A Comparison of Measures of the Bilateral Limb Deficit During Short and Long Time Isometric Knee Extensions
U Kuruganti, P Parker, M Tingley, G Sleivert

Citation

Abstract
Aim: To investigate the presence of the Bilateral Limb Deficit (BLD) during isometric knee extensions and the differences in voluntary activation and muscle fatigue during bilateral and unilateral contractions. Methods: Twelve subjects (6 female, 6 male, (mean ± standard deviation) age = 27.6 ± 6.9 years) completed a series of short (5-second) and long (30-second) isometric knee extensions during which force, myoelectric signal (MES) amplitude and voluntary activation were measured. Results: No BLD was detected during the isometric contractions and voluntary activation (estimated using the twitch interpolation technique) did not differ between unilateral and bilateral conditions. The mean voluntary activation levels were significantly higher (p<.05) during the short (5-second) contractions (91% activation) than the first five seconds of the long (30-second) contractions (80% activation). Unilateral and bilateral contractions resulted in similar decreases in fatigue (measured as a decline in mean frequency). Significant differences were detected in the mean frequency (14 – 17 Hz) between short and long contractions (p < 0.001). Finally, it was found that the current used to elicit the maximal twitch force differed between unilateral and bilateral contractions suggesting that there are differences in the twitch response that may contribute to the BLD. Conclusion: These data showed that the BLD is not present during isometric knee extensions and that voluntary activation and neuromuscular fatigue are similar for bilateral and unilateral conditions. Differences were detected in voluntary activation between short and long contractions and between the current required to elicit a supramaximal twitch during bilateral and unilateral contractions.

INTRODUCTION
The bilateral limb deficit (BLD) describes the difference in maximal or near maximal force generating capacity of muscles when they are contracted alone or in combination with the contralateral muscles. The BLD has been observed in a number of different studies and while several studies have suggested theories to explain its origin, the underlying mechanism of the deficit is unknown. The BLD may reflect neural inhibition during bilateral contractions (Archontides & Fazey 1993; Howard & Enoka 1991), but that is not established (Archontides & Fazey 1993; Jakobi & Chilibeck 2001). If BLD is more pronounced in older adults it might be due to a reduction in one type of muscle fibre (Owings and Grabiner 1998; Hernandez et al. 2003). However, studies on BLD with respect to age have been contradictory. Most of the literature has suggested that the BLD is probably predominantly due to neural factors (Archontides & Fazey 1993, Howard & Enoka 1991, Ohtsuki 1983, Ohtsuki 1994, Owings & Grabiner 1998). Two areas that have received little attention are the role of voluntary activation and neuromuscular fatigue between bilateral and unilateral contractions.

The interpolated twitch technique is a widely used measure of voluntary activation of muscle. It involves interjecting a maximal or supramaximal electrical stimulus onto contracting muscle to determine if all the motor neurons have been recruited or if some are not firing impulses at a high enough frequency for maximal force generation. Twitch interpolation is instantaneous (unlike myoelectric signal or MES data, which are measured over a window of time) and provides a reliable measure of muscle activation as it measures only the voluntary activation of those motor neurons in which axons are stimulated and capable of contributing to the measured force. The technique involves eliciting a ‘supramaximal twitch’ at rest, that is the twitch at which there is no further increment in twitch force, and then using this twitch as the stimulus during maximal voluntary contractions (MVCs). If the stimulus does not increment force, the muscle is producing its maximum force and the voluntary activation is optimal (close to 100%).
Twitch interpolation has not been extensively used to examine the BLD, and when used the results have been equivocal. Specifically, only four studies (Häkkinen et al. 1999, Herbert & Gandevia 1996, Jakobi & Cafarelli 1998, van Dieën et al. 2003) have previously examined reduced voluntary activation as a cause of the bilateral deficit, and three of these examined isometric knee extension. While both Jakobi & Cafarelli (1998) and van Dieën et al. (2003) showed similar voluntary activation results, only the latter established statistically significant differences between bilateral and unilateral voluntary activation levels and a BLD.

The results of examining the BLD in comparison with muscle fatigue have also been inconclusive to date. Early reports (Vandervoort et al. 1984) found that during fatigue, there is a lesser decline in bilateral strength than unilateral and that, while at the beginning of a protocol the bilateral strength was significantly less than the unilateral strength, this difference became insignificant by the end of the fatigue protocol. This was contradicted by Vandervoort’s later work (Vandervoort et al. 1987), which reported that while the mean values of strength under bilateral and unilateral conditions were approximately the same initially, after the fatigue protocol the bilateral peak torque was 25% of the initial value, while the unilateral peak torque was 37% of the initial value. This indicated that there was a greater loss of force in the bilateral test. The differences could be attributed to the different muscle groups studied (upper verus lower body musculature) and the trained state of the upper versus lower body.

It has also been shown that there are right and left differences in fatigability during bilateral sustained maximum voluntary contractions (Koh et al. 1993). That study investigated the bilateral difference in fatigability during sustained maximum voluntary elbow flexion from right-handed oarsmen and found that the fatigability was greater for the left arm than the right arm. Owings and Grabiner (1998) investigated the effects of muscle fatigue on the size of the BLD using two contraction speeds. They showed that the size of the BLD after fatigue was dependent on the speed of the contraction. Of the studies that have examined bilateral and unilateral contractions under fatigue conditions, none has used the twitch interpolation technique to gain insight into voluntary activation levels during fatigue.

**PURPOSE**

The purposes of this investigation were to determine if the BLD was present in untrained adults during isometric knee extensions and to determine if voluntary activation is compromised when limbs contract simultaneously. In addition, bilateral and unilateral fatigue tests were conducted to determine if there were differences in how a muscle fatigues when it is contracted (bilaterally or unilaterally). Finally, the fatigue tests were performed while stimulating the muscle at 5-second intervals to determine if the twitch response during fatigue was different between bilateral and unilateral contractions.

The null hypotheses were as follows: 1) there is no difference between mean voluntary activation of the quadriceps under bilateral and unilateral conditions, 2) there is no difference in the mean frequency of bilateral and unilateral isometric contractions before and after a fatigue test and 3) there is no difference in the twitch response between bilateral and unilateral maximal isometric contractions of the quadriceps.

**MATERIALS AND METHODS**

Electrical stimulation of the muscles of the leg was used to determine the ability of the nervous system to activate a muscle maximally, by comparing the force exerted during a maximum voluntary contraction with the force evoked at rest. The amount of additional force generated with the electrical stimulus indicated whether voluntary activation was maximal or not. If there was little increment in force with the stimulus, then it was presumed that activation was maximal (Herbert & Gandevia 1996, Jakobi & Cafarelli 1998, Jakobi & Chilibeck 2001).

**SUBJECTS**

Twelve subjects (6 female, 6 male, (mean ± standard deviation) age = 27.6 ± 6.9 years, height = 175.4 ± 11.6 cm, mass = 74.8 ± 18.9 kg) voluntarily participated in this study. None of the subjects had previous strength training experience. None of the subjects were instructed as to whether the bilateral forces should be equivalent to, greater than or less than the unilateral forces. All subjects were familiarized with the testing apparatus in a familiarization session at least 24 hours prior to the test session. Subjects were asked to visit the laboratory three times, once for the familiarization session, and twice for a series of unilateral and bilateral trials. The two testing sessions were randomized. This research was approved by the University
of New Brunswick Research Ethics Board.

INSTRUMENTATION

A custom-built force chair was used to collect data. The subject was asked to sit in the chair and was strapped in via Velcro straps. The ankle was secured to a force transducer (Precision Transducers Ltd., Auckland) and the force data were sampled at 1000 Hz and displayed and analysed using data acquisition software (Windaq version 1.51, Dataq, Ohio, USA). Subjects were told to try to extend their knee as hard as they could by pushing against the ankle strap. The knee angle was set to approximately 85 degrees of knee flexion (0 degrees corresponded to full extension) and the hip angle was set to 90 degrees. The process of stimulating a nerve or muscle produces synchronous firings of units. This does not necessarily produce the same total force as when the muscle units are asynchronously activated by the CNS. Behm et al. (2001) and Van Diëen, et al. (2003) suggested that the use of superimposed multiple stimulation rather than twitch interpolation is more reliable. Therefore, rather than a single stimulus, paired stimuli (also known as a doublet) were used to enhance the resolution of the twitch. An isolated constant current stimulator (Digitimer stimulator model DS7A, Hertfordshire, England) was used to interject a twin rectangular pulse stimulus (doublet, square wave pulse, width, 200 µS; maximum voltage, 400 V) onto the quadriceps through carbon rubber electrodes (Empi, 2” X 4”) with gradually increasing current until there was no longer any increase in the twitch force. A lateral view of the test set-up is shown in Figure 1.

FAMILIARIZATION SESSION

The familiarization session consisted of a screening process to ensure that the subject was healthy and fit. The subject was also asked to review and sign an informed consent form. The subject was then provided with an overview of the twitch interpolation technique, which involves stimulating the quadriceps muscle, to ensure they were comfortable with the procedure.

During the familiarization session, each subject’s supramaximal twitch response for unilateral left, unilateral right and bilateral conditions was determined by placing the stimulating carbon rubber electrodes over the quadriceps muscle and using the isolated constant current stimulator (Digitimer stimulator model DS7A, Hertfordshire, England) to interject a twin rectangular pulse stimulus (duration = 200 µS, delay = 30 mS) during rest onto the quadriceps with gradually increasing current until there was no longer any increase in the twitch force. The stimulus, which no longer generates any further force from the quadriceps muscle, is called the “supramaximal twitch” and the subject was instructed that this current (or close to it) would be used for the remainder of the stimulation tests. The supramaximal twitch was then elicited at the beginning of each test session and used for stimulation for that session. The average supramaximal twitch current for unilateral right extensions was 340 ± 119 mA, and for the left extensions, the supramaximal twitch current was 350 ± 128 mA. For bilateral trials, the average supramaximal twitch current used to stimulate both muscles (total current for one lead to two legs) was 549 ± 131 mA. While the current needed for the supramaximal bilateral twitch stimulation was greater than that required for either of the unilateral condition, it was not proportional (i.e. twice as high).

TEST PROTOCOL

During all testing sessions subjects were allowed to watch a computer screen, which provided feedback regarding the force produced. In addition, subjects were verbally encouraged to ‘push as hard as they could’ throughout the contraction. The testing sessions consisted of either a series of unilateral contractions or a series of bilateral contractions. Half of the subjects performed the unilateral trials on the first test session day and the bilateral trials on the second test session day, and the remainder did the opposite. During the unilateral trials, half of the subjects began testing with their dominant leg first, and the remainder did the opposite. The dominant leg was determined by kicking a ball to the subject and asking the subject to return it. The subject was asked to do this 2 – 3 times. The leg used consistently was defined as the dominant leg. The majority of the subjects were right-legged. The order of the tests and the order of dominant versus non-dominant leg testing were randomized.

Myoelectric signal (MES) data were collected from the agonist (quadriceps) and antagonist (hamstrings) muscles of the active leg throughout the contraction. Disposable silver-silver-chloride surface electrodes (Duotrode, bipolar configuration) were placed on the vastus lateralis of the right and left legs to record surface myoelectric signals during the MVCs. The location of the electrodes was indicated with a semi-permanent marker to ensure that electrode placement was maintained throughout the testing sessions. The electrodes were connected to a high performance electromyography/processor system (Moroz...
The data were sampled at a rate of 1000 samples per second. The signal was low and high pass filtered at 15 and 700 Hz, amplified, full wave rectified and smoothed (20 ms time constant). Surface MES data were used for analysis of voluntary contractions. During stimulated contractions, the twitch force was used to measure activation.

The experimental set-up (bilateral trials) used is shown in Figure 2. Notice that both legs were secured at the ankle and attached to a force transducer. The stimulating electrodes were placed at the approximate ends of the quadriceps muscle. The ground electrode was placed at the knee and the recording electrodes were placed over the vastus lateralis muscle of the quadriceps and the biceps femoris of the hamstrings. Feedback was provided through a computer screen indicating the amount of force being produced.

During the test sessions strength was measured in two ways; maximum voluntary strength and twitch force. Maximum voluntary strength was measured from the subject exerting as much force as possible using the force transducer. Subjects were instructed to push with the active leg (left, right or both legs) as “hard as you can.”

Twitch force was measured by manually delivering two short, supramaximal twitches (doublet) to the subject’s quadriceps muscle of the active leg during the voluntary effort.

Once the voluntary strength and twitch interpolation tests were complete, subjects were administered two fatigue tests, one without stimulation and the second with stimulation. These tests consisted of maintaining a maximum voluntary isometric contraction of the active leg (left, right, or bilateral) for 30 seconds or until exhaustion. Again, surface electrodes were used to measure the electrical activity of the quadriceps and hamstrings. The subject was then allowed to rest for 30 minutes. Finally, the subjects were administered a second fatigue test during which a supramaximal twitch was delivered to the quadriceps at 5, 15, 25 seconds and then once again immediately after the contraction was completed.

**MEASURES OF BILATERAL LIMB RATIO USING VOLUNTARY ISOMETRIC FORCE**

The amount of force deficit or Bilateral Limb Ratio (BLR) was calculated similarly to previous investigations (Ohtsuki 1983).

\[
\text{BLR}_{\text{Force}}(\%) = \frac{\text{Total Bilateral Peak Force}}{\text{Total Unilateral Peak Force}} \times 100 \quad \text{(Equation 1)}
\]

**MEASURES OF BILATERAL LIMB RATIO USING MYOELECTRIC SIGNAL ACTIVITY**

To examine the myoelectric signal in the time domain, the raw signals were processed through a root mean square (RMS) calculation over a one-second window, during maximum voluntary contraction. The mean amplitude (A, measured in mV) and the standard deviation about this measure were obtained for each muscle. The RMS and \(\text{BLR}_{\text{MES}}\) were calculated as follows:

\[
A = \text{RMS}\{m(t)\} = \sqrt{\frac{1}{T} \int_{T}^{T} m^2(t) \, dt} \quad \text{(Equation 2)}
\]

Where \(A = \text{RMS value of the MES (mV)}\)

\(\text{‘}m(t)\text{’} = \text{raw MES signal at time } t\)

\(T = \text{window length (1 second)}\)

where BR denotes the bilateral right measure, BL denotes the bilateral left measure, UR denotes the unilateral right measure, and UL denotes the unilateral left measure.

**UNILATERAL AND BILATERAL TWITCH INTERPOLATION DIFFERENCES**

The purpose of the twitch interpolation test was to determine if the nervous system was fully activating the muscle, by comparing the force exerted during a maximum voluntary contraction with the force produced when the muscle was artificially stimulated using current preset to the supramaximal twitch level. Figure 3 illustrates the superimposed twitch and the control twitch for one subject. The two superimposed twitches were elicited at approximately 1.7 and 4.2 seconds (during exertion) with a control twitch elicited at approximately 7.2 seconds (during relaxation). The force amplitudes of the superimposed and control twitches were then used to calculate voluntary activation (VA). The amplitude of the first twitch was approximately 31 N, and amplitude of the second twitch was approximately 28 N. These two twitches were averaged to give the amplitude of the superimposed twitch (29.5N). The amplitude of the control twitch was approximately 226 N.
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Figure 3

\[ \text{BLR}_{\text{MES}} (\%) = \left( \frac{A_{\text{BR}} + A_{\text{BL}}}{A_{\text{UR}} + A_{\text{UL}}} \right) \times 100 \]  
(Equation 3)

Using twitch interpolation, voluntary activation (VA) was calculated as in previous studies (Herbert & Gandevia 1996, Jakobi & Chilibeck 2001) as:

Figure 4

\[ \text{VA} = \left( 1 - \frac{\text{superimposed twitch}}{\text{control twitch}} \right) \times 100 \]  
(Equation 4)

For the data displayed in Figure 3 the VA was calculated to be:

Figure 5

\[ \text{VA}_{\text{Figure 3}} = \left( 1 - \frac{29.5}{226} \right) \times 100 = 86.9\% \]

The maximum voluntary and twitch forces of each leg under unilateral and bilateral conditions were compared to determine whether neural inhibition was present on either side. In addition, a bilateral deficit was quantified using voluntary activation data as follows (Khodiguian et al. 2003):

Figure 6

\[ \text{BLD}_{\text{VA}} = 100 - (\text{Unilateral VA} - \text{Bilateral VA}) \]  
(Equation 5)

A large bilateral deficit would then be indicated by a \( \text{BLD}_{\text{VA}} \) below 100% and a small bilateral deficit would be indicated by a \( \text{BLD}_{\text{VA}} \) close to 100%.

MEASURES OF UNILATERAL AND BILATERAL MUSCLE FATIGUE - VOLUNTARY FORCE CONTRACTIONS

Fatigue was indexed using the mean frequency (MF) of the power spectrum of the MES. The MF was calculated using the frequency spectrum for the vastus lateralis muscles from the right and left legs. A power spectral analysis was performed on a two second window for each muscle. A fast Fourier transformation (Hanning window processing) was performed using 512 ms segments, overlapping each other by half their length (256 ms). The MF was calculated every two seconds over the entire contraction (approximately 30 seconds) as follows:

Figure 7

\[ \text{MF} = \frac{\int_{0}^{2} f \Phi(f) df}{\int_{0}^{2} \Phi(f) df} \]  
(Equation 6)

Where \( \Phi(f) \) is the power spectrum of the signal.

MEASURES OF UNILATERAL AND BILATERAL MUSCLE FATIGUE - TWITCH FORCE CONTRACTIONS

The fatigue contractions administered during the stimulated force trials were examined to determine if voluntary activation is compromised during fatigue and to determine if there were differences depending on whether the leg was contracted alone or bilaterally. The voluntary activation (VA, Equation 4) was measured at 5, 15, and 25 seconds during unilateral and bilateral fatigue tests and compared.

One-sample t-tests were conducted to determine if there was a difference between unilateral and bilateral force production, voluntary activation and mean frequency. The alpha level was set to 0.05.

RESULTS

BILATERAL LIMB RATIO – FORCE

Only three of the twelve subjects showed any bilateral deficit (\( \text{BLR}_{\text{Force Subject 7}} = 85.84 \% \), \( \text{BLR}_{\text{Force Subject 11}} = 94.89 \% \) and \( \text{BLR}_{\text{Force Subject 12}} = 49.61 \% \)). The mean \( \text{BLR}_{\text{Force}} \) calculated using force, as described by Equation 1, was 104.30 ± 20.42 indicating that, on average, there was no bilateral deficit detected during isometric knee extensions. In addition, a one-sample t-test showed no significant difference from 100%, indicating no bilateral facilitation. The \( \text{BLR}_{\text{Force}} \) found in this experiment was similar to other studies of isometric knee extensions (Häkkinen et al. 1999, McLean et al. 1998, Schantz et al. 1989).

BILATERAL LIMB RATIO – MYOELECTRIC SIGNAL

The \( \text{BLR}_{\text{MES}} \) measured during the 5-second contractions did not indicate the presence of bilateral deficit (mean \( \text{BLR}_{\text{MES}} \): 116.8 ± 38.9%). Similar to the force data, the means were not significantly different from 100 %, indicating no bilateral facilitation.

SUPRAMAXIMAL TWITCH CURRENTS FOR
UNILATERAL AND BILATERAL CONTRACTIONS

The current needed to elicit a supramaximal twitch differed between unilateral and bilateral contractions. The mean (± standard deviation) currents for each condition are shown in Table 1. As can be seen the total current needed for the bilateral condition was less than the sum of the unilateral currents. A paired t-test showed that the total unilateral supramaximal twitch current was significantly greater than the bilateral current (p=0.003).

Similar to the BLR_{\text{force}} and BLR_{\text{MES}}, a BLR was calculated using the total bilateral current over the total unilateral current needed to elicit a supramaximal twitch (BLR_{\text{supramax. current}}). A BLD was detected in ten of the twelve subjects and the majority of subjects (8) exhibited deficits between 13 and 30%. The mean BLR_{\text{supramax. current}} was 82.48 ± 13.30% indicating that there is a difference in the twitch response between bilateral and unilateral conditions prior to the contraction.

VOLUNTARY ACTIVATION DURING UNILATERAL AND BILATERAL CONTRACTIONS

Voluntary activation measures were all similar (Table 2), with no statistically significant differences between left-right, bilateral-unilateral extensions.

BILATERAL LIMB RATIO – VOLUNTARY ACTIVATION

The BLD_{VA} calculated using voluntary activation data showed that there was no significant difference in bilateral and unilateral voluntary activation levels (BLD_{VA} = 103.29 ± 4.48 %) during the 5-second contractions. This indicates that, on average, activation levels did not differ between bilateral and unilateral conditions.

FATIGUE DATA

While no bilateral deficit was detected in the force, MES or activation data during the 5-second isometric contractions, it was suspected that there might be differences in the fatigue rates between bilateral and unilateral contractions. The fatigue was indexed with the mean frequency calculated every two seconds over the entire fatigue contractions. The amount of decay of the fatigue was the percent drop from the first 2-second segment to the last two-second segment.

Table 3 shows the average mean frequency for the five-second isometric contractions as well as at the beginning and at the end of the fatigue contraction. Columns 1 and 2 of Table 3 show that the average mean frequency is lower for the short, 5-second contractions than the early portion of the 30-second contraction. The average mean frequency (across subjects) during the first two seconds of the fatigue contraction was 62.95 ± 7.58 Hz for the left leg and 63.74 ± 4.46 Hz for the right leg. At the end of the 30-second contraction the average mean frequency for the left leg was 48.89 ± 5.43 Hz and 49.40 ± 5.05 Hz for the right leg. The mean frequency dropped by 21.4 % for the unilateral left knee extension and 22.3 % for the unilateral right knee extension. This drop was statistically significant, with all p-values approximately equal to 0.

There was no statistically significant difference in the average amount of decay in the mean frequency between bilateral and unilateral contractions. The mean frequency dropped by 20% to 25% for all contractions during fatigue contraction.

The 30-second maximum voluntary contraction fatigue test was also conducted with simultaneous muscle stimulation. This was done in order to determine if there were any differences in the amount of voluntary activation between bilateral and unilateral contractions, particularly as a muscle starts to fatigue. As can be seen in Table 4 the average voluntary activation level was found to be approximately 80 % throughout the contraction for both the left and right legs. During the five second contractions, the voluntary activation levels were ~ 91% for the unilateral trials (Table 3). Paired t-tests indicated that the voluntary activation values reported in Table 2 (short contractions) are significantly different from those reported in the first column of Table 4 (early in the fatigue) for all conditions (unilateral and bilateral, p<0.05). This indicates that there was no significant loss in activation during the shorter unilateral contractions whereas there was a marked loss five seconds into the fatigue test. Interestingly, the voluntary activation did not decrease significantly from five to thirty seconds during the fatigue test. This suggests that the subjects were either highly motivated to maintain the level of the contraction, or while there was an inability to maximally activate the quadriceps during the contraction, the amount of activation remained relatively constant.

Similar to the unilateral fatigue test, voluntary activation levels were less than those reported in Table 2 during the initial five seconds of the bilateral fatigue contractions, and only slightly during the last twenty-five second (Table 5).
The bilateral right leg showed the greatest decrease from 83.1% to 74.1%, however when a paired t-test was conducted, this difference was not found to be statistically significant.

The voluntary activation levels during the five-second bilateral contractions was ~94% (Table 2). Similar to the unilateral contractions, there was a significant overall loss of voluntary activation during the fatigue contractions compared to the shorter five-second contractions. Overall voluntary activation levels after the first five seconds of the fatigue contractions were approximately 10% lower than those found during the five-second contractions.

Voluntary activation levels were compared from the first five seconds of the contraction to the last five seconds of the fatigue contraction to determine if there was a significant drop due to fatigue. It was found that while there were slight decreases in the voluntary activation levels measured, the decreases were not significant. It is possible that while the fatigue protocol was sufficient to elicit a marked reduction in mean frequency, it may not have been long enough to detect a drop in voluntary activation.

Finally, the BLR was calculated using both force and MES data over the duration of the fatigue contraction (30-seconds) and no bilateral deficit was detected (Table 5). This was similar to the lack of bilateral deficit in the shorter (5-seconds) contractions.

**Figure 8**
Table 1. Mean current needed to elicit supramaximal twitch at rest during unilateral and bilateral conditions.

<table>
<thead>
<tr>
<th>Contraction</th>
<th>Supramaximal Twitch Current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unilateral Left</td>
<td>350.4 ± 128.4</td>
</tr>
<tr>
<td>Unilateral Right</td>
<td>340.4 ± 119.0</td>
</tr>
<tr>
<td>Total Unilateral</td>
<td>690.8 ± 232.8</td>
</tr>
<tr>
<td>Bilateral</td>
<td>548.8 ± 131.2*</td>
</tr>
</tbody>
</table>

* - Indicates that the current needed to elicit a supramaximal twitch was less (p<0.05) for bilateral contractions than the total current needed unilaterally (left + right).

**Figure 9**
Table 2. Mean voluntary activation levels (percent of maximal 100%) during 5-second unilateral and bilateral stimulated contractions.

<table>
<thead>
<tr>
<th>Contraction</th>
<th>Voluntary Activation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unilateral Left</td>
<td>89.6 ± 6.4</td>
</tr>
<tr>
<td>Unilateral Right</td>
<td>92.4 ± 3.7</td>
</tr>
<tr>
<td>Bilateral Left</td>
<td>93.5 ± 3.3</td>
</tr>
<tr>
<td>Bilateral Right</td>
<td>94.2 ± 4.4</td>
</tr>
</tbody>
</table>

**Figure 10**
Table 3. Mean frequency (Hz) during the 5-second and during the first 5 seconds (early) and last 5 seconds (late) portions of the 30-second fatigue contraction. Differences between the late and early portions of the fatigue contraction are indicated in column 4 along with the decrease in mean frequency in column 5.

<table>
<thead>
<tr>
<th>Contraction</th>
<th>Early</th>
<th>Late</th>
<th>Difference (Hz)</th>
<th>% Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unilateral Left</td>
<td>63.7 ± 4.5*</td>
<td>49.4 ± 5.1</td>
<td>-14.1 ± 6.6*</td>
<td>21.4</td>
</tr>
<tr>
<td>Unilateral Right</td>
<td>63.6 ± 7.6*</td>
<td>48.9 ± 5.4</td>
<td>-14.3 ± 4.6*</td>
<td>25.3</td>
</tr>
<tr>
<td>Bilateral Left</td>
<td>63.6 ± 8.3*</td>
<td>46.9 ± 5.5</td>
<td>-16.7 ± 8.1*</td>
<td>25.4</td>
</tr>
<tr>
<td>Bilateral Right</td>
<td>62.9 ± 6.2*</td>
<td>49.1 ± 6.5</td>
<td>-13.8 ± 8.6*</td>
<td>21.3</td>
</tr>
</tbody>
</table>

* - Indicates that the differences between the mean frequencies of the short contraction and the early portion of the long contraction are statistically significant (p<0.05).

† - Indicates that the decrease in mean frequency was statistically significant (p<0.05). Mean frequencies were calculated during the first two seconds of the contraction (early) and at the end of the thirty-second contraction (late).
Table 4: Mean voluntary activation levels (percent of maximal 100%) at 5, 15, and 25 seconds of the 30-second fatigue contractions. The differences in activation after the unilateral and bilateral fatigue contractions are shown in column 5.

<table>
<thead>
<tr>
<th>Contract</th>
<th>At 5</th>
<th>At 15</th>
<th>At 25</th>
<th>Difference (25 sec – 5 sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unilateral Left</td>
<td>82.6 ± 6.0</td>
<td>79.9 ± 8.6</td>
<td>80.3 ± 7.8</td>
<td>-2.7 ± 7.7</td>
</tr>
<tr>
<td>Unilateral Right</td>
<td>82.2 ± 7.7</td>
<td>81.9 ± 10.3</td>
<td>79.3 ± 9.6</td>
<td>-2.9 ± 10.0</td>
</tr>
<tr>
<td>Bilateral Left</td>
<td>83.9 ± 8.7</td>
<td>83.9 ± 9.3</td>
<td>80.2 ± 14.5</td>
<td>-3.7 ± 12.9</td>
</tr>
<tr>
<td>Bilateral Right</td>
<td>83.1 ± 6.7</td>
<td>80.7 ± 11.0</td>
<td>74.1 ± 23.5</td>
<td>-9.0 ± 12.1</td>
</tr>
</tbody>
</table>

Table 5. BLR and BLR for short (5-second) and long (30-second) contractions. Neither type of contraction exhibited BLD.

<table>
<thead>
<tr>
<th>Contraction</th>
<th>Short 5 Second MVC</th>
<th>Long 30 Second Fatigue Contractions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At 2 Seconds</td>
<td>At 10 Seconds</td>
</tr>
<tr>
<td>BLR&lt;sub&gt;ref&lt;/sub&gt;</td>
<td>104.3 ± 20.4</td>
<td>96.1 ± 13.0</td>
</tr>
<tr>
<td>BLR&lt;sub&gt;ref&lt;/sub&gt;</td>
<td>116.5 ± 38.9</td>
<td>106.9 ± 29.6</td>
</tr>
</tbody>
</table>

Figure 14
Figure 2: Experimental Set-up: bilateral test session set-up. The stimulating and recording surface electrodes are placed identically as shown in Figure 2. During bilateral contractions, both ankles are secured firmly to the force transducers.

Figure 15
Figure 3: Example of superimposed twitch during 5-second MVC. The two superimposed twitches are at approximately 1.7 seconds and 4.2 seconds. The control twitch was elicited immediately after the contraction at approximately 7.2 seconds. The amplitude of the control twitch in this example was 226 N.

DISCUSSION
This investigation found that no bilateral deficit (force) was detected during short (five-second) isometric knee extensions. This was similar to other studies of isometric knee extension (Jakobi & Cafarelli 1998, Schantz et al.)
1989). It is important to remember that the setup for this experiment only allowed for isometric knee extensions and the literature has shown that the presence of the deficit in these types of contractions is equivocal.

This experiment also supported the findings of Jakobi & Cafarelli (1998), who used twitch interpolation to look at isometric contractions from the knee extensors and found the ability to voluntarily activate the quadriceps was not altered in a bilateral contraction compared with a unilateral contraction. Similar voluntary activation levels were found for unilateral and bilateral contractions (~93%) and no difference was detected in the voluntary activation levels between bilateral and unilateral isometric knee extensions. The voluntary activation levels found in this study were similar to other studies (Babault et al. 2001, Jakobi & Cafarelli 1998, van Diëen et al. 2003) and lower than other reports (Babault et al. 2002). The variability in muscle activation levels of the knee extensors reported between studies is most likely due to differences in the force chair set-up (Jakobi and Cafarelli 1998) and the use of direct femoral nerve stimulation rather than muscle stimulation (Babault et al. 2001), as the characteristics and training status of the subjects across studies were similar. The lack of reduction in voluntary activation in bilateral contractions could also be symptomatic of the twitch interpolation technique. The process of stimulating a nerve or muscle consists of synchronous stimulus firings. This does not necessarily produce the same total force as when the muscle is asynchronously activated by the CNS. Van Dieen, et. al. (2003) suggested that the use of superimposed tetanic stimulation (a train of pulses) rather than twitch interpolation is more reliable. In future studies it would be useful to use a brief tetanus to enhance the resolution of the twitch. However, this can cause discomfort to the subject.

The supramaximal twitch is elicited when the muscle is at rest and its current is that at which maximal activation is elicited. A BLR_{Supramax. Current} showed that there is a deficit when the bilateral and unilateral supramaximal twitch currents are compared (mean BLR_{Supramax. Current} = 82.48 ± 13.30%). This suggests that even though the measures of BLR using force, MES and voluntary activation did not detect a BLD during isometric knee extensions, there are differences in the twitch response between the two conditions prior to onset of contraction (see Table 2). This difference could have been due to experiment variability such as electrode placement between unilateral and bilateral trials, however this is unlikely. Subjects were asked to attend the lab three times in order to limit the fatigue between the numerous unilateral and bilateral tests. The experiment was designed as a crossover study with half of the subjects starting with the unilateral tests and the other half beginning with the bilateral tests, which would have blocked out the effect of testing day on the data. It has also been suggested that the timing of the superimposed twitch relative to the motor unit trains may cause variability in the interpolated twitch and the increasing the number of electrical twitches can reduce the variability (Suter & Herzog 2001). Therefore the present work used a twin pulse (doublet) rather than a single pulse. The issue of the supramaximal twitch amplitude needs detailed examination to determine if this is, indeed, a contributing factor in the cause of the BLD.

While the MES fatigue data clearly indicated that the subjects did exhibit fatigue (indicated by a decline in mean frequency, Table 3), the mean frequency at the beginning and at the end of the fatigue contractions were similar for unilateral and bilateral conditions. In addition, the rate of fatigue was similar between unilateral and bilateral fatigue tests. The mean frequency dropped by approximately 20% for all contractions during the fatigue contractions. In terms of the voluntary activation, no significant decreases were detected in the voluntary activation levels during unilateral and bilateral fatigue contractions. Overall, however, the voluntary activation levels during the fatigue contractions were lower than those found during the five-second contractions (Columns 1 and 2 of Table 4). It is possible that the activation levels detected during the short contractions (approximately 93 %) are not reflective of significant inhibition in neural drive. However, early in the longer contractions the voluntary activation levels are lower, approximately 80%, perhaps due to a drop in motivation, the inability of the subject to maintain the contraction or some other compromise in neural drive. Breaks were given between trials, and as the subject was asked to visit the lab on three occasions, the fatigue tests were randomized. Regardless, there was no difference detected between bilateral and unilateral fatigue contractions which indicates that during the isometric knee extensions neural drive was not affected by the type of contraction (unilateral versus bilateral).

An interesting result of this work was that the voluntary activation levels were significantly different between the short (5-second) contractions and the first five seconds of the...
longer (30-seconds) contractions. While every precaution was taken to ensure that the subject was highly motivated, it is possible that the activation dropped for the longer contractions because the subject knew that they had to sustain the contraction for a longer period of time. It has been shown that the perception of effort is a limiting factor in exercise (Kayser 2003) and this may account for the differences.

The differences between the short and long contractions were also reflected in the mean frequency data (Table 3). The reported values of mean frequency are lower for the short contractions than the long contractions. This difference could be due to the differences in electrode configuration; even a slight change in electrode positioning can affect the mean frequency.

Because the BLD has been shown to be more prevalent in dynamic lower limb contractions (Jakobi & Chilibeck 2001) it would be worthwhile studying isokinetic contractions with the addition of the twitch interpolation technique, to determine if the voluntary activation levels change. One of the challenges of this type of study is applying the twitch interpolation technique to dynamic strength testing. Usually this technique is done under isometric conditions, where the maximal force can easily be identified. The reliability of eliciting a twitch during the maximum torque produced during dynamic contractions should be investigated.

Voluntary movement is a complex process that is further impacted by neuromuscular phenomena such as the BLD. There has been a renewed interest in the study of the BLD due to the implications it can have on the functioning of the neuromuscular system (Archontides & Fahey 1993, Jakobi & Chilibeck 2001). Further understanding of the limitations caused by the deficit and the mechanisms that can be used to improve or eliminate the deficit can improve neuromuscular function.

The results from this investigation indicated that the BLD as measured using force or MES data is not exhibited during isometric knee extensions and suggest that standard measures of voluntary activation and neuromuscular fatigue are the same for bilateral as for unilateral isometric knee extensions.

The voluntary activation did not decrease over the course of the 30-second fatigue contraction. However, it was shown that both mean frequency and voluntary activation do differ depending on whether a subject is asked to produce a short or long maximal voluntary contraction. This suggests that the perception of effort is an important consideration when measuring voluntary activation.

It was found that the current required to elicit a supramaximal twitch (at rest) was greater for unilateral contractions than bilateral contractions, indicating that there is a difference in central drive between the two conditions prior to voluntary contractions. Work is currently in process to examine the differences in the supramaximal twitch current amplitude between bilateral and unilateral contractions.

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References


A Comparison of Measures of the Bilateral Limb Deficit During Short and Long Time Isometric Knee Extensions


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