INTRODUCTION
Understanding the patterns in force variability throughout the time-history of a fatiguing contraction may be useful in predicting instantaneous relative effort levels associated with an absolute known force demand, thus providing a ratio that could indicate fatigue level. Such a finding would provide a great deal of utility in ergonomic applications where fatigue can be a limiting factor in work task design. To date, studies investigating force variability in fatiguing contractions have shown that the standard deviation (SD) and coefficient of variation (CV) of the force output increase with fatigue [1], although few researchers have sought to use this measure to predict relative effort. Although unsuccessful, Robinson et al. (1994) did attempt to classify submaximal and maximal isometric efforts using torque CV. Their findings show good classification of maximal isometric efforts using CV, but poor classification of submaximal isometric efforts due to highly variable CVs under submaximal conditions.

More recently, researchers have begun to study frequency domain changes in force variability, or physiological tremor, during fatiguing contractions. Huang et al. (2006) found a notable increase in the spectral peak, in the 8-12 Hz range, due to fatigue. However, they noted that these changes were most apparent due to fatigue induced from low-level contractions rather than high-exertion contractions. By way of explanation for the upwards shift in frequency content during low-level fatiguing contractions, they hypothesize a correlation between the recruitment of additional motor units. The fact that most, or all, motor units would have been initially recruited in the high level contractions may explain why the same phenomenon was not seen in high-level contractions. These results are supported by literature showing that mechanical-reflex properties are responsible for tremors below 7 Hz [4], the central nervous system mediates tremors in the 8-12 Hz range [5], and oscillations in exertion force signals between 16-30 Hz are due, in part, to cortical inputs [6]. Thus, it is clear that different physiological phenomena may work to influence oscillations, or variability, within a force exertion signal.

The purpose of this study was to quantify changes in force variability during fatiguing force-varying submaximal isometric exertions of the elbow flexors, using different filtering techniques to identify a method useful for predicting relative effort. Assuming a successful prediction of effort, then fatigue, defined as a decrease in force generating capacity, could likewise be estimated using the filtered data by determining the difference between relative exertion effort and force produced. It was hypothesized that, as local muscular fatigue increased during the protocol, there would be an increase in the variability of the total elbow joint flexor moment of force. It was further hypothesized that, should increased force variability be a consequence of fatigue, the magnitude of force variability at a given contraction level could be used to predict the net instantaneous fatigue status of the contracting muscles required to produce the joint moment.

METHODS
Seven healthy female subjects volunteered for this study (age: 21.1 years ± 0.4, height: 169.4cm ± 6.5, mass: 67.5 kg ± 8.8). Subjects sat in a height-adjustable chair alongside a custom-made aluminum structure (80/20 Inc., IN, USA) of fixed height. The right arm rested comfortably on a foam pad, elbow flexed to 90°, with the forearm supinated, and shoulder abducted to 90°. A reinforced cuff was placed around the subject’s distal forearm, and served to keep the wrist and fingers in a neutral posture. The cuff was fixed to a cable that was attached to an in-line uni-axial force transducer. Surface electromyography (SEMG) data were collected from the right biceps brachii, brachioradialis, brachialis and triceps brachii muscles using a Bortec AMT-8 amplifier (Bortec Biomedical Ltd., Calgary AB). Disposable bipolar Ag-AgCl surface EMG electrodes (MediTrace 133 adhesive electrodes), with an inter-electrode distance of 30mm, were placed over the muscle bellies on a line parallel to the orientation of the muscle fibers of the desired muscles.

Subjects performed three different isometric elbow flexion exertion trials. The first trial was used to determine the maximal voluntary contraction (MVC) force in this posture. Subjects then traced a pattern on a computer monitor that consisted of 11 randomly selected 7-second plateaus at target force levels ranging from 10-95% MVC. This served as a rested force variability calibration trial. Next, subjects performed a fatiguing trial. They were required to trace a pyramid-like template that consisted of 15-second submaximal exertion plateaus of 20, 40, 60, 40, 20, and 0% MVC. A 5-second MVC and 5-second rest period followed each plateau. This exertion pattern was repeated until there was a 40% decrease in force generating capacity.

The force transducer (MLP-300-C0, A-Tech Instruments, Scarborough, Canada) and differentially amplified SEMG (gain = 1000 and 5000, common mode rejection ratio = 115dB at 60Hz), input impedance = 10GΩ) data were collected with LabVIEW software (National Instruments, Austin Tx.) using a PC compatible computer and converted by a 12-bit A/D card (National Instruments, Austin Tx.). Data were synchronously sampled at 1000 Hz. Post-processing of the force signal was performed using a custom-made LabView program.

Post-processing included extracting windows of data from the rested calibration and fatiguing pyramid trials, followed by signal filtering. For the rested calibration trial, 3-second windows of data were extracted from the middle portion of each of the 7-second plateaus. For the fatiguing trial, 10-second windows of data were extracted from each of the 15-second submaximal plateaus, and 3-second windows were extracted from each of the 5-second post-plateau MVCs. To extract these data, an algorithm was developed that selected...
the most stable window from the force data within the respective 7-, 15-, or 5-second plateaus. The force data from each of these windows was linearly detrended, and filtered using 41 different types of 6th order Butterworth filters with cutoff frequencies between 0.5 Hz and 30 Hz (Table 1). The standard deviations were calculated across each of the processed windows of data. The average force from each window was calculated before data processing. The average rectified EMG across each window of data was also calculated. Additionally, the mean power frequency (MnPf) for the first and last second of data from each window was calculated.

In this preliminary analysis, the slope of the relationship between the SD from each set of processed force data and the total accumulated fatigue was computed and assessed for variance by computing the coefficient of determination. Total accumulated fatigue was tracked by calculating the deficit in force generating capacity during each of the post-plateau MVE contractions using the non-processed force data. Additionally, changes in MnPF and EMG signals were plotted against time to observe trends associated with total accumulated fatigue.

Table 1: Processing methods used to filter the force data. Single-pass 6th order Butterworth filters were used for the lowpass (LP), highpass (HP), and bandpass (BP) methods.

<table>
<thead>
<tr>
<th>Filter Method</th>
<th>Filter Region</th>
<th>Filter Frequency Cutoff (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowpass ≤ 6 Hz</td>
<td>LP 6, LP 5, LP 4, LP 3, LP 2</td>
<td></td>
</tr>
<tr>
<td>Highpass ≤ 6 Hz</td>
<td>HP 1, HP 2, HP 3, HP 4, HP 5, HP 6</td>
<td></td>
</tr>
<tr>
<td>&gt; 6 Hz</td>
<td>HP 10, HP 15, HP 20, HP 25, HP 30</td>
<td></td>
</tr>
<tr>
<td>Bandpass 2 Hz Bands</td>
<td>BP 1-3, BP 2-4, BP 3-5, BP 4-6, BP 5-7, BP 6-8</td>
<td></td>
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<tr>
<td>4-8 Hz Bands</td>
<td>BP 7-9, BP 8-10, BP 9-11, BP 10-12, BP 11-13, BP 12-14</td>
<td></td>
</tr>
<tr>
<td>5 Hz Bands</td>
<td>BP 12-17, BP 13-18, BP 14-19, BP 15-20, BP 16-21, BP 17-22</td>
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</table>

RESULTS AND DISCUSSION

This preliminary analysis shows that changes in force variability, as measured by computing the SD of detrended and processed force data, occur during fatiguing isometric elbow flexion contractions, and that these changes are dependent on exertion force (Figure 1). More specifically, a frequency spectrum analysis of the force data over the course of the fatiguing protocol shows inconsistent frequency spectrum shifts between force exertion levels. This is consistent with literature showing discrepancies between changes in frequency content of a fatiguing force signal in the 8-12 Hz frequency range between 25 and 75 % MVC contractions [3]. However, the nature of the shifts observed in the present study were different from those previously reported [3]. As shown by a positive slope in Figure 1, we observed a greater increase in the SD with fatigue in the 40 and 60 % MVC force exertion data than in the 20 % MVC data in both the 1-4 and 8-14 Hz ranges. This may be rationalized by the fact that both the 40 and 60 % MVC exertion levels were below the 75 % MVC high-level contraction studied previously [3]. If the rested 40 and 60 % MVC contractions do not initially recruit all the motor units within the muscle, then the remaining motor units may be recruited during the course of the fatiguing contraction, thereby causing an upward shift in the frequency content of the signal to the 8-14 Hz range, similar to what was previously observed [3]. Additionally, given the nature of the pyramid-like protocol used, it is expected that more fatigue would have been induced during the 40 and 60 % MVC exertions than in the 20 % MVC contractions. This inequality in fatigue between plateaus may explain the difference in frequency domain trends with fatigue observed between our results and those from the literature [3]. However, when the SDs are plotted against accumulated fatigue, within a given plateau, there is a shift towards a decrease in the power in the 8-12 Hz range in the 40 and 60 % MVC contractions. While this later analysis method supports the literature [3], it is not useful in identifying an instantaneous effort level for applied ergonomic purposes because it requires previous knowledge of the force time-history.

The EMG data support the force signal results by showing that fatigue accumulated primarily during the 40 and 60 % MVC plateaus, as noted by a decrease in MnPF. In fact, the MnPF increased between the start and end of the 20 % MVC plateau, when immediately preceded by the 40 % MVE, suggesting that recovery, and not fatigue, may have occurred during these 20 % MVC plateaus.

Figure 1: Slopes of the force signal standard deviation vs. total fatigue accumulated throughout the experimental protocol for each of the bandpass (BP) filtering techniques.

CONCLUSIONS

While the results from this preliminary investigation do not offer conclusive evidence to suggest a specific method to quantify force variability for the purpose of predicting instantaneous effort, they do highlight frequency domain trends during fatiguing force-varying isometric elbow flexion contractions that may develop into useful algorithms.

REFERENCES