Neuromuscular fatigue of elbow flexor muscles of dominant and non-dominant arms in healthy humans

D.M. Williams, S. Sharma, M. Bilodeau

Graduate Program in Physical Therapy and Rehabilitation Science, University of Iowa, Iowa City, IA 52242, USA

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Abstract

The purpose of this study was to assess differences in fatigue-related changes in variables related to structures within the neuromuscular system, between the dominant and non-dominant elbow flexor muscles of right-handed individuals. Two experimental sessions were performed on the right arm and one on the left arm. For each session, maximum voluntary torque, level of voluntary activation, M-wave amplitude, twitch/train or twitch/doublet torque ratio and EMG median frequency were obtained before and up to 20 min after a sustained maximum isometric fatigue task. Our main results were: 1) reproducible fatigue-induced changes in all variables of interest between the two sessions performed with the right arm, 2) significantly greater failure in voluntary activation and neuromuscular propagation with sustained activity for the non-dominant compared with dominant side, and 3) no effect of dominance on MVC torque, endurance time, and fatigue-induced changes in EMG median frequency and elicited torques. These results suggest that the preferential use of elbow flexor muscles with the dominant arm leads to more fatigue resistance in certain structures/mechanisms of the neuromuscular system, but not in others. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The human neuromuscular system displays great plasticity in its ability to adapt to the functional demands it experiences. Long-term preferential use of selected muscle groups (e.g., with hand dominance) can lead to morphological and physiological adaptations in muscle structure and function [12]. For example, the extensor carpi radialis brevis muscle has a higher percentage of Type I fibers in the dominant limb compared to the non-dominant limb [8]. During gripping activities of the hand this muscle is active in securing maximum grip by augmenting the function of the finger flexors. The chronic overuse of the dominant extensor carpi radialis brevis with gripping activities could explain the morphological differences it demonstrates as compared to its non-dominant counterpart. Likewise the muscles of the torso are used in an asymmetric manner. Back muscles on the non-dominant side are called upon more frequently to compensate for the loads and forces applied to and delivered by the dominant upper extremity during daily activities. Bagnall et al. [2] studied the sacrospinalis and multifidus muscles of the torso and found a significantly higher percentage of type I fibers on the left side of the spine compared with the right side.

Fiber composition changes brought about by chronic overuse associated with side dominance have been suggested as an explanation for differences in neuromuscular fatigue characteristics between dominant and non-dominant muscles of the hand [1,5,19,22] and trunk [15]. Tanaka et al. [19] reported a significantly slower time to peak tension in the first dorsal interosseous muscle of dominant versus non-dominant hands and a lesser decrease in force production from the beginning to the end of a fatigue task in the former hand. Zijdewind et al. [22] found that the amplitude of the compound muscle action potential (M-wave) showed a greater decline for the non-dominant versus the dominant first dorsal interosseous muscle following an electrically elicited fatigue task. De Luca et al. [5] found that the median frequency of the electromyographic (EMG) signal
decreased faster with sustained activity in the non-dominant first dorsal interosseous of right-handed individuals, whereas no statistically significant difference could be found in left-handed subjects. The lack of findings in left-handed subjects was explained by the fact that these left-handed subjects were actually ambidextrous. Merletti et al. [15] studied the longissimus dorsi muscle and found a statistically significant effect of hand dominance on fatigue indexes (normalized initial slope of the mean and median frequency of EMG signals) of longissimus dorsi in right hand dominant but not left hand dominant subjects. They found that myoelectric manifestations of neuromuscular fatigue were greater in the longissimus dorsi on the same side as the dominant hand. This would correspond to the “non-dominant” side paraspinal musculature. These findings are all consistent with a greater type I muscle fiber content in muscles of the dominant compared with non-dominant side.

The same type of adaptations due to dominance could occur in the more intermediate musculature of the upper extremity such as elbow flexor muscles if the level of preferential overuse is sufficient, however this has not been thoroughly documented. Such knowledge would improve our understanding of factors leading to neuromuscular adaptations. Therefore, the purpose of this study was to compare the neuromuscular fatigue characteristics of the biceps brachii and brachioradialis muscles of both dominant and non-dominant upper extremities of healthy subjects. A secondary purpose was to evaluate the reproducibility of the response to the same fatigue protocol performed on two different days. Preliminary results have been reported in abstract form [20,21].

2. Methods

2.1. Subjects

Data were collected from eight healthy volunteers (22–43 years; 5 men, 3 women), with no history of upper extremity orthopedic problems or neurologic disorders that could influence muscle force production or motivation. Table 1 provides demographic information on these subjects. All subjects gave written informed consent prior to participating in the study, which was approved by the University of Iowa Institutional Review Board.

2.2. Materials

Subject hand preference (in the performance of ten everyday tasks) was evaluated using a modified Edinburgh Handedness Inventory [16]. A laterality quotient (LQ) was computed scoring left to right-handedness on a scale from −100 to +100. Handedness is determined by the LQ with subjects with a LQ $>25$ being termed right-handed, subjects with a LQ $<-25$ being termed left-handed, and subjects with a LQ $=0$ signifying no hand preference.

Testing was conducted twice on the right upper extremity and once on the left upper extremity with at least 1 week separating each test session. The experimental task of interest was isometric elbow flexion at 90°. Subjects were seated in an apparatus that held the shoulder abducted at 90° and 45° anterior to the frontal plane, the elbow flexed at 90° and the forearm in a neutral position between supination and pronation. The elbow was supported on a padded shelf with the lateral epicondyle aligned directly below the axis of a multiaxial force transducer (JR3 Inc, Woodland, California). The forearm was stabilized in a padded wrist cuff attached to a metal arm extending from the transducer. Elbow flexion efforts were performed by pulling against the wrist cuff. The shoulders and waist were also stabilized using a shoulder harness and waist belt to prevent unwanted contributions of other body segments to elbow flexion torque readings.

The skin over the biceps brachii (BB) long head (BBL), short head (BBS), brachioradialis (BR) and triceps brachii (lateral head) muscles was lightly abraded with an alcohol-soaked gauze. Bipolar surface electrodes (Ag-AgCl disks with an 8-mm diameter, 20-mm fixed interelectrode distance) were placed longitudinally over the belly of the four muscles in a direction parallel to the muscle fibers. The common reference electrode was...
placed over the dorsum of the contralateral hand. EMG signals were pre-amplified at the electrode site (×30) and fed into a differential amplifier with adjustable gain setting (×1000–5000; frequency range between 15 and 4000 Hz; CMRR: 87 dB at 60 Hz; Input impedance: >15 Megohms at 100 Hz; Noise: <2.0 µV RMS referred to input; Therapeutics Unlimited, Iowa City, Iowa). EMG signals were sampled at 2000 Hz for BBS, BBL and TB and 10 000 Hz for the BR. A higher frequency was used for the BR to allow for a better resolution for the characterization of M-waves. Elbow flexion torque was sampled at 1000 Hz. Electrical stimulation was delivered to BB and BR using a constant current stimulator (Model S8800/SIU8T stimulus isolation unit; Grass Instrument Co., Quincy, Massachusetts). The BB was stimulated directly with two self-adhesive surface electrodes (50 mm×50 mm). The cathode was placed over the motor point and the anode over the distal portion of the muscle. The BR was stimulated through the radial nerve with a bipolar stimulating electrode (10-mm diameter and 30-mm spacing) located on the distal 1/3 of the upper arm. Before the experimental tasks were performed, a supramaximal level of electrical stimulation was sought by increasing the stimulation intensity until no further increase in the respective muscle response could be noticed (M-wave amplitude or torque response), or until the maximum output of the stimulator was reached.

2.3. Procedures

Once subjects were stabilized in the apparatus, they were instructed to perform six warm-up contractions into elbow flexion. Subjects were presented with visual feedback of their elbow flexion torque for all tasks. They then performed three elbow flexion maximum voluntary contractions (MVC), with a 2-min rest period between MVCs. Subjects ramped up to their maximum in 2 s, held it for 3–5 s, and then relaxed. During the holding portion, three supramaximal trains of electrical stimulation (12 pulses, 1 ms duration, at 100 Hz) were delivered to BB about 1 s apart to assess the maximality of the contraction. Upon resting, three trains of stimuli followed by three single pulses (1 ms pulse duration), all about 1 s apart, were delivered to BB. Five to six single pulses (1 ms pulse duration) were then delivered to the radial nerve to elicit responses in BR, followed by five to six doublets (100 Hz), again all about 1 s apart. One MVC in elbow extension was also performed, concluding the pre-fatigue measurements. Fifty-percent of the highest MVC was determined and used as the target end point for the fatigue task, which consisted of a maximal effort in elbow flexion held until torque decreased below 50% of the pre-fatigue MVC for 5 s. Immediately following the termination of the fatigue task (time 0), the subject was instructed to perform an MVC and the same stimulation protocol as applied to the pre-fatigue MVCs was delivered. The same post-fatigue measures (MVCs and stimulation protocol) were recorded at 1, 2, 5, 10, 15 and 20 min following the fatigue task.

2.4. Data analysis

Variables of interest were: endurance time, MVC flexion torque, the level of voluntary activation (see formula below), M-wave peak-to-peak amplitude, twitch/train (BB) and twitch/doublet (BR) torque ratios, and the median frequency of the EMG power spectrum of BB and BR. The ability of a subject to maximally activate BB (level of voluntary activation) was assessed with the interpolated twitch technique [10]. The level of voluntary activation was calculated with the following formula: \[ 1−(\text{amplitude of superimposed train torque/amplitude of control train torque})\]×100. The superimposed train torque is the average extra torque (above the voluntary torque) produced by the three trains of electrical stimulation given to the BB during an MVC, whereas the control train torque is the torque produced by the trains of stimulation given to the BB with the subject at rest. The twitch/train or twitch/doublet torque ratio is the ratio of the torque elicited by single pulses of stimulation to that of the torque elicited with trains (BB) or doublet (BR) of stimulation. Such a torque ratio of low-to-high frequency of stimulation is thought to reflect changes in mechanisms related to excitation-contraction coupling (e.g., low-frequency fatigue)[7]. Frequency analysis of EMG signals (512 points for BB or 2048 points for BR, raised cosine filter, fast Fourier transform) was performed on a 1-s window of data corresponding to the maximum torque exerted during a given MVC. The 512-point (256 ms for BB) and 2048-point (205 ms for BR) windows overlapped each other by half their length, and a mean power spectrum was obtained for a given 1-s window of EMG signal. The median frequency, the frequency that divides the power spectrum in two parts of equal power, was obtained for each MVC.

The highest value in a given set of electrical stimulation (e.g., M-waves, twitch/train/doublet torque) was selected for statistical analysis for all variables of interest. Two-way Analyses of Variance (ANOVA) for repeated measures were utilized to evaluate the effect of side (right and left), session (first and second session for the right arm) and time (pre-fatigue, immediately post-fatigue, 1-min of recovery and 20 min of recovery) on most variables of interest. When differences were found between sides, paired t-tests were used to assess the difference between specific pairs of observations with the use of a Bonferroni correction (with an alpha level of 0.05 and 4 time points (see above): 0.05/4 = 0.0125 for the corrected alpha level). Paired t-tests were conducted on endurance time. To further assess the repeatability of
fatigue related changes in our variables of interest, the Standard Error of Measurement (SEM) [17] and intra-class correlation coefficients (ICCs) were also calculated. However, because a set fatigue level (50% of pre-fatigue) was implemented to end the fatigue task, low between-subject variability was found for most variables. This led to artificially low ICC values, which do not optimally reflect reliability in such instances. Therefore, only the results of the repeated measures ANOVA performed on the session and time factors and the SEM data will be provided concerning reliability. The SEM, as used here, is indicative of the range of scores that can be expected on retesting. The level of significance for all tests was established at 0.05.

3. Results

3.1. Repeatability

No differences were found for any of the variables with regards to the session factor or session×time interaction. This indicated that there was no difference between the two sessions performed on the right side. Therefore, the pooled data from these two sessions were used in the analyses testing the effect of side (right versus left). Table 2 summarizes the SEM data for all the variables of interest.

3.2. LQ, endurance time and MVC torque

Results of the Edinburgh Handedness Inventory revealed that all subjects were highly right-hand dominant (Table 1). Endurance time did not vary significantly between the three different sessions (mean ± standard deviation endurance time: right side, first session: 63.4 ± 13.7 s; right side second session: 60.8 ± 10.9 s; left side: 63.1 ± 17.2 s; p>0.05). There was no difference in pre-fatigue MVC elbow flexion torque between the right (first session: 88.6 ± 37.5 Nm; second session: 90.1 ± 41.7 Nm) and left arm (88.2 ± 41.5 Nm) or both sessions performed with the right arm (p>0.05). Subjects demonstrated a consistent decrease and progressive recovery of MVC torque following the fatigue task (Fig. 1). The non-dominant side (left) demonstrated a slightly slower recovery of MVC torque compared to the dominant side, however, this was not statistically significant (side×time interaction, p>0.05).

3.3. Level of voluntary activation

Individual and group mean data for the level of voluntary activation are shown in Fig. 2. Before fatigue, the ability of subjects to maximally activate BB was equal between the right (first session: 95.9 ± 6.9%; second session: 96.4 ± 6.3%) and left (97.2 ± 4.1%) hand (p>0.05). However, subjects demonstrated a greater decrease in the level of voluntary activation with fatigue on the left compared with the right side, which led to a significant interaction between side and time for this variable (p<0.05). Paired t-tests revealed a significant difference between the two sides at 10 min of recovery (p<0.0125). The difference observed immediately after the fatigue task (0 min) did not reach significance (p=0.059). This was most likely explained by a higher variability at this time point.

3.4. Elicited responses

Fig. 3 shows the individual and group data for M-wave amplitude. For the right side, either no change (second sessions) or a slight increase in amplitude (potentiation, first session) was observed following the fatigue task (Fig. 3b; no significant difference between the two sessions). In contrast, the left side showed a significant decrease in M-wave amplitude immediately following the fatigue task. This led to a significant interac-

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**Table 2**

<table>
<thead>
<tr>
<th>Variable</th>
<th>% change with fatigue</th>
<th>SEM</th>
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<tbody>
<tr>
<td>Endurance time</td>
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</tr>
<tr>
<td>MVC Torque</td>
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<td>6.3</td>
</tr>
<tr>
<td>Voluntary activation</td>
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<td>4.0</td>
</tr>
<tr>
<td>M-wave amplitude</td>
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<td>7.1</td>
</tr>
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<td>BBS MF</td>
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<td>19.3</td>
</tr>
<tr>
<td>BBL MF</td>
<td>31.8</td>
<td>12.6</td>
</tr>
<tr>
<td>BR MF</td>
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<td>11.7</td>
</tr>
<tr>
<td>BB Twitch torque</td>
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<td>15.3</td>
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<tr>
<td>BB Train torque</td>
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<tr>
<td>BB Twitch/train ratio</td>
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<td>18.9</td>
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<td>BR Twitch torque</td>
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<td>BR Doublet torque</td>
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<tr>
<td>BR Twitch/doublet ratio</td>
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<td>9.5</td>
</tr>
</tbody>
</table>

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**Fig. 1.** Mean (+ standard deviation) maximum voluntary elbow flexion torque shown before (pre), immediately after fatigue (0) and up to 20 min of recovery (1–20). Data is shown for both sessions performed with the right arm and for the single session performed with the left arm. Data have been normalized to pre-fatigue values.
3.5. Median frequency

Fig. 5 shows group data of the BBL median frequency following the fatigue task. All three muscles monitored (BBS, BBL, and BR) displayed a similar initial decrease in median frequency immediately post-fatigue and a progressive recovery back to pre-fatigue values by about 5 min. No significant differences were found in the fatigue-related behavior of the median frequency between the right and left side ($p > 0.05$). Also, the triceps brachii muscle was minimally active during the elbow flexion efforts, and the activity was not different between the right and left side during the fatigue task (no significant interaction between side and time for the EMG root mean square amplitude of this muscle).
Fig. 4. Mean (+ or − standard deviation) train torque (top panel) or twitch torque (bottom panel) shown for the biceps brachii before (pre), immediately after fatigue (0) and up to 20 min of recovery (1–20). Data for both sessions on the dominant side (right) have been pooled and are compared to the single session performed on the non-dominant side (left). Data from the brachioradialis muscle presented with similar trends (not shown).

4. Discussion

The main results of this study were: 1) significant differences between dominant and non-dominant sides (right versus left side of right-handed subjects) in fatigue induced changes in the level of voluntary activation and M-wave amplitude, 2) no effect of dominance on fatigue-related changes in endurance time, MVC torque, twitch/train torque ratio and EMG median frequency, and 3) reproducible fatigue-related changes in our variables of interest.

4.1. Dominance

Before fatigue was induced, the capacity of subjects to maximally activate their BB was equally high (≈96–97%) for both the dominant and non-dominant side. Therefore, the level of voluntary activation does not seem to be influenced by dominance in the fresh (unfatigued) state. However, a significant effect of dominance on voluntary activation was evidenced with fatigue. In our right-handed subjects, the level of voluntary activation was significantly decreased after the fatigue task performed with the left side, but not with the right side. This suggests that a greater failure in central drive (central fatigue) can occur in non-dominant muscles with sustained activity. Evidence for the presence of greater central fatigue in non-dominant muscles has also been observed in a hand muscle [23].

Similarly, whereas a small degree of M-wave potentiation was observed for the BR of the dominant side, a significant decrease in M-wave amplitude was found for the non-dominant BR following fatigue. M-wave potentiation following sustained activity is a common observation for the elbow flexor muscle group [3,4,11]. However, it appears that the less frequent and potentially sustained use of muscles on the non-dominant side is not associated with potentiation, but rather failure in neuromuscular propagation. A greater failure in neuromuscular propagation in non-dominant compared with dominant muscles has also been reported for the first dorsal interosseous muscle [22]. As mentioned in the introduction, this type of observation has been explained by fiber type changes associated with the prolonged preferential use of dominant side muscles. However, factors other than fiber type differences could also explain such differences in fatigue-related changes in M-waves between dominant and non-dominant muscles. For example, Duchateau and Hainault [6] observed a lesser change in M-wave area with fatigue following a 3-month, moderate intensity training period. They explained some of the changes in M-wave response to fatigue by an improvement of synaptic mechanisms. A similar phenomenon could occur with the preferential use of dominant versus
non-dominant elbow flexor muscles, without significant changes in fiber type composition (see discussion on median frequency and torque ratio below).

It should be noted, however, that the greater failure in voluntary activation and neuromuscular propagation on the non-dominant side did not lead to significant differences in endurance time. Consequently, the functional significance of the differences observed between sides for these two variables is questionable. It is possible that the safety margin built in the neuromuscular system is sufficient to fully compensate for the increased failure in voluntary activation and neuromuscular propagation observed in the non-dominant elbow flexor muscles.

In contrast to previous studies on distal upper limb and trunk muscles [5,15], we found no significant differences between the dominant and non-dominant side with regard to the changes in the EMG median frequency with fatigue. The shift in the EMG signals toward lower frequencies can be influenced by the fiber type composition of the muscle [9,13,14]. Therefore, our results suggest that a difference in fiber type composition, as observed for hand and trunk muscles [2,8], is not present in elbow flexor muscles. This could be explained by a more symmetrical use of these muscles in daily activities compared to the preferential use of the dominant hand (or trunk muscles) leading to a greater proportion of type I fibers. The absence of a difference between dominant and non-dominant sides for the fatigue-related changes in the twitch/train (BB) or twitch/doublet (BR) torque ratio also supports a similar fiber type content for muscles of both the right and left arm. The presence of low-frequency fatigue following the sustained MVC muscles of both the right and left arm. The presence of —

References


David M. Williams received a Master’s of Physical Therapy degree (MPT) in 1993 from the Mayo Foundation (Rochester). He is currently a doctorate student in the Graduate Program in Physical Therapy and Rehabilitation Science, University of Iowa. He is also a licensed, practising physical therapist.

Shreela Sharma received a B.Sc. degree in Physiotherapy in 1996 from the University of Bombay, India and a M.A. in Physical Therapy in 1999 from the University of Iowa. She is currently finishing an internship with the University of Houston to obtain registration as a dietitian and will be on Faculty at the University of Houston in the Human Nutrition and Foods program in January 2002.

Martin Bilodeau received a B.Sc. degree in Physiotherapy in 1988 and a Ph.D. degree in Biomedical Sciences (Rehabilitation) in 1993 from the University of Montreal. He was a Post-doctoral Fellow in the Department of Biomedical Engineering at the Cleveland Clinic Foundation until 1995. He has been an Assistant Professor in the Graduate Program in Physical Therapy and Rehabilitation Science, University of Iowa since 1996. His current research interests include the study of neuromuscular fatigue, aging and stroke.