Effect of fatigue on force fluctuations in knee extensors in young adults

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This study investigated the hypothesis that fatiguing exercises led to increased force fluctuations during submaximal isometric knee extensions and to decreased accuracy and steadiness in the time and frequency domains. Sixteen young adults (eight males, eight females) were tested, in a seated posture with 90° knee flexion, to assess their ability to reproduce target extensor torques set at 15 per cent and 20 per cent of their maximum voluntary isometric contraction, both before and after fatiguing exercises. Normalized mean (NMAE) and peak (NPAE) of the absolute error were both used to quantify accuracy, whereas normalized standard deviation of the absolute error (NSAE) was used to quantify steadiness of the torque trials in the time domain. Mean and median power frequencies (MnPf, MdPf) and normalized peak power (NPkP) were used to assess the spectral structure of the torque signals. NMAE, NSAE and NPAE all showed excellent intra- as well as intersession reliabilities (intraclass correlation values greater than 0.75 and low standard error of measurement values), demonstrating repeatability of the test set-up. NMAE, NSAE and NPAE increased significantly post-fatigue (greater than 42%), together with a shift towards higher frequency (MnPf and MdPf) components, indicating that the set-up was sensitive enough to detect the decreased force accuracy and steadiness of the musculature after fatigue. Increased force variability in both the time and frequency domains could therefore explain decreased steadiness after fatigue.

Keywords: muscle fatigue; force fluctuation; power spectrum; steadiness; knee extensors; physiological tremor

1. Introduction

Muscle weakness, particularly in the quadriceps and ankle dorsiflexors (Tinetti 1986; Moreland et al. 2004), has been identified as one of the major risk factors for falls (Berg et al. 1997; Masud & Morris 2001; Moreland et al. 2004).

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Although muscle strength in the lower extremity has been correlated with gait parameters such as stride length and sit–stand performance, this primary parameter of muscle competence seems not to be related to improved endurance or static balance, or to restoring overall functional ability (Chandler et al. 1998; Ringsberg et al. 1999). One plausible reason for this could be that most daily activities are performed at submaximal levels (Grabiner & Enoka 1995), thus rarely using the benefits that additional strength could bring. During voluntary submaximal contraction, force fluctuation is observed, caused by the recruitment of multiple motor units to exert the force, and which results in an inability of the musculature to generate constant forces (Enoka & Fuglevand 2001). Not only do such fluctuations hinder the capability to exert a desired force but they also impair the ability to produce an intended movement trajectory (Harris & Wolpert 1998). Consequently, the quality of the force produced can be assessed by quantifying both its accuracy, as the difference between a target force and the actual force generated, as well as the magnitude of the fluctuations, which can be considered a measure of steadiness (Enoka et al. 1999).

Muscular force steadiness and strength both deteriorate with age (Christou & Carlton 2001; Lord et al. 2003), injury (Hortobágyi et al. 2001) and fatigue (Tracy & Enoka 2002; Lord et al. 2003; Tracy et al. 2005), which has also been associated with increased fall risk especially in older women (Schwendner et al. 1997). This increase in unsteadiness has been reported in the upper extremity both during as well as after sustained contractions (Maughan et al. 1986; Huang et al. 2006; Contessa et al. 2009) and after repetitive fatiguing tasks (Dartnall et al. 2008; Dundon et al. 2008). However, except for a few studies on fatigue during sustained contractions (Maughan et al. 1986; Clark et al. 2005), the relationship between fatigue and unsteadiness in the lower extremity, and therefore during functional activities, remains uninvestigated.

The inherent fluctuations during voluntary force production possess an oscillatory behaviour that is composed of a range of frequencies, normally between 0 and 3 Hz (Kouzaki et al. 2004). Physiological tremor, which results from the rhythmic modulation of multiple motor units caused by stretch reflex oscillations, however, has been reported to occur at frequencies of 8–12 Hz (Freund 1983; Löscher et al. 1996; McAuley & Marsden 2000). Analyses in the frequency domain can therefore elucidate the periodic structure of this force variability, which is related to the underlying steadiness of the force production in the muscles and thereby effective task performance. The increased occurrence of tremor should therefore be visible as a shift towards higher frequency components of force generation after fatigue.

Since an increase in force magnitude has been associated with an increase in muscle activation (Fuglevand et al. 1993; Hunter et al. 2003; Sogaard et al. 2006; Missenard et al. 2009) and a shift in spectral power towards higher frequency components (Slifkin & Newell 1999), it is likely that the increased muscle activation associated with fatigue (Fuglevand et al. 1993; Hunter et al. 2003; Sogaard et al. 2006), even at the same loading levels, will result in a similar frequency shift. Moreover, increased muscle activation is thought to be responsible for additional variability (unsteadiness) in force production (Missenard et al. 2008). An understanding of the changes in force variability in both the time and frequency domains could therefore help in explaining the decreased steadiness as well as the increased fall risk in subjects that is associated with fatigue.
We therefore hypothesize that an increase in variability of the knee extensor force production will be observed post-fatigue, and that this increase in variability will be accompanied with a shift in the power spectral profile of force signals towards high-frequency components. The objectives of this study were therefore to firstly establish the reliability and reproducibility of force fluctuation measurements in the knee extensor test set-up and then to quantify the effects of fatigue on force fluctuations in both the time and frequency domains.

2. Material and methods

(a) Participants

Sixteen young healthy adults (eight males and eight females) from the local community, with no self-reported injuries, illnesses or musculoskeletal disorders, volunteered to participate in this study. Their mean (s.d.) age, body mass and height were 28.9 (2.3) years, 71.8 (13.3) kg and 176.8 (11.4) cm, respectively. All participants provided written informed consent and the procedure was approved by the local Ethics Committee before beginning the experimental procedures.

(b) Experimental design and procedures

Force fluctuations and accuracy of force control were assessed by measuring the ability of the knee extensors to steadily and accurately reproduce a target torque level in a standardized test set-up. In order to firstly assess the test–retest reliability of the experimental set-up, individuals were tested on three separate session days (minimum 48 h between sessions). To further investigate the effects of fatigue on force fluctuations, each participant was assessed one additional time on the final day, but directly after fatiguing squat exercises.

(i) Test set-up

Individuals were seated on a dynamometer (Biodex 3 Pro, Biodex Medical Systems Inc., USA) in a standardized posture, using a belt to secure the pelvis (figure 1). The rotational flexion–extension axis of the dynamometer was matched to the rotational axis of the knee joint, with the knee maintained at approximately 90° flexion. A cuff was tightened around the shank and the Biodex attachment to ensure that any relative movement was minimized. Since the measurements in this study were isometric and conducted at 90°, any errors owing to inertia or gravity were avoided (Herzog 1988; Arampatzis et al. 2004).

Prior to the start of each session, maximum voluntary isometric contractions (MVICs) of the knee were obtained, by providing standardized instructions and verbal encouragement to the participants to push as hard as they could, trying to reach their peak exertion 2–3 s after the start of the trial. The MVICs, which lasted for 5 s, were measured three times with a minimum of 30 s pause between contractions (Christou & Carlton 2001), with individuals provided with a further break after the stipulated pause, if needed. After ensuring that the highest recorded values were within 5 per cent of each other, the maximum session value of all contractions was taken as the MVIC. Finally, 15 per cent and 20 per cent of this MVIC were used as the reference target extensor torques (TETs) to assess torque control during testing.
Figure 1. Experimental set-up for maximum voluntary isometric contraction and muscular force fluctuation tests. The dominant limb of the participant was first aligned with the rotational axis of the Biodex and then placed at 90° flexion and fastened to the Biodex attachment to avoid relative movement (a). Participants were requested to perform isometric knee extensions by pushing against the Biodex attachment. Target extensor torques (TETs) were displayed on a screen and participants were asked to match the target by performing knee extensions (b). Real-time visual feedback for the active torques was provided by overlaying the TETs on the screen.

(ii) Torque measurements

To assess the control of external torques, TETs, provided as constant torque plots (at 15% and 20% MVIC), were then displayed on the monitor and participants were instructed to match the torque level as well as they could for the duration of each test (approx. 15 s) by performing isometric knee extension (figure 1b). The active torque applied by the participant was provided as a visual feedback at 10 Hz, which overlaid the TET. Participants were provided with adequate practice sessions to familiarize themselves with the testing procedures. The presentation order of the signals was randomized with both TETs (i.e. 15% and 20% of the MVIC) presented three times.

(iii) Fatiguing exercises

After the pre-exercise torque control trials, each participant was requested to perform squat exercises, specifically chosen to induce fatigue in the knee extensors (quadriceps). An intermittent exercise protocol was used and participants were requested to start in an upright position with feet shoulder-width apart and with weights (approx. 40% body weight) carried on a barbell over the shoulders, squat down to approximately 90° knee flexion, and return to their start position.
Each set of squat exercises consisted of eight repetitions and a 30 s rest period was provided between sets. Each participant performed a minimum of 11 sets of squat exercises with the final set including continuous squats as long as participants could complete an entire repetition. The exercises were terminated when participants indicated that they were unable to perform the exercise further. To assess the extent of fatigue, a single post-exercise MVIC was measured, with at least a 15 per cent reduction in the pre-fatigue MVIC observed in all subjects.

Post-exercise torque control trials were conducted immediately after the fatiguing exercises at the same level of torque as in the pre-exercise torque trials. The post-exercise measurements, for both the 15 per cent as well as the 20 per cent MVIC, were conducted only once, in order to avoid the effects of recovery.

(c) Data collection and analysis

(i) Torque measurements

All torque measurements were collected at 3000 Hz, using LABVIEW (LABVIEW 8.6, National Instruments, Inc., USA). To avoid transients during initiation and termination of the torque trials, the first 7 and last 2 s of data were removed (as, in certain cases, participants required up to 5 s to reach the target torques plus 2 s boundary conditions). Each dataset was then low pass-filtered using a fourth-order, zero-phase lag, Butterworth filter, with a 25 Hz cut-off frequency (Jones et al. 2002). In addition, it was confirmed that little power (less than 5%) of torque existed at frequencies greater than 25 Hz.

(ii) Time-domain measures

All measures evaluated in the study, were normalized to each participant’s pre-fatigue MVIC. Accuracy of torque production was quantified using the normalized mean absolute error (NMAE) of the torque signal, calculated as the average value of the absolute difference between the real-time participant exertion and the TET (Hortobágyi et al. 2001, 2004). Force fluctuation (unsteadiness of torque production) was determined using the normalized standard deviation of absolute error (NSAE), calculated as the standard deviation of the absolute difference between the real-time participant exertion and the TET (Christou & Carlton 2001; Hortobágyi et al. 2001, 2004; Tracy et al. 2004; Missenard et al. 2008). In addition, normalized peak absolute error (NPAE) was obtained to indicate the maximum deviation from the target signal.

(iii) Frequency-domain measures

In order to analyse the torque signals in the frequency domain, fast Fourier transform (FFT), after zero-padding, was used to calculate the power spectra for frequencies of the torque signal. Mean (MnPF) and median (MdPF) power frequency of the torque signals were then calculated as spectral measures of central tendency in the frequency domain (Williams et al. 1997) to provide information regarding the distribution of power (amplitude) over the range of frequencies. Peak power in the spectrum was normalized to the total power in the torque signal spectrum (NPkP) at the modal frequency to provide a
measure of the proportion of power that occurred at the dominant frequency (Slifkin & Newell 1999). To assess whether there was a shift towards higher frequency components in the torque signals post-fatigue, the power spectrum obtained from the FFT was first normalized to the total power in the spectrum and then divided into low (less than 4 Hz), middle (4–8 Hz) and high frequency (8–20 Hz) bands (Slifkin & Newell 1999).

(d) Statistical analysis

(i) Intra- and intersession reliability

The current study investigated both the intra- and intersession reliability of the torque control measurement set-up. For intrasession reliability assessment, three repetitions were taken into account from a single measurement session, and, for the intersession reliability, the average value of the three repetitions was taken for all dependent measures for each of the three separate sessions of measurement, pre-fatigue.

Intraclass correlations (ICCs) were calculated to assess relative reliability of the torque control tests both within and between testing sessions (Shrout & Fleiss 1979). Cronbach’s alpha, as well as the standard error of measurement (s.e.m.), was calculated as measures of the absolute reliability (Bravo & Potvin 1991; Deneger & Ball 1993) of force fluctuation measurements between sessions, with sessions treated as a random effect (Eliasziw et al. 1994). ICC values are defined as the ratio between the true variance (difference between the total and error variances) and the total variance. The level of ICCs therefore represents the level of consistency between the measurements as well as the agreement within measurements (Bruton et al. 2000). In this study, the intrasession reliability was determined using the ICC(2,1) model to assess the individual repetitions within a session, and the intersession reliability was calculated using the ICC(2,3) model to examine the mean of session repetitions (Shrout & Fleiss 1979). Thus, for both intra- and intersession ICC calculations, a two-way random effects analysis of variance (ANOVA) was used, with both participants and sessions treated as random effects and the total error variance split into intersession variance and residual error variance (Shrout & Fleiss 1979; Deneger & Ball 1993). ICC values range from 0 (no reliability) to 1 (perfect reliability), with an ICC less than 0.4 rated as poor, 0.4 to less than 0.6 as fair, 0.6 to less than 0.75 as good, and greater than or equal to 0.75 as excellent (Bruton et al. 2000).

(ii) Effect of fatigue

A mixed-factor ANOVA was conducted to analyse the effect of fatigue and force level on measures of force fluctuation. Both factors fatigue and force had two levels each, fatigue (pre- and post-fatigue) and force level (15% and 20% MVIC). For pre-fatigue, the average value of the three repetitions from the session (day) was taken. Least significant differences were used to illustrate post hoc comparisons. A significance level of $p < 0.05$ was set for all analyses. The SPSS software package (v. 17.0 SPSS Inc., USA) was used for statistical analyses.

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3. Results

In general, ICC, Cronbach’s alpha and s.e.m. indicated excellent levels of reliability for time-domain measures for the test set-up at both (15% and 20% MVIC) pre-fatigue force fluctuation measurements for within- as well as between-test sessions (table 1). Frequency-domain measures displayed good to excellent reliabilities for within sessions, but lower values for between sessions. A significant decrease in steadiness and accuracy of torque control was observed post-fatigue.

(a) Intra- and intersession reliability of force fluctuation measures

Intrasession reliabilities were excellent for time-domain measures NMAE (greater than or equal to 0.808), NSAE (greater than or equal to 0.817) and NPAE (greater than or equal to 0.914) during torque production (table 1). Furthermore, low s.e.m. values (less than or equal to 0.006) for the same measures indicated high repeatability of the test set-up.

Intersession reliabilities were also excellent (greater than 0.75) for all three measures (NMAE, NSAE and NPAE). Although not as low as the intrasession values, the intersession s.e.m. values still denoted high repeatability of the test set-up.

When the frequency domains of the torque signals were examined, intrasession repetitions resulted in ICC values of reliability that were good to excellent (0.567–0.868), but these were considerably lower for intersession tests.

(b) Effect of fatigue on force fluctuations

Fatigue led to a significant increase in all time-domain force fluctuation measures (table 2), with NMAE increasing by 47.7 per cent, NSAE by 42.9 per cent and NPAE by 52.1 per cent post-fatigue (figure 2a). Significant main effects of fatigue were also observed in MdPF and NPkP with a 71.7 per cent increase in MdPF and 20.1 per cent decrease in NPkP post-fatigue (figure 3a). Thus, not only did fatigue lead to reduced accuracy and steadiness in torque production tasks, but these fluctuations of torque also occurred at higher frequency components (figure 3). In addition, the higher torque level (20% MVIC) led to significantly higher NMAE, NSAE and NPAE (figure 2b), demonstrating an increase in variability and inaccuracy in torque production at the higher torque level.

Significant interactive effects of fatigue and force level were observed in MnPF (figure 3b). Post hoc comparisons showed higher MnPF post-fatigue than pre-fatigue, and the 20 per cent torque level led to a higher MnPF than the 15 per cent torque level post-fatigue.

Fatigue led to a decrease in power in the lower frequency bands (less than 4 Hz) accompanied by an increase in power in the higher frequency bands (8–20 Hz). There was no significant effect of fatigue in the middle frequencies (figure 4), resulting in an overall shift towards higher frequency components in the torque signal after fatiguing exercises.
Table 1. Intrasession and intersession reliability of force fluctuations at 15% and 20% MVIC. The values for ICC, together with the 95% one-sided lower bound confidence interval (CI), show the relative reliabilities. Cronbach’s alpha and s.e.m. are presented as measures of absolute reliability. The intrasession ICC was calculated using the ICC(2,1) model and the intersession reliability was calculated using the ICC(2,3) model (Shrout & Fleiss 1979).

<table>
<thead>
<tr>
<th>force level</th>
<th>measure</th>
<th>intrasession reliability</th>
<th>intersession reliability</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>ICC</td>
<td>mean</td>
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<td>15% MVIC</td>
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<td>0.773</td>
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<td></td>
<td>NSAE</td>
<td>0.914</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>NPAE</td>
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<td>0.819</td>
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<td></td>
<td>MnPF</td>
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<tr>
<td></td>
<td>MdPF</td>
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<td>0.284</td>
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<tr>
<td></td>
<td>NPkP</td>
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<td>0.538</td>
</tr>
<tr>
<td>20% MVIC</td>
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<tr>
<td></td>
<td>NSAE</td>
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<td></td>
<td>NPAE</td>
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<tr>
<td></td>
<td>NPkP</td>
<td>0.868</td>
<td>0.733</td>
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Figure 2. (a) Effects of fatigue (pre-fatigue (open bars) and post-fatigue (filled bars)) on time-domain measures; namely, normalized mean (NMAE), normalized peak (NPAE) and normalized standard deviation of absolute error (NSAE) of force fluctuation. (b) Effects of force level (15% (open bars) and 20% MVIC (filled bars)) on time-domain measures of force fluctuation, NMAE, NPAE and NSAE. Significance \((p < 0.05)\) is indicated by asterisks (*).

Table 2. Fatigue had a significant effect on force fluctuation measures in both the time (NMAE, NSAE and NPAE) and frequency (MnPF, MdPF and NPkP) domains. Force level (15% or 20%) led to significant differences in NMAE, NSAE, NPAE and NPkP. Furthermore, MnPF had significant interactive effects of fatigue and force level. \(p\)-values from ANOVA using fatigue, force level and the interaction between fatigue and force level are presented.

<table>
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<tr>
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<th>NPAE</th>
<th>MnPF</th>
<th>MdPF</th>
<th>NPkP</th>
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<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>0.003</td>
<td>0.001</td>
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<tr>
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<td>&lt;0.001</td>
<td>&lt;0.001</td>
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<td>0.294</td>
<td>0.026</td>
</tr>
<tr>
<td>fatigue × force level</td>
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<td>0.086</td>
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<td>0.096</td>
<td>0.410</td>
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</table>

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Figure 3. (a) Effects of fatigue on frequency-domain measures, mean (MnPF) and median power frequency (MdPF) and normalized peak power (NPkP). MnPF and MdPF are presented in hertz and normalized peak power (NPkP%) is presented as the percentage of total power in the torque signal. Fatigue led to significant changes in MnPF, MdPF and NPkP ($p < 0.05$), indicated by asterisks (*). Open bars, pre-fatigue time period; closed bars, post-fatigue time period. (b) Significant interactive effects of fatigue and force level were observed on MnPF. Post hoc comparisons revealed that 20% MVIC (dark grey bars) led to higher MnPF than 15% MVIC (light grey bars), indicated by asterisks (*).

4. Discussion

An understanding of the changes in force variability in both the time and frequency domains could help explain the decreased steadiness and the fall risk in subjects who are associated with fatigue (Schwendner et al. 1997). Since the relationship between fatigue and unsteadiness in both the time and frequency domains of the lower extremity remains uninvestigated, this study aimed to determine whether a reduction in steadiness of the force signal is
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Figure 4. A significant decrease ($p < 0.05$) in normalized power in the lower frequency band (less than 4 Hz) was accompanied by a significant increase in power in the higher frequency bands (greater than 8 Hz), indicating physiological tremor. The asterisks (*) indicate significant differences between pre- and post-fatigue proportional power in the low- and high-frequency bands, respectively. There were no differences in the middle frequencies after fatigue. Open bars, pre-fatigue; filled bars, post-fatigue.

associated with a shift towards higher frequency components. As a first step, the reliability and repeatability of a torque control test set-up was established by assessing young, healthy subjects and was used to test the change in levels of force fluctuation after fatiguing exercises. The results indicated that time-domain measures of accuracy and steadiness of continuous torque production had excellent reliabilities (Shrout & Fleiss 1979; Bruton et al. 2000), whereas frequency-domain measures had relatively lower values of reliability. Furthermore, fatiguing exercises led to reduced accuracy and steadiness in continuous torque production of the knee extensors and the associated torque signal showed a shift towards higher frequencies.

Using the set-up in the current study, accuracy of torque production (NMAE) was found to be approximately 1.5–2.3% of the MVIC at 15 and 20 per cent torque levels, respectively (figure 2). These results are completely in agreement with Hortobágyi et al. (2001), who reported a force accuracy for the control of quadriceps muscle force within 2–3% of the target force. The slightly lower values observed in our study could be due to the subjects’ force production being normalized to the maximum isometric contractions. Similarly, the values for the standard deviation of the absolute error (NSAE), normalized to the MVIC, ranged from 1.2 to 1.6% of the MVIC. These values are analogous with the normalized standard deviation of force reported as approximately 2 per cent of the MVIC for continuous force production (Christou & Carlton 2001; Missenard et al. 2009).

Although the reliability of frequency-domain measures for postural sway, particularly mean and median power frequencies, are known to be lower than time-domain measures (Lafond et al. 2004; Lin et al. 2009), the reliability

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of quantifying force fluctuation measures, in either the time or frequency domains, have remained uninvestigated. Both the intra- and intersession reliabilities of the test measures in 16 subjects in this study were found to be excellent in the time domain. Measures in the frequency domain, on the other hand, showed intrasession reliabilities ranging from good to excellent, whereas the intersession reliabilities were only poor to fair (table 1). Furthermore, force fluctuation measures were more reliable at the 15 per cent MVIC force production task than at the 20 per cent MVIC task. Since all participants were measured on the same standardized experimental set-up, any lower levels of intersession reliability were more likely to be due to the natural variability associated with the phenomenon of force fluctuation than any differences associated with, for example, seating posture. Frequency-domain measures provide an insight into the periodic structure of the force fluctuations (Slifkin & Newell 2000). Low intersession reliability in the frequency domain relative to the time domain would therefore suggest that, although the accuracy and steadiness levels of the generated force are repeatable between sessions, the periodic structure of the generated force is more variable. This variability seems to be associated with the physiological organization of the motor unit pool (Missenard et al. 2009), including recruitment of the motor units (Adam & De Luca 2005; Moritz et al. 2005; Tracy et al. 2005) and synchronization of the motor unit pool (McAuley & Marsden 2000). From the results of this study, it seems that, during submaximal voluntary contraction, motor units are recruited in a pattern that ensures effective task performance (as demonstrated by measures of accuracy and steadiness in the time domain), but that the periodic structure of the generated force is affected by an inherent shakiness, or physiological tremor (Freund 1983; Löschler et al. 1996; McAuley & Marsden 2000). Assessment in the frequency domain therefore appears to allow access to an understanding of shakiness or tremor in the generated force.

ICCs have been used in this study to assess the reliability of the test set-up. While this method has been criticized as a predictor of reliability, it provides a value of consistency as well as agreement between measurements. If the variance between subjects is high, even though the intrasubject variance may be low, it is still possible to obtain high values of ICC. In order to resolve these issues, s.e.m. and Cronbach’s alpha, as measures of absolute reliability, have also been presented. Values of s.e.m. were lower for time-domain reliability, indicating good average reliability. Intrasession Cronbach’s alpha values were generally higher for 15 per cent MVIC levels than for 20 per cent MVIC levels, suggesting that fluctuations at higher force production levels might be less repeatable.

Force fluctuations during voluntary contractions occur because of the fact that multiple motor units are recruited by the muscle at submaximal levels, with increasing force levels resulting in increased fluctuations (Enoka et al. 1999; Slifkin & Newell 1999). This increase in fluctuation is reportedly a result of the increase in the number of motor units recruited and is thus constrained by the total number of units in the muscle. Here, decreased accuracy was shown by higher NMAE and NPAE, and decreased steadiness was shown by increased NSAE (figure 2a) in force fluctuations with increased levels of force-matching tasks, at 15 per cent when compared with at 20 per cent MVICs. These results
are in agreement with the previous studies which reported that higher levels of submaximal force output resulted in greater inaccuracy and unsteadiness, in particular at lower levels of effort (Enoka et al. 1999; Slifkin & Newell 1999; Laidlaw et al. 2000).

The post-fatigue shift in spectral components of the torque signal towards higher frequencies (increase in mean power frequency), in combination with the reduction in proportional peak power, provides evidence of the broadening of spectral power structure. This implies increased noise in the signal as well as greater periodicity in the force variability measurements (Slifkin & Newell 1999). Furthermore, Missenard et al. (2009) showed that increased muscle activation during fatigue was the factor responsible for increased force variability, suggesting physiological organization of the motor unit pool as a possible reason. The results of this study showed decreased normalized power in the low-frequency band, no differences in the middle frequencies, but increased normalized power in the high-frequency band, post-fatigue. Here, it is likely that either more motor units are recruited to perform the same task or that the firing frequencies of the same recruited motor units are enhanced (Bigland-Ritchie et al. 1986; Adam & De Luca 2005; Sogaard et al. 2006; Missenard et al. 2008; Contessa et al. 2009). The resulting shift towards higher frequency components of the generated force post-fatigue, particularly at frequencies between 8 and 12 Hz, is consistent with the occurrence of physiological tremor (Freund 1983; Löscher et al. 1996; McAuley & Marsden 2000; Kouzaki et al. 2004). The results presented in this study indicate that fatigue perturbs the production of force, with the output fluctuating not only at a higher magnitude but also at a higher frequency, resulting in increased force signal complexity or noisiness (periodicity in the force signal), such as increased tremor in the force signal. The shift towards higher frequency components observed in this study after fatiguing exercises therefore seems to be indicative of higher levels of muscle activation as well as an increase in physiological tremor, and therefore confirms the study hypothesis.

The results of this study have demonstrated that reduced levels of accuracy and steadiness of force production and a broadening in the power spectral profile occurred post-fatigue. This is important for the quality of task performance during activities of daily living (Harris & Wolpert 1998). These results confirm not only that fatigue led to an increase in the magnitude of variability of the force production, but also resulted in a change in the structure of the force production signals, indicative of decreased steadiness (Slifkin & Newell 1999) and increased tremor (Kouzaki et al. 2004). Such changes in the quality of task performance after fatigue may contribute to the additional fall risk in the elderly (Schwendner et al. 1997). Although a shift towards higher frequency components in the force signal after fatigue has been shown in young healthy subjects, it seems that this broadening of the spectral components, together with the associated unsteadiness of force control, could play a role in understanding control mechanisms during fatigue.

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References


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Tracy, B. L. & Enoka, R. M. 2002 Older adults are less steady during submaximal isometric contractions with the knee extensor muscles. *J. Appl. Physiol.* 92, 1004–1012.

