The Muscle Activation–Force Relationship Is Unaffected by Ischaemic Recovery

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Abstract/Résumé

Since reported changes in muscle activation following fatigue could be affected by alterations in muscle contractile properties, the plantar flexors’ activation–force relationship was investigated before and following an isometric, intermittent, submaximal, fatigue protocol. Voluntary and evoked force and muscle activation was tested pre- and post-fatigue with ischaemic and nonischaemic recovery. The muscle activation–force relationship of ischaemic and nonischaemic groups was best described by a second-order polynomial equation with similar y intercepts, slopes, and curvature of the slopes. A significantly increased muscle activation–force slope during recovery may be attributed to decreased muscle activation and not impaired muscle kinetics. The index of muscle activation immediately postfatigue was not significantly different between ischaemic and nonischaemic groups (88.5% vs. 92.7%). No significant difference in the estimate of muscle activation postfatigue with polynomials and interpolated twitch (IT) ratios (superimposed/potentiated doublets) suggested that IT ratios can be used as a general estimate of muscle inactivation following fatigue.

Les modifications de l’activation d’un muscle épuisé peuvent être affectées, semble-t-il, par la variation des propriétés contractiles; dès lors, le but de cette étude est d’établir la relation activation–force des fléchisseurs plantaires avant et après un effort isométrique sous-maximal intermittent jusqu’à épuisement. La relation activation–force est analysée dans

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The interpolated twitch technique (ITT) has been used as an estimate of muscle activation in a variety of fatigued (Bigland-Ritchie et al., 1978, 1983, 1986; Merton, 1954; Newham et al., 1991; Vollestad et al., 1988) and nonfatigued young (Belanger and McComas, 1981; Bellemare et al., 1983; Dowling et al., 1994; Gandevia and McKenzie, 1988; Rutherford et al., 1986) and aged (Vandervoort and McComas, 1986) individuals, as well as with clinical populations (Allen et al., 1994; Lloyd et al., 1991; Minotti et al., 1992; Norregard et al., 1994; Rice et al., 1992; Rutherford et al., 1986, 1990). The technique involves detecting superimposed evoked torques upon a voluntary contraction. Many studies have calculated a ratio between the amplitude of the superimposed torques and resting torques (interpolated twitch ratio) to quantify the extent of muscle inactivation (Allen et al., 1994; Bigland-Ritchie et al., 1978, 1986; Rice et al., 1992).

A number of fatigue studies have used a single interpolated twitch (IT) ratio to estimate the extent of fatigue-induced muscle inactivation (Bigland-Ritchie et al., 1978, 1986; McKenzie and Gandevia, 1991), based on the assumption of a linear relationship between muscle activation and force output that is not affected by fatigue. However, the IT ratio–force relationship is best described by a second-order polynomial (Bulow et al., 1993; Dowling et al., 1994), so that a single IT ratio cannot be used as an accurate estimate of muscle activation. Furthermore, the IT ratio–force relationship may be affected by fatigue, making comparisons of pre- and postfatigue activation levels invalid. Reports that fatigue does not affect (Bigland-Ritchie et al., 1978, 1983; Merton, 1954; Vollestad et al., 1988) or results in decreases in muscle activation (Ikai et al., 1967; McKenzie and Gandevia, 1991; McKenzie et al., 1992; Newham et al., 1991) as measured by the IT ratio could be affected by fatigue-induced changes in the kinetics (contractile properties) of the superimposed and resting torques (IT ratio). If the effects of fatigue alter the IT ratio–force relationship, muscle activation differences may be due to an inaccurate instrument that significantly affects fatigue-induced changes in muscle contractile properties. One of the objectives of this study was to determine whether changes occurred in the muscle activation (IT ratio)–force relationship following fatigue and to determine whether a single IT ratio could be used to estimate changes in activation levels postfatigue. The response of voluntary and evoked contractile properties changes over time with recovery from fatigue (Alway et al., 1987; Kroon and Naeye, 1988;
Garland et al., 1988; McKenzie and Gandevia, 1991). Different fatigue protocols can result in either depression (Bigland-Ritchie et al., 1983; Grange and Houston, 1991; Houston and Grange, 1990; McKenzie and Gandevia, 1991; Vollestad et al., 1988) or potentiation (Dolmage and Cafarelli, 1991; Grange and Houston, 1991; Houston and Grange, 1990) of twitch torque, possibly affecting the IT ratio–force relationship. Ischaemic conditions have been utilized in a variety of studies to prolong the effects of fatigue during the recovery period (Woods et al., 1987; Garland and McComas, 1990). In an attempt to ensure a consistent postfatigue testing condition, both ischaemic and nonischaemic recovery were investigated to compare the effects of prolonged and normal recovery on the IT ratio–force relationship. In addition, another objective was to test the validity of utilizing a single IT ratio to estimate changes in muscle activation postfatigue.

**Experimental Design and Methodology**

**SUBJECTS**

Twelve subjects (6 males and 6 females; 27.7 ± 6.0 yr, 163.9 ± 28.4 cm, 71.5 ± 15.6 kg) were equally divided into ischaemic and nonischaemic recovery groups. Subjects were recruited from McGill University students and staff. All subjects were fully informed of the procedures and signed a consent form prior to experimentation. The study was approved by McGill University’s Ethics committee.

**EXPERIMENTAL SET-UP**

Subjects were seated in a straight-back chair with their hips, knees, and ankles flexed at 90°. Subjects had their leg secured in a modified boot apparatus (Belanger and McComas 1981). Tibial nerve surface-stimulating electrodes were placed on the popliteal space and distal portion of the triceps surae. Electrodes were shifted and polarity reversed during initial stimulation to determine the optimal arrangement for the greatest peak torque. Thorough skin preparation for all electrodes included sanding of the skin around the designated areas, followed by cleansing with an isopropyl alcohol swab.

**EVOKED AND VOLUNTARY TORQUE**

Stimulating electrodes were connected to a high-voltage stimulator (Digitimer Stimulator; Model DS7). The amperage (10 mA to 1 A) and duration (50–100 μs) of a 100-V rectangular pulse was progressively increased until a plateau was achieved in the peak twitch torque, indicating maximum stimulation. Doubles were elicited by two twitches with an interval of 10 ms (100 Hz). All evoked and voluntary torque were detected by a force transducer (PF; custom design; quads: BLH Electronics, Universal 3SB load cell), amplified (recording amplifier and AC–DC differential amplifiers from Neurolog Systems-Model NL900A) and monitored on oscilloscope (Tektronix Model 2220). All data were stored on computer (Seanim ASI 9000 486 DX) after being directed through an analog-digital board (Lab Master) (2,000 Hz). Data were recorded and analysed with a custom-designed software program (Actran; Distributions Physiomonitor Ltd.).
INTERPOLATED TWITCH TECHNIQUE (ITT)

Three maximal doublets, interspersed at 900-ms intervals, were evoked and superimposed on a series of 3-s duration, submaximal (20, 40, 60, and 80%) voluntary contractions to estimate an average superimposed signal. Only the smallest or occluded superimposed signal was recorded with MVCs (3 trials). In addition to eliciting a doublet from a previously relaxed muscle, two potentiated doublets were recorded at 1-s intervals following the voluntary contractions. Superimposed doublets, rather than twitches, were utilized to increase the signal-to-noise ratio. Torque signals were sent through both a low- and high-gain amplifier. The resident software program offset the high-gain superimposed signal, 100 ms before each stimulation for improved resolution (Figure 1). A ratio comparing the amplitudes of the superimposed doublets with the potentiated doublet (ITT ratio), represented muscle force that was not voluntarily activated. The percentage of recruited force was estimated from a single IT ratio by subtracting the ratio from a value of 1 and multiplying by 100 to represent an index of muscle activation during a voluntary contraction pre- and postfatigue. All maximal and submaximal contraction (100, 80, 60, 40, and 20% of MVC) forces were correlated with their respective IT ratios in order to generate second-order polynomial equations for all subjects.

FATIGUE

After testing, subjects proceeded with the fatigue test. The fatigue protocol had subjects gradually increase the intensity of their contraction for 3 s until 50% of the MVC was attained. This intensity was maintained for 10 s, followed by a 3-s gradual decrease to a resting state. The sequence was resumed after a 4-s rest period. The contraction cycles (work:rest ratio of 16 s:4 s) continued until the effects of fatigue disrupted a subject's ability to maintain the 50% MVC for the 10-s period.

RECOVERY

Groups were tested during a 2-min recovery period either under ischaemic or nonischaemic conditions. Ischaemia was initiated immediately postfatigue, in an attempt to ensure that fatigue-related muscle deficits were maintained during recovery testing. A deflated air-pressure cuff was placed over the proximal segment of the calf prior to the fatigue test, and was inflated and maintained at over 200 mmHg within seconds following fatigue. Both groups performed a MVC with the IT immediately postfatigue followed by a series of randomly selected submaximal contractions (20, 40, 60, and 80% of postfatigue MVC) with IT every 30 s. The ischaemic group had the cuff deflated and removed 2 min into the recovery period.

STATISTICAL ANALYSES

Second-order polynomial regression equations were used to determine the line of best fit for the IT ratio–force relationship. To determine the point of the curve where the curve crosses the x axis (predicted MVC), it was necessary to solve the quadratic polynomial equation \( ax^2 + bx + c = 0 \). The real solution (rational number) was considered as the predicted MVC and compared to the observed MVC.
Figure 1. These diagrams illustrate the voluntary force output of an individual with three superimposed doublets followed by two evoked potentiated doublets. Torque signals were sent through both a low (amplification 1,000×, top diagram) and high (amplification 10,000×, bottom diagram) gain amplifier. The removal of the high gain signal in the upper figure gives an appreciation of the difficulty in ascertaining the existence of superimposed torques. Since the high gain signal was initially saturated, the resident software program offset the high gain superimposed signal, 100 ms before each stimulation for improved resolution (bottom diagram). A ratio comparing the amplitudes of the superimposed doublets with the potentiated doublet (IT ratio), represented muscle force which was not voluntarily activated. The percentage of recruited force was estimated from a single IT ratio by subtracting the ratio from a value of 1 and multiplying by 100 to represent an index of muscle activation during a voluntary contraction pre- and postfatigue.
pre- and postfatigue. Differences between the observed and predicted MVCs were analysed using one-way ANOVAs with repeated measures. A one-way ANOVA for separate groups was used to compare group differences for the y intercept (c), slope (bx), and curvature of the slope (ax²) as derived from the second-order polynomial equations. F ratios were considered significant at p < .05. If significant interactions were present, a Tukey post hoc test was conducted. Descriptive statistics include mean ± standard deviation (SD). Data in the figures are presented as mean ± standard error (SE).

Results

Prefatigue

There were no significant differences between ischaemic and non-ischaemic groups for MVC, potentiated doublet, or index of muscle activation during an MVC (Table 1). Similar values for the y intercept (c), slope (bx) and curvature of the slope (ax²) with a second-order polynomial indicated comparable IT ratio–force relationships for ischaemic (100.6 + 1.65x + 6.56x²; r = .99) and nonischaemic (104.9 + 1.86x + 7.92x²; r = .98) groups. Ten of the 12 subjects could fully activate their plantarflexors during a MVC.

Although no significant difference between observed and predicted MVC from the IT ratio–force relationship was apparent, the estimation of MVC with a second-order polynomial had a prediction error of 5.8% in the fully activated subjects.

Recovery

There were no significant differences between the groups in the number of contractions to fatigue (Table 2) or percentage decrease in MVC following fatigue.

Both groups demonstrated significant muscle inactivation following fatigue. The 11.5% (±6.4) decrease in the ischaemic recovery group’s index of muscle activation as derived from a single MVC IT ratio immediately postfatigue was not significantly different from the non ischaemic group (7.3 ± 6.5%). Nor were there significant differences in ischaemic and nonischaemic groups in the prediction of the MVC using IT ratios and second-order polynomials (Table 2). Although there

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Prefatigue Ischaemic and Nonischaemic Voluntary and Evoked Force</th>
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<tr>
<td>Groups</td>
<td>Observed MVC (Nm)</td>
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<tr>
<td>Ischaemic</td>
<td>101.9 ± 47.2</td>
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<tr>
<td>Nonischaemic</td>
<td>114.6 ± 47.8</td>
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Note. PotD = potentiated doublet, MVC = maximum voluntary contraction. Index of muscle activation = 1 – IT ratio × 100. Second-order polynomials derived from the IT ratio–force relationship.
Table 2  Postfatigue Voluntary and Evoked Force With Ischaemic and Nonischaemic Subjects

<table>
<thead>
<tr>
<th>Groups</th>
<th>Number of contractions</th>
<th>Observed MVC (Nm)</th>
<th>Index of muscle activation (%) (IT ratio)</th>
<th>Predicted MVC (Nm) (IT ratio)</th>
<th>Predicted MVC (Nm) (polynomials)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ischaemic</td>
<td>56.9 ± 14.1</td>
<td>69.7 ± 16.3*</td>
<td>88.5 ± 6.4*</td>
<td>79.0 ± 17.1</td>
<td>78.9 ± 22.7</td>
</tr>
<tr>
<td>Nonischaemic</td>
<td>63.4 ± 11.8</td>
<td>83.7 ± 37.0*</td>
<td>92.7 ± 6.5*</td>
<td>91.1 ± 38.6</td>
<td>82.6 ± 41.5</td>
</tr>
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</table>

Note. MVC = maximum voluntary contraction. Index of muscle activation = 1 – IT ratio × 100. Predicted MVC values derived from second-order polynomial equations (IT ratio–force relationship).

*p < .01, difference from prefatigue values.

were no significant differences in the y intercepts, slopes and curvature of the lines (second-order polynomial) between the groups during recovery, both groups experienced a significant (p < .0003) upward shift of the IT ratio–force relationship slope postfatigue (Figures 2 and 3).

Discussion

One of the major findings of this paper was the similarity of the curvilinear muscle activation (IT ratio)–force relationship pre- and postfatigue. Although there were no significant differences in the y intercepts and in the curvature of the second-order polynomials pre- and postfatigue, the slope of the polynomial shifted significantly higher following fatigue in both groups. The change in the slope of the polynomial would be expected with the fatigue-induced decreases in muscle activation as reported in a number of other studies (Ikai et al., 1967; McKenzie and Gandevia, 1991; McKenzie et al., 1992; Newham et al., 1991). Further evidence supporting fatigue-induced muscle inactivation was provided by Gandevia et al. (1995), who reviewed evidence for alterations in recruitment (IT ratio), rate coding (force–frequency relationship), and motor cortical stimulation. Subjects in the present study were requested to perform specific submaximal and maximal loads (20, 40, 60, 80, and 100%) pre- and postfatigue. However, the loads used postfatigue were calculated as a percentage of a fatigued (nonischaemic and ischaemic MVC decreased 26.9% and 31.5%, respectively), partially inactivated (7–11%) muscle. The shifting of the slope without a difference in the slope curvature would indicate that all the percentage loads of the fatigued muscle would be expected to have greater inactivation as well.

Changes in the slope of the IT ratio–force relationship are derived from changes in the superimposed doublet to potentiated doublet ratios. Alterations in the polynomial slope might not be due to differences in muscle activation but due to modifications in muscle kinetics that affect the response to evoked stimulation. A lack of significant difference in the potentiated doublet amplitude pre- (21.1 ± 7.0 Nm) and immediately postfatigue (20.5 ± 1.8 Nm) would suggest that the
Figure 2. Muscle activation (IT ratio)–force relationship pre- (squares) and postfatigue (circles) in the nonischaemic recovery group. Maximal and submaximal contraction forces were correlated with their respective IT ratios in order to generate second-order polynomial equations. The second-order polynomial equations with respective $R^2$ values illustrate the similarity of the relationship pre- ($y = 104.9 - 1.86x + 0.0079x^2; R^2 = .98$) and postfatigue ($y = 104.72 - 1.08x - 0.0006x^2; R^2 = .97$). Calculations from the second-order polynomial equations were used to compare observed and predicted MVCs pre- and postfatigue. Pre- and postfatigue IT ratios were correlated with pre- and postfatigue MVCs respectively. Data represent subjects’ average values with standard error bars indicating sampling distribution of MVC (horizontal bars) and IT ratio (vertical bars) sample means.

Figure 3. Muscle activation (IT ratio)–force relationship pre- (squares) and postfatigue (circles) in the ischaemic recovery group. The second-order polynomial equations with respective $R^2$ values illustrate the similarity of the relationship pre- ($y = 100.6 - 1.66x + 0.0065x^2; R^2 = .99$) and postfatigue ($y = 103.28 - 0.803x - 0.0013x^2; R^2 = .99$). Refer to Figure 2 for more details.
evoked doublet was not significantly affected by possible impairments in excitation-contraction coupling. This is contrary to the reports of fatigue-induced impairments in evoked twitch amplitude (Bigland-Ritchie et al., 1983; Grange and Houston, 1991; Houston and Grange, 1990; McKenzie and Gandevia, 1991; Vollestad et al., 1988). However, the force output of a doublet can be potentiated or summated due to increases in myosin light chain phosphorylation, Ca+ deposition and sensitivity (Desmedt and Hainaut, 1968; Duchateau and Hainaut, 1986; Small and Stokes, 1992). The insignificant difference in doublet force pre- and postfatigue provided a consistent reference value for the IT ratio. Since the same stimuli were utilized with the superimposed torque, changes in the IT ratio are more likely to be derived from alterations in muscle activation than impairments in muscle function. The similarity in the muscle activation–force relationship pre- and postfatigue (y intercepts and slope curvature) would indicate that the use of a second-order polynomial equation should provide a valid estimate of muscle activation following fatigue.

Although the accuracy of the postfatigue prediction may be similar to the prefatigue prediction with a second-order polynomial, is the estimate of muscle inactivation from a single IT ratio similar to the polynomial? Some fatigue studies have used a single IT ratio to estimate the extent of muscle inactivation with fatigue (Bigland-Ritchie et al., 1978, 1986; McKenzie and Gandevia, 1991). Considering the lack of significant difference between postfatigue single IT ratios and polynomial equations for both ischaemic and nonischaemic recovery groups (Table 2), the use of single IT ratios should provide a general estimate of muscle inactivation following fatigue.

**Summary**

With the exception of an increased slope during recovery, IT ratio—force relationships were similar for both pre- and postfatigue in the ischaemic and nonischaemic groups. The increased slope during recovery for both groups could be attributed to decreases in muscle activation or changes in muscle kinetics. The lack of change in the amplitude of the potentiated doublet pre- and postfatigue would suggest that alterations in the slope were not due to changes in muscle kinetics. Greater muscle inactivation postfatigue with the ischaemic group was supported by greater IT ratios and greater differences in the prediction of MVC with a second-order polynomial. A lack of significant difference between the second-order polynomial predictions and estimates of muscle inactivation with a single IT ratio postfatigue suggest that a single IT ratio may be used as a general estimate of muscle inactivation post-fatigue.

**References**


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