actual forces and the predicted forces from each of the polynomial regression models. Lines of agreement represent two standard deviations from the mean of the differences between actual force and predicted force. (A) 10–90% VI fitted with a linear model, (B) 10–90% VI fitted with a quadratic model, (C) 10–90% VI fitted with a cubic model, (D) 40–90% VI fitted with a linear model, (E) 40–90% VI fitted with a quadratic model and (F) 40–90% VI fitted with a cubic model.

40–90% VI versus force relationships, all models (linear, quadratic and cubic) predicted peak forces that were significantly lower than the actual peak force and underestimated peak force from 26% to 28% (table 1). Behm *et al* (1996) reported that there was a slightly better prediction of force from the models that did not include the lower contraction intensities (<40% MVC); however, when the lower contraction intensities were excluded from the polynomial models in this study it did not improve the prediction error. Behm *et al* (1996) examined the % VI versus force relationships and reported that the difference between actual and predicted peak force was 5.8%; however, the authors used the peak force recorded during the ITT method as the actual force. In this study, comparing the predicted peak forces from all the polynomial models to the peak force recorded during the ITT MVC (and not the MVC without stimulation) resulted in differences ranging from 4.9% to 8.1%, which are similar to the differences that Behm *et al* (1996) reported between the predicted and actual peak force recorded during the ITT MVC. Overall, regardless of the polynomial model (best fit, linear, quadratic or cubic), the predicted peak forces from the submaximal force levels (that were based on an MVC without stimulation) underestimated the actual force from 22% to 28% (figure 3). Another possible

explanation for the lack of accuracy in the prediction of true force from the models in this study is because the triceps surae are reported to only produce around 80% of total plantar flexor force (Sale *et al* 1982). The contribution of other muscles may partially explain the lack of accuracy in force prediction. Therefore, future research is needed to test these models on other muscle groups, such as the leg extensors and forearm flexors.

In summary, there were differences in peak force recorded during the ITT MVC and MVC without stimulation. This would suggest that researchers must be cautious when interpreting the results of an intervention or treatment based on the force recorded during the ITT MVC. However, including more practice ITT MVC trials to give the subjects more experience with the technique and then also monitoring the peak force recorded during the ITT MVC and comparing it to an MVC without stimulation may be helpful. In addition, caution is warranted when interpreting the % VI at high intensities (>80% of MVC) in highly activated subjects. The possible plateau in the % VI versus force relationship at higher contraction intensities could result in low sensitivity of the ITT technique (figure 2), which would make it difficult to demonstrate changes in motoneuron excitability as a result of a treatment or intervention. Future research is needed to examine if the ITT method overestimates voluntary activation at low to moderate intensity contractions and, subsequently, to examine if monitoring voluntary activation at these contraction levels is most appropriate for assessing experimental motoneuron excitability changes. Furthermore, the use of polynomial regression to predict force from the ITT method during submaximal contractions resulted in a 22–28% underestimation of actual force. Further research is needed to improve existing models or determine a more appropriate model for predicting peak force from the use of the ITT method during submaximal contractions of the plantar flexors, which may include the use of exponential models fitted to these relationships.

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