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Variability in the interpolated twitch torque for maximal and submaximal voluntary contractions

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Oskouei, M. A. E., B. C. F. van Mazijk, M. H. C. Schuiling, and W. Herzog. Variability in the interpolated twitch torque for maximal and submaximal voluntary contractions. *J Appl Physiol* 95: 1648–1655, 2003.— First published May 30, 2003; 10.1152/japplphysiol.01189.2002.—The superimposed twitch technique is frequently used to study the degree of motor unit activation during voluntary effort. This technique is one of the preferred methods to determine the activation deficit (AD) in normal, athletic, and patient populations. One of the limitations of the superimposed twitch technique is its variability under given contractile conditions. The objective of this research was to determine the source(s) of variability in the superimposed twitch force (STF) for repeat measurements. We hypothesized that the variability in the AD measurements may be caused by the timing of the twitch force relative to the onset of muscle activation, by force transients during the twitch application, by small variations in the actual force from the nominal target force, and by variations in the resting twitch force. Twenty-eight healthy subjects participated in this study. Sixteen of these subjects participated in a protocol involving contractions at 50% of their maximal voluntary contraction (MVC) effort, whereas the remaining 12 participated in a protocol involving contractions at 100% of their MVC. Doublet-twitch stimuli were superimposed onto the 50 and 100% effort knee extensor muscle contractions, and the resting twitch forces, voluntary knee extensor forces, and STFs were then measured. The mean resting twitch forces obtained before and after 8 s of 50% of MVC were the same. Similarly, the mean STFs determined at 1, 3, 5, and 7 s into the 50% MVC were the same. The variations in twitch force were significantly smaller after accounting for the actual force at twitch application than those calculated from the prescribed forces during the 50% MVC protocol ($P < 0.05$). Furthermore, the AD and the actual force showed statistically significant negative correlations for the 50% MVC tests. The interpolated twitch torque determined for the maximal effort contractions ranged from 1 to 70%. In contrast to the protocol at 50% of MVC, negative correlations were only observed in 5 of the 12 subjects during the 100% effort contractions. These results suggest that small variations in the actual force from the target force can account for the majority of the variations in the STFs for submaximal but not maximal effort contractions. For the maximal effort contractions, large variations in the STF exist due to undetermined causes.

superimposed twitch technique; activation deficit

THE INTERPOLATED TWITCH TECHNIQUE was first described in 1928 by Denny-Brown (8), and it is frequently used to study the degree of motor unit activation during voluntary effort (4). During contraction, an electrical stimulus (typically a single or doublet twitch) is superimposed onto a muscle or its nerve, and the evoked interpolated twitch torque (ITT) or superimposed twitch force (STF) is measured (4, 18, 27). The ITT is a measure of the number of motor units that are not maximally recruited during voluntary contraction. Therefore, the ITT is an index of the level of completeness of muscle activation. If the superimposed twitch technique is applied properly, the electrical stimulus fully activates all motor units of a muscle, and in the case of incomplete motor unit activation, the stimulus produces an increment in force (27). Consequently, the ITT decreases as voluntary muscle activation increases (4, 27, 29). The ITT is typically normalized to the resting twitch torque (RTT), the torque elicited by a superimposed twitch applied to a relaxed muscle. This normalized value (ITT/RTT) is termed the activation deficit (AD). Sometimes the ITT is normalized with respect to the voluntary torque and is used to estimate central activation failure (27).

The superimposed twitch technique is one of the preferred methods to determine AD in normal (4, 5, 15, 21), athletic (17), and patient populations (16, 25, 28, 29). However, one of the limitations of the twitch interpolation technique is its great variability for repeat measurements; therefore, it is often considered a qualitative rather than a precise quantitative measure of muscle activation (10). For example, a contraction at 60% of maximal voluntary effort may be associated with a variation in AD values from ~10 to 50% in a given subject (Fig. 1*A*).

When measured across a number of subjects, variations in the AD, expressed as raw data ($n = 20$ subjects, Fig. 1*B*) or as means ± SD ($n = 20$ subjects, Fig. 1*C*), tend to be even greater than those observed in a single subject (29).

Because of the great variability in the superimposed twitch technique, this approach is limited for clinical applications and basic science questions. For example, the superimposed twitch technique has been used successfully to show differences in AD between normal reference populations and patient populations with musculoskeletal injuries or diseases (16, 28, 30). However, it has been impossible to classify individual sub-

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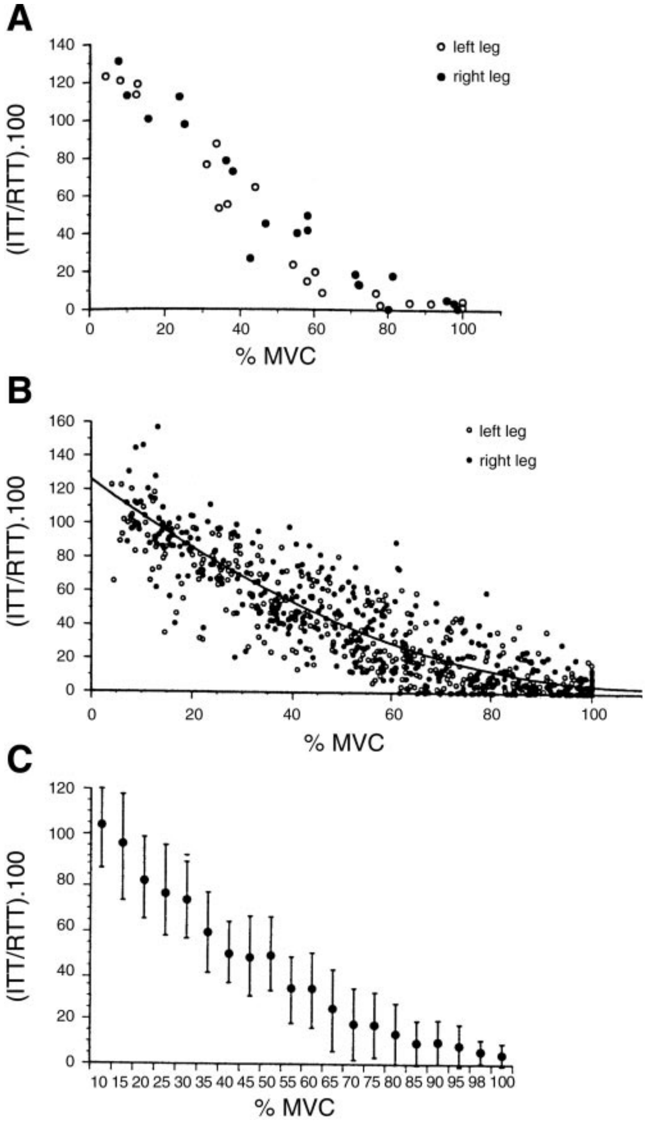

Fig. 1. *A*: normalized interpolated twitch torque (ITT) as a function of the level of voluntary contraction for the right and left legs of 1 representative subject. *B*: normalized interpolated twitch torque as a function of the level of voluntary contraction for the right and left legs of 20 subjects. *C*: mean (±1 SD) of the normalized ITT as a function of the level of voluntary contraction in 20 subjects. RTT, resting twitch torque; %MVC, percentage of maximal voluntary contraction (29).

jects consistently into a patient or a normal reference group (M. A. E. Oskouei and W. Herzog, unpublished observations). Furthermore, having eliminated experimental error from the STF measurements, the basic question arises as to what are the sources of the great variablility in STF under apparently identical experimental conditions.

Previously, we had speculated that the variability in the STF was associated with the fact that the superimposed twitch constituted a stochastic process within the individual pulse trains of the motor units during voluntary contraction. The timing of the superimposed twitch relative to the ongoing pulse trains has been shown to change the observed STF significantly (27). In general, if the timing of an electrical stimulus was close to a pulse of the ongoing pulse train, then a "doublet-like" effect with a large STF was generated. In contrast, if the electrical stimulus given somewhere near the middle of two consecutive pulses of the ongoing pulse train, then a lesser force was generated (27). This observation corresponded well with earlier observations of the so-called "catch property" reported in cat hindlimb muscles (7). This explanation was well supported by experiments simulating a single voluntary pulse train corresponding to one motor unit. On the basis of the modeling approach of Fuglevand et al. (11), it seems that the variations in the STF of a knee extensor muscle with 300 motor units (22) can be decreased to <1% of the mean STF. This value is likely within the error of measurement of all published superimposed twitch techniques (1). Therefore, it was concluded that the large variability in the STF for repeat measurements cannot be explained by the stochastic nature of the timing of the electrical stimuli relative to the ongoing voluntary motor unit pulse trains.

The objective of this study is to determine and reduce or eliminate the origin(s) of the variability in the STF for repeat measurements. Specifically, the goals of this study were to test the hypotheses that potentiation (20), force transients during twitch application, variability in the resting twitch values, and small variations in the voluntary forces from nominal target values could account for the experimentally observed variability in STF. The effects of potentiation and the rate of change in force were studied for submaximal (50%) contractions. The effects of small force variations and variable RTTs were studied at submaximal (50%) and maximal (100%) voluntary contractions (MVCs).

METHODS

Subjects

Twenty-eight subjects participated in this study. Sixteen healthy subjects (8 men and 8 women), with a mean age of 27 ± 6 yr, height of 173 ± 10 cm, and mass of 72 ± 19 kg, participated in the submaximal protocols involving 50% effort contractions. Twelve healthy subjects (8 men and 4 women; age 30 ± 7 yr, height 178 ± 10 cm, mass 73 ± 11 kg) participated in the maximal protocol involving 100% effort contractions. All subjects were moderately active and were recruited from students and members of the Faculty of Kinesiology. Written, informed consent was obtained from all subjects, and the study protocol was approved by the University of Calgary Ethics Committee on Human Subjects.

Preparation and Warm-Up

Three test protocols involving knee extensor contractions on a dynamometer (Biodex) with the twitch interpolation technique (4, 23) comprised the main test. Before testing, the subjects were allowed to warm up freely. After the warm-up, the subjects were secured onto the dynamometer chair such that the axis of rotation of the left leg coincided with the fixed axis of rotation of the dynamometer. The tibia, just above the ankle, the thigh, just above the knee, and the torso across the shoulders were fixed to the dynamometer arm and chair, respectively.

To stimulate the knee extensors electrically, two carbon-impregnated rubber electrodes (4.3 × 10.3 cm), thinly coated with conductive gel, were secured onto the shaved and cleaned skin above the femoral nerve and the distal part of the anterior femur (29). Once attached, the electrodes were connected to a Grass stimulator (model S88) via an isolation unit approved for human use (26–30). Doublet twitches (0.8-ms square-wave pulses separated by 8 ms) were then delivered at increasing voltages until a further increase in voltage failed to produce an increase in twitch force.

50% Effort Protocols

After this initial preparation, the subjects were allowed to perform isometric and dynamic knee extensor contractions for target-specific warm-up until they indicated that they were ready to start the experiment. At this point, the subjects in the 50% effort test group performed three MVCs at a knee angle of 90° flexion (0° is the fully extended knee). Rest between contractions was determined by the subjects, but a minimum of 3 min was enforced.

The best of the three contractions, if it did not exceed the second best contraction by $>5\%$, was taken as the MVC. If the two best contractions differed by $>5\%$, a maximum of two further MVCs were performed to determine the MVC, as described above. The 50% force level was then determined, and a line on an oscilloscope in front of the subjects was set at 50% of the MVC for visual feedback. After a subject-determined rest (minimum of 3 min), two submaximal test protocols (50%) were performed in a random but balanced design.

50% MVC: Protocol 1. The first protocol was aimed at evaluating the variation in the interpolated twitch force for a given level of knee extensor force and to determine whether the timing of the superimposed twitch relative to the achievement of the steady-state force might influence the interpolated twitch force. The subjects were asked to perform a 50% of MVC contraction at a knee angle of 90° flexion for 8 s. The 50% of MVC target was visibly displayed on the oscilloscope, together with the instantaneous force. Therefore, the subjects could continuously evaluate the accuracy of their task. Before the 8-s 50% of MVC contraction, the subjects received three supramaximal doublet twitches separated by 1 s with their knee extensors perfectly relaxed (resting twitch force). Similarly, at 3 s after the test contraction, the subjects were given three additional resting twitches (Fig. 2*A*). During the 8 s at 50% of MVC, the subjects were given four superimposed doublet stimulations, at 1, 3, 5, and 7 s after they had reached the 50% of MVC target force. This test was repeated 10 times with a (minimum) 2-min rest interval, for a total of 40 superimposed twitch stimulations, 10 each at 1, 3, 5, and 7 s after achievement of the 50% of MVC force.

50% MVC: Protocol 2. The second protocol was aimed at investigating whether a systematic increase or decrease in force had a measurable effect on the STF at 50% of MVC. The subjects performed two tests that were presented in a random but balanced order. In the first test, they performed an isometric knee extensor contraction at a knee angle of 90° as follows: first they increased the force until they reached 40% of their MVC, held this force for 2 s, and then steadily increased the force up to 60% of their MVC and held that force for another 2 s. A doublet twitch was superimposed at the instant when the subjects crossed the 50% of MVC value (Fig. 2*B*, *arrow 1*). This test was repeated six times by each subject, with a (minimum) rest of 2 min between contractions.

The second test was identical to the first one, except that the subjects started at 60% of MVC and then decreased their force to 40% of MVC. As above, the doublet twitch was given as the subjects crossed the 50% of MVC value (Fig. 2*B*, *arrow 2*). This test was also repeated six times, with a (minimum) rest of 2 min between contractions.

100% Effort Protocol

Protocol 3. The subjects ($n = 12$) were asked to perform 10 maximal voluntary knee extensor contractions with a 2-min (minimum) interval between contractions. Before and after each contraction, three resting twitch stimuli, hereafter called the unpotentiated RTT and potentiated RTT, respec-

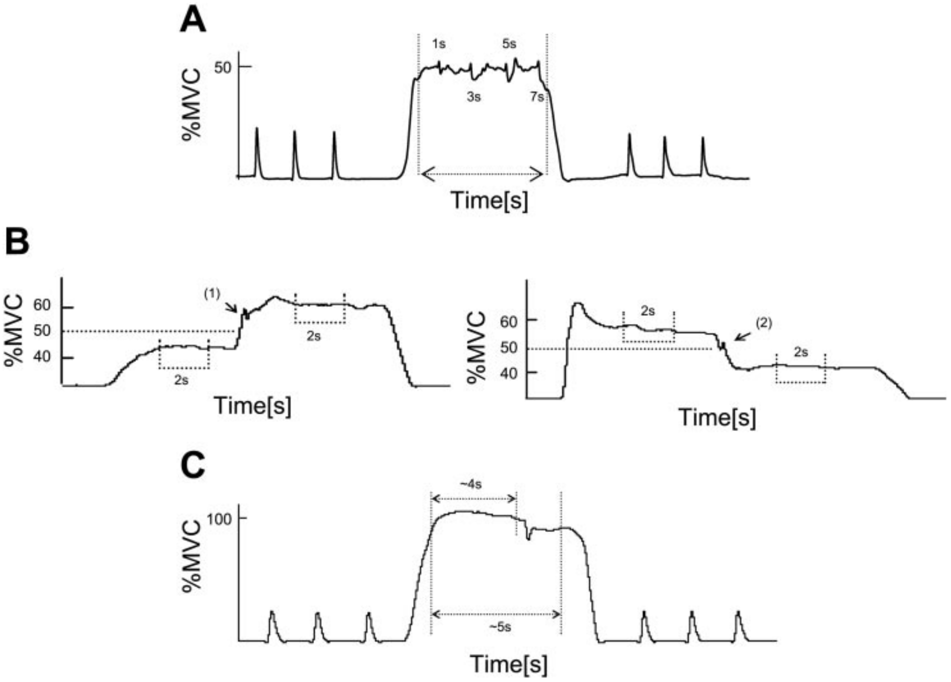

Fig. 2. Protocols. *A*: *protocol 1*. Effect of the timing of the superimposed twitch application on the magnitude of the superimposed twitches was determined (see text for details). *B*: *protocol 2*. Subjects were asked to increase their force from ~40 to ~60% of MVC. A superimposed twitch was then applied when the subjects reached 50% of their MVC (*arrow 1*), and the subjects were asked to decrease their force from ~60% of MVC to ~40% of MVC. A superimposed twitch was applied when the subjects reached 50% of their MVC (*arrow 2*) (see text for further details). C: *protocol 3*. Three RTTs were given before and after 5 s of 100% of MVC isometric knee extensor contractions. A superimposed twitch torque was given at ~4 s after the achievement of the maximal force.

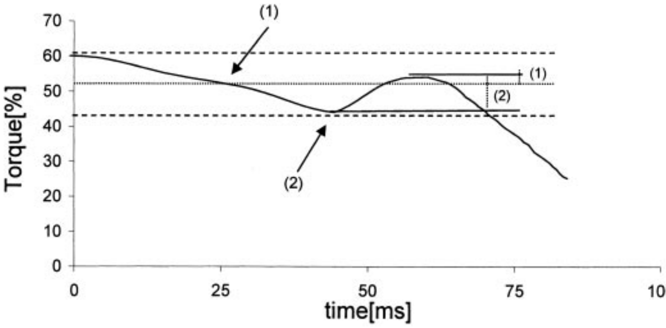

Fig. 3. Example of an experiment in which the subjects were asked to decrease their isometric force from 60 to 40% of MVC. The superimposed twitch was given precisely when the subject crossed the 50% of MVC line (computer triggered, *arrow 1*). The superimposed twitch was calculated in 2 ways: *1*) the electromechanical delay was not accounted for, and the peak twitch force was calculated from the 50% of MVC value; and *2*) the electromechanical delay was accounted for, and the superimposed twitch was calculated from the base of the twitch (*arrow 2*) to the peak twitch force.

tively, were given. The average peak force of these three twitches was taken as the mean RTT, and it was used for the normalization of the superimposed twitch torque. Each MVC was sustained for 5 s (19). A doublet-twitch stimulus was superimposed onto the fully contracted muscle 4 s after a steady-state force was reached, and the corresponding torque level was determined for a 500-s period immediately preceding the superimposed twitch.

Measurements and Analysis

The resting twitch forces, voluntary knee extensor forces, and STFs were measured by using CODAS data-acquisition software at 2,000 Hz per channel. The STFs were divided by the mean resting twitch force obtained before the test contractions. Furthermore, linear regression was used to identify possible intra- and intersubject relationships between the RTT and the AD.

When an electrical stimulus is given to the motor nerve, there is some delay before the force effect of the stimulation is seen. This delay was accounted for when calculating the "delayed" STF by calculating the STF from the force value at the onset of the twitch, rather than the instant when the twitch was applied (Fig. 3).

In *protocols 1* and *3*, the subjects were asked to produce a steady-state, 50 and 100% of MVC force, respectively. However, when the superimposed twitch was applied, no subject was ever precisely at 50 or 100% of MVC force. To evaluate the effect of variations in the voluntary force from the target level of 50% of MVC, or the deviation from the maximal voluntary effort that gave the greatest torque (hereafter taken as 100% of MVC), a best-fit linear regression analysis was performed between the actual voluntary force and the corresponding STF. Variations in the twitch force were then calculated as ± 1 SD from the mean value or as ± 1 SD from the corresponding value on the best-fitting regression line (Fig. 4).

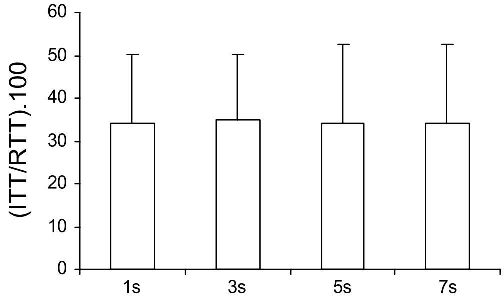

Fig. 5. Mean (±1 SD) of the normalized superimposed twitch torques at 1, 3, 5, and 7 s of the 50% of MVC for 16 subjects repeated 10 times each.

Nonparametric, repeated-measures statistics (Wilcoxon signed-rank test and Kruskal-Wallis test) were used to determine whether there was a difference in the resting twitch forces obtained before and after the 8 s of 50% of MVC contractions in *protocol 1* and to determine the possible differences in the twitch forces applied at 1, 3, 5, and 7 s into the 50% of MVC contractions in *protocol 1*, respectively. Similarly, nonparametric, repeated-measures statistics were used to determine differences between the STFs from *protocol 1* (steady 50% of MVC contraction) and those from *protocol 2* (increasing from 40 to 60% of MVC or decreasing from 60 to 40% of MVC). All of these twitches were given at a nominal value of 50% of MVC (*protocol 1*), or were automatically triggered at 50% of MVC in *protocol 2* (both experiments). All statistics were performed by including and excluding the electromechanical delay. The level of significance was set at $\alpha = 0.05$ in all cases.

RESULTS

50% MVC: Protocol 1

The resting twitch forces obtained before and after the 8 s of 50% of MVC were the same, indicating that either there was no potentiation or that the potentiation effects were eliminated by the doublet electrical twitch application. Similarly, the STFs determined at 1, 3, 5, and 7 s into the 50% of MVC were the same (Fig. 5).

The variations in twitch force, after accounting for the actual force at twitch application (i.e., ±1 SD from the regression line), were significantly smaller than those calculated from the mean of the STFs (Fig. 6). The regression lines between the actual force at twitch

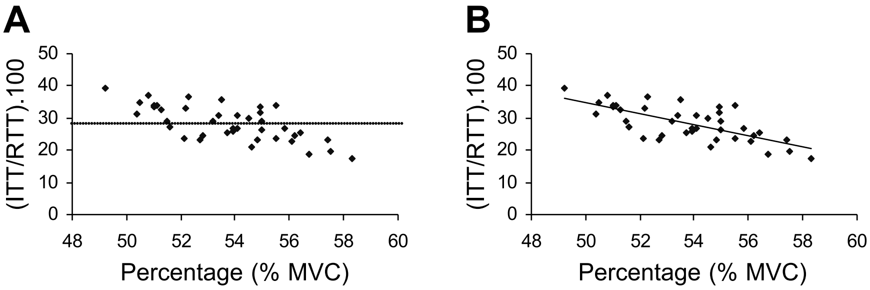

Fig. 4. *A*: variability in the ITT calculated from the mean ITT (28%) for a representative subject and 40 twitches. *B*: variability in the ITT calculated as the deviation from the best-fitting regression line between the actual percentage of MVC and the AD.

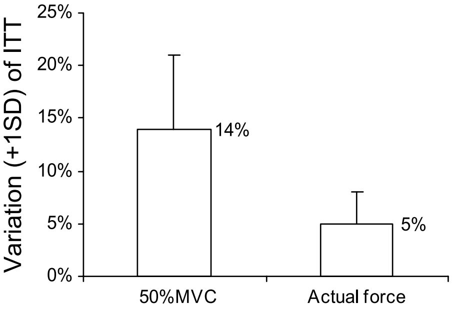

Fig. 6. Mean (± 1 SD) of the variability in the superimposed twitch torques from the 50% of MVC target force and from the actual force at twitch application for 16 subjects repeated 10 times each. The variations in the superimposed twitch torque from the actual forces were reduced to ~⅓ of those obtained at a nominal target force of 50% of MVC, indicating that the superimposed twitch torque is sensitive to small force variations around the 50% of MVC target force.

application and the STF were negative ($P < 0.05$) for all 16 subjects, indicating that the STFs were decreasing with small increases in the voluntary force. Figure 7 (*A*, *B*, and *C*) shows three subjects in whom accounting for the actual force at the time of twitch application reduced the variations in twitch force the most (*subject 13*), the least (*subject 11*), and by an average amount (*subject 1*).

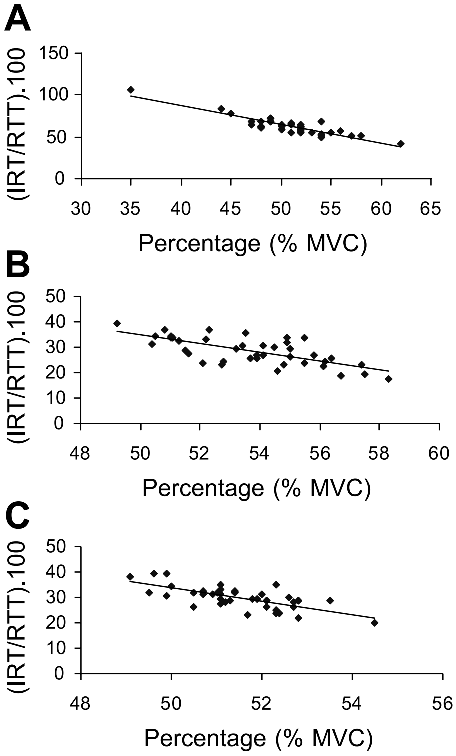

Fig. 7. Best-fitting linear regression line between the actual force at twitch application and the normalized superimposed twitch torque for 3 subjects undergoing 40 tests each. Accounting for the actual force reduced the variation in the superimposed twitch force the most for *subject 13* (*A*), the least for *subject 11* (*B*), and by an average amount for *subject 1* (*C*).

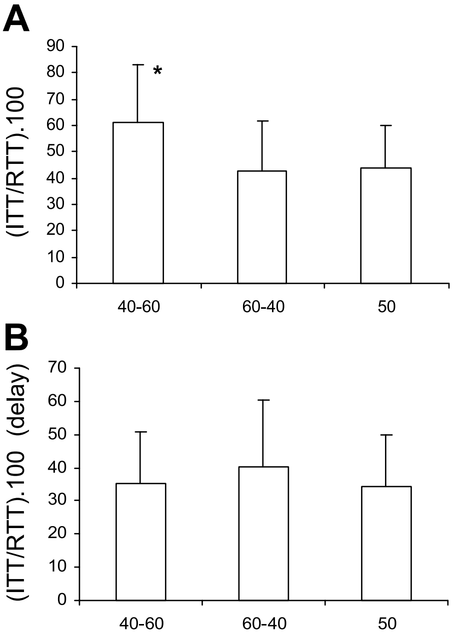

Fig. 8. Mean (± 1 SD) of the normalized superimposed twitch torque at 50% of MVC for 16 subjects repeated 10 times each when increasing from 40 to 60% of MVC (40–60), decreasing from 60 to 40% of MVC (60–40), and performing isometric contractions at 50% of MVC (50). If the electromechanical delay was not accounted for (*A*), the condition of 40–60 gave a greater ITT than the conditions of 60–40 or 50. If the electromechanical delay was taken into account, the ITTs were the same for all conditions (*B*).

50% MVC: Protocol 2

The STF was significantly greater at 50% of MVC when the force increased from 40 to 60% of MVC, compared with when the force decreased from 60 to 40% of MVC or when the force was "steady" at 50% of MVC (*protocol 1*) (Fig. 8*A*). However, when accounting for the electromechanical delay, the STFs were the same for all conditions (Fig. 8*B*).

100% MVC: Protocol 3

The RTTs before and after the 5 s of 100% of MVC contractions were the same (not shown). The interpolated twitch torque, and the corresponding AD determined for the maximal effort contractions, showed great variability (Fig. 9). In contrast to *protocol 1* (50% of MVC), in which all linear regressions between the AD and the actual force were statistically significant and negative, significant negative correlations were

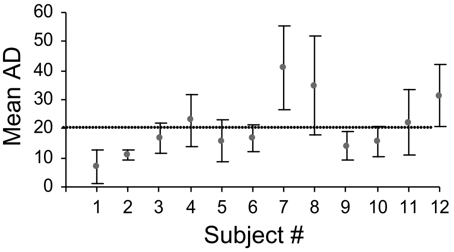

Fig. 9. Mean (± 1 SD) of activation deficit (AD) for all 12 subjects and 10 repeated contractions for each subject.

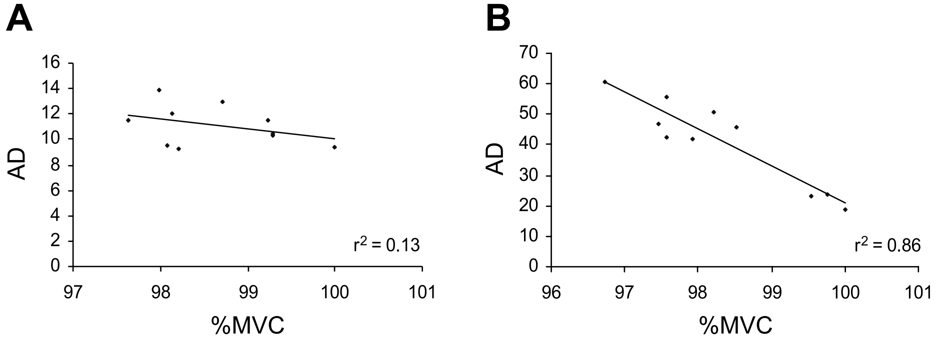

Fig. 10. AD as a function of the MVC for 2 representative subjects and 10 trials each: a representative subject in whom the AD and actual force (%MVC) were not significantly correlated (*A*) and another subject in whom the 2 variables were significantly correlated (*B*) (see text for further details).

only observed in 5 of the 12 subjects in the 100% effort group. The remaining seven subjects also had negative relationships between their AD and voluntary force, but these relationships were not statistically significant (Fig. 10).

The mean values of the AD for the five subjects who had statistically significant negative correlations between their AD and voluntary force for the maximal effort contractions were all >20% (*subjects 4, 7, 8, 11, 12*; Fig. 9). The seven subjects showing no significant correlation between the two variables all had mean AD values below 20% (*subjects 1, 2, 3, 5, 6, 9, 10*; Fig. 9).

The relationship between the AD and the actual force for the maximal effort contractions was statistically significant for all subjects combined. However, only 28% of the variation in the AD could be explained by the corresponding variation in the actual force (Fig. 11). Note that a small variation in the MVC values (~6%) was associated with ADs ranging from ~1 to 70%.

The relationship between RTTs and the corresponding AD measurements were not statistically significant for 11 of the 12 subjects (not shown). The mean correlation coefficient across all 12 subjects was $r = -0.05 \pm 0.16$, with r being positive for four and negative for eight subjects. Across all subjects, the RTTs were significantly correlated with the AD ($r^2 = 0.22$). This suggests that the variations in the AD and RTT can account for some of the intersubject variations in the AD, but they do not appear to contribute to the intrasubject variations in the AD.

DISCUSSION

Since the classic study by Merton (23), the superimposed twitch technique has been used to assess fundamental muscle properties (2, 4, 9, 12, 18), to evaluate patients with musculoskeletal diseases and injuries (16, 25, 28, 30), and to elucidate the details of movement control (4, 9). However, the large intra- and intersubject variability of this technique has limited its applicability and use. In previous work, we had speculated that the stochastic nature of the timing of the superimposed twitch relative to the naturally occurring activation pulses may have produced this variability (27). However, theoretical analysis revealed that this speculation was incorrect, because the expected variation caused by this source was in the range of ~1%, rather than the observed 20, 30, or even 50%.

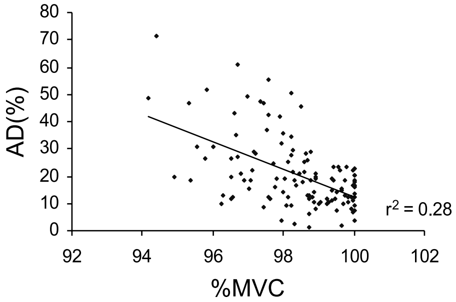

Fig. 11. AD as a function of %MVC for 12 subjects undergoing 10 trials each.

Here, we tested systematically whether the variations in the superimposed twitch technique could be explained *1*) by potentiation effects, *2*) by force transients at the time of application of the superimposed twitch, *3*) by variations in the absolute force magnitude from the target value (i.e., 50 or 100% of MVC in our case), and *4*) by variations in the RTTs.

Potentiation

For the specific muscle group and test conditions (50 and 100% of MVC, 90° of knee flexion), potentiation did not influence the STFs. We assumed that possible effects due to potentiation did not contribute to the variations in the AD or RTTs obtained before and after the tetanic test contractions, because of the doublet nature of the superimposed twitches. It is well established that single twitches show posttetanic potentiation quite readily (13), whereas these effects are diminished or absent in doublet twitches (14). Therefore, it is quite possible that potentiation effects may cause variability in the AD if single twitches were used for the superimposed twitch and/or the resting twitch measurements. Thus, based on the results of this study as well as others (14), we suggest that doublet rather than single twitch stimuli should be used in the superimposed twitch technique.

Force Transients

Force transients, or systematically increasing or decreasing forces at the instant of superimposed twitch application, appeared to have an effect on the STF. Specifically, it appeared that if force was increasing at the time of twitch application, then the STF was greater than the twitch forces obtained during the "steady" force experiments or when the force was decreasing at the instant of twitch application. However, when the electromechanical delay was accounted for, and the STF was not calculated from the force level at which twitch application occurred but rather from the force level when the twitch took effect (which steadily increased in the experiments in which force was increased from 40 to 60% of MVC), no effect of the transient forces on the STFs was observed (Fig. 8*B*). This result suggests that STFs should always be calculated from the onset of the twitch response when force transients may affect the results. This would likely be important in dynamic (nonisometric) contractions, as well as in tests where the force varies (i.e., anisotonic contractions).

Actual Force

Although the absolute forces are typically measured when the superimposed twitch technique is used, we are not aware of any studies in which the variations in the superimposed twitch torque were related to the ever-present small variations in the actual forces.

When the STFs were plotted as a function of the actual force magnitudes (in percentage of MVC) in *protocol 1* (50% of MVC), all 16 subjects showed a statistically significant, negative correlation; in other words, greater forces were associated with smaller STFs (Fig. 7). Therefore, when the STF was expressed relative to the actual force magnitudes rather than the nominal 50% of MVC, the variations in the STFs were greatly reduced (Fig. 6). However, when the same procedure was applied to the 12 subjects who attempted 100% of MVC contractions, only 5 had the corresponding negative correlations between their AD and the actual force (Fig. 10*B*). For the remaining seven subjects, this correlation was not significant (Fig. 10*A*), and a linear regression across all subjects showed a significant but weak negative relationship between the AD and the actual force (Fig. 11). The five subjects who showed a significant relationship in the 100% of MVC tests had the greatest mean ADs (all above 20%), whereas those with nonsignificant correlations all had mean AD values of <20%. This result suggests that those subjects who showed a significant relationship did not approximate their "true" maximal knee extensor force as closely as those who did not show that relationship. Combined with the results of the submaximal contractions (50% of MVC tests), these findings suggest that small variations in the actual force from the target force can account for the majority of the variations in the STFs for submaximal but not maximal or near-maximal effort contractions. For near-maximal effort contractions, large variations in the STF persisted, which we could not explain.

RTTs

Even after the RTTs were averaged for each test across three values, as done here, they still vary by a small amount within subjects. Because the AD is calculated as the ratio of ITT to RTT, greater RTTs might be systematically associated with decreasing ADs. However, the variations in the RTT were too small to contribute significantly to the variations observed in the ADs within subjects. However, across all subjects, ~22% of the variations in AD were explained by the corresponding variations in the RTT. We have no ready explanation for the variability in the RTT either within or across subjects.

In summary, from the results of this study, we conclude the following: *1*) young, healthy human subjects show substantial variability in force when asked to perform repeated 50 or 100% of MVC knee extensor contractions; *2*) variations in the force deficit were not associated with muscle potentiation, likely because of the doublet nature of the superimposed twitch and the fact that the resting twitches were given before and after the test contractions; *3*) variations in the force deficit were affected by systematic force transients at the instant of twitch application. However, these could be effectively abolished by accounting for the electromechanical delay between twitch application and twitch onset; and *4*) STFs are very sensitive to small changes in voluntary force during submaximal effort contractions. However, if these variations in voluntary forces are properly accounted for, the variations in the AD are greatly reduced. For maximal effort contractions, the STF still varied greatly, but these variations could not (or only to a small degree) be explained by variations in the actual knee extensor forces. The variability of the STF during maximal effort contractions remains a mystery. This result is disappointing, because maximal effort contractions are the most frequently used contractions in the clinical setting to assess motor function in patients with musculoskeletal injuries and diseases.

Recommendations

On the basis of the results of this study, we propose the following steps to reduce the variations in the superimposed twitch technique, and the associated determination of AD: *1*) use doublet twitches for the superimposed and resting twitches; *2*) account for the electromechanical delay, particularly in dynamic and anisotonic testing; *3*) calculate the AD based on the actual, not the target force, particularly for submaximal contractions; and *4*) account for variations in the RTTs, particularly when comparisons are made across subjects. Also, multiple measurements of the RTT should be performed to reduce the variability in repeat measurements within subjects.

DISCLOSURES

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