Differential control during maximal concentric and eccentric loading revealed by characteristics of the electromyogram

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Abstract

Maximal eccentric loading has been associated with higher levels of spindle afferent activity but lower levels of integrated EMG as compared to maximal concentric loading. Elbow flexor EMG was recorded from 17 subjects during concentric (CONC) and eccentric (ECC) elbow flexion at 70° s⁻¹ using a Kin-Com dynamometer. We hypothesized that peak EMG amplitude would be more sensitive to fluctuations in facilitation by the spindle primary afferents via the segmental stretch reflex pathway, and that the mean EMG would be more reflective of the ongoing level of muscle activation. A ratio of peak to mean EMG (P/M EMG ratio) was predicted to be larger during maximal eccentric loading than maximal concentric loading. The peak EMG (P < 0.013) and the P/M EMG ratio (P < 0.001) were significantly greater during the ECC condition than the CONC condition. In a subgroup of three subjects who underwent 3 weeks of eccentrically biased weight training, EMG, peak torque and torque variability were assessed before and after training. P/M EMG ratio decreased, while peak torque and torque variability increased following the training. Differences in the P/M EMG ratio appear to reflect differences in the way eccentric and concentric muscle actions are controlled and do not simply represent less control during the eccentric task. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Strength; Training; Isokinetic loading; EMG

1. Introduction

Eccentric (lengthening) muscle actions are very common during many daily activities such as walking, running and jumping. The primary role of eccentric muscle actions in these activities has been described as one of deceleration and energy absorption [1]. Forces obtained during maximal eccentric muscle actions may be 40% greater than during maximal concentric actions [2,3]. Because of these high forces, muscle strains and myotendinous injury are more commonly associated with activities involving eccentric loading than activities involving only concentric loading [4,5].

When testing human subjects on isokinetic dynamometers, maximal eccentric torque is usually less than would be expected from in vitro modeling [6–10]. Several authors have postulated that this discrepancy may be due to the action of a tension-limiting neural regulatory mechanism to prevent excessive muscle loading [7–9]. The observation of less integrated electromyographic (EMG) activity produced during maximal eccentrically controlled movements as compared to concentrically controlled movements [9,10] supports the view that the neural drive is reduced during eccentric loading.

Through reflex activation, peripheral afferent feedback can contribute to the neural drive during eccentric loading. Muscle spindle afferent feedback increases considerably during eccentric muscle loading compared with that observed during concentric and isometric loading [11]. When transitions are made between isometric and eccentric muscle actions, the increase in spindle afferent feedback is associated with increases in the EMG [11]. There is also evidence that peripheral afferent feedback contributes from 40 to 60% of the neural drive to the soleus while it eccentrically lengthens during the stance phase of gait [12] (see [13]). These findings suggest that skeletal muscle is
activated differently when it is lengthening as compared to when the muscle is shortening or under isometric conditions [14–16]. The proportion of neural drive supplied by the peripheral afferents and the inhibitory control exerted by peripheral afferents and central mechanisms are likely quite different during eccentric as compared to isometric and concentric muscle actions.

Differences in the way muscle is activated under concentric and eccentric conditions may be revealed in the characteristics of the ensemble EMG. Since the integrated EMG, which reflects the ongoing level of muscle activation, has been found to be less during maximal eccentric as compared to maximal concentric loading [9,10], we would predict that the mean-rectified EMG (averaged over the duration of the movement) would also be less during eccentric loading. In contrast, the magnitude of the peak EMG potentials, which reflects the instantaneous level of muscle activation, has been found to be greater during maximal eccentric as compared to maximal concentric loading [15,17,18]. This is based on the observation that motor unit discharge can be synchronized by spindle afferent input [11,19] and the magnitude of the peak EMG is related to the degree of motor unit synchronization [17, 20:206, 21, 22]. Therefore, the purpose of this study was to identify differences in the way eccentric and concentric muscle activation is controlled by comparing a ratio of the peak to mean EMG during maximal isokinetic loading of the elbow flexor muscles. First, we hypothesized that maximal eccentric loading would result in greater peak EMG than that associated with maximal concentric loading. Second, because the mean EMG during maximal eccentric was predicted to be less than that associated with maximal concentric loading, we would also predict that a ratio of the peak to mean EMG would be greater during maximal eccentric muscle actions.

A post hoc decision was made subsequent to initial testing to measure the torque variability during isokinetic loading in a subset of three subjects. In addition, these subjects underwent three weeks of resistance training following which they were retested. This was included to give guidance for future studies. It has been shown previously that the variability in measured isokinetic torque is effected by the intensity of the effort prescribed [23,24]. Further, the initial adaptations to exercise are neural and are inclusive of changes in agonist activation and co-activation of antagonist muscles [25]. Given the novelty of the isokinetic task, we hypothesized that there would be greater torque variability in the eccentric condition. We also predicted that peak torque would increase, and torque variability and P/M EMG ratio would decrease following training.

2. Methods

2.1. Subjects

Seventeen volunteers (8 male, 9 female) were recruited from the Student Recreation Center of the University of Florida, and Gainesville Health and Fitness Center, Gainesville, FL. Mean age was 24.1±3.2 (SD) yr, and body mass index 22.3±4.6 kg m⁻². A sample size of at least 12 was indicated by power calculations derived from pilot data. To avoid the subjects developing delayed onset muscle soreness following a novel eccentric task [1], only subjects who were accustomed to resistance training were recruited for the study. Thus, subjects had to have weight-trained their upper extremities twice a week for at least three months to be included in the study. Exclusion criteria included the existence of current musculoskeletal pathology affecting the upper quadrant, any medical limitations to their exercise, and a history of anabolic steroid use. Subjects read and signed an informed consent approved by the Institutional Review Board of the University of Florida before participating in the study. All testing was performed in the Biomechanics Laboratory of the Health and Human Performance Department, Department of Exercise and Sport Sciences, University of Florida.

2.2. Equipment

Bipolar self-adhesive surface EMG electrodes (16 mm Ag/AgCl) were placed 30 mm apart (center to center) over the muscle belly of the biceps brachii muscle of the subject’s dominant arm and the leads secured with adhesive tape in an attempt to minimize movement artifact. The skin of the subject was cleaned with alcohol to decrease skin impedance. EMG was recorded from the elbow flexors using the Data Logger data acquisition system (Paromed, Medizintechnik, Germany) at a sampling frequency of 1060 Hz. The amplifiers of this system have an input impedance of 10 GΩ, a signal to noise ratio of 40 dB, and a common mode rejection ratio of 80 dB at 60 Hz. A gain of 1 K was used with a low-frequency cutoff of 10 Hz. The EMG data was analyzed off-line using a personal computer (Gateway P200).

2.3. Experimental setup

Arm dominance was determined by asking the subject which arm he or she would use to throw a ball. Eccentric and concentric loading of the elbow flexors was performed on a Kin-Com 125 AP dynamometer at a constant velocity of 70° s⁻¹ (Chattanooga Group Inc., Chattanooga, TN). This velocity was chosen since it represented the angular velocity at which student athletes
at the University of Florida are instructed to move their forearm during resistance exercise utilizing free weights. That is, two seconds up for the concentric phase and 2 s down for the eccentric phase through a normal ROM of elbow flexion of ~140°. Prior to testing each subject, external calibration of both force and speed were performed on the dynamometer.

During all isokinetic tests, the subject sat upright on the dynamometer seat in the standard position for testing of elbow flexion described in the Kin-Com software. To limit trunk motion, subjects were secured with two seatbelts placed across their chests. The axis of motion of the elbow of the dominant arm was aligned with the axis of the actuator arm of the dynamometer. The joint line palpated immediately superior to the radial head was used as an estimate of the axis of elbow motion. Subjects gripped a handle attached to the actuator arm during testing which maintained the forearm in full supination.

2.4. Testing protocol

After five submaximal warm up contractions, each subject performed three maximal isokinetic concentric contractions (CONC) and three maximal isokinetic eccentric actions (ECC). Order effects were minimized by randomization of testing mode order. Each subject was allowed 15 s rest between trials at each condition and three minutes rest between conditions. Maximum subject effort was encouraged in three ways. Prior to testing, subjects were instructed to give maximal efforts on each and every test trial. During testing, subjects were verbally encouraged to give maximal efforts [26]. After each trial subjects were shown a modified perceived exertion scale [27] and asked what they perceived their level of effort to be for that trial. If not maximal, they were required to repeat the trial after 3 min rest.

Subsequent to the initial testing, a post hoc decision was made for three subjects (2 male, 1 female) to train their elbow flexors for three weeks utilizing a free weight task that emphasized the eccentric muscle actions. Prior to training, the concentric one repetition maximum (C1RM) was determined for a standing biceps curl exercise using a standard Olympic weight lifting bar (20.5 kg). If the subject was able to complete a full repetition of elbow flexion without assistance or associated trunk motion, weight was added to the bar. The weight lifted was increased until the subject was unable or unwilling to complete a full repetition of elbow flexion without assistance. Three minutes of rest were given between attempts at lifting the weighted bar.

The twice a week training sessions utilized partner training in which the subject was assisted during the concentric phase of a standing arm curl and instructed to slowly lower the weight. Using the C1RM as the starting weight, subjects performed three sets of ten repetitions with three minutes of rest between sets. If the subject completed ten repetitions in the final set, the weight was increased by 2.25 kg. If the repetition count was less than eight, the weight was decreased 2.25 kg. Subjects were instructed not to otherwise modify their activities during this three week period. Following training, these subjects were re-tested using the same protocol as previously outlined.

2.5. Data analysis

To quantify the EMG, the signal was processed by full wave rectification. EMG onset time was determined by identifying the point at which the EMG amplitude was consistently maintained (>50 ms) two standard deviations above the mean baseline noise of the EMG system. The duration of the EMG was consistently 1.57 s. This represented the movement time of the isokinetic dynamometer set at 70° s⁻¹. The single peak amplitude and the average EMG amplitude during this period was obtained for all seventeen subjects. In addition, the five largest peak EMG amplitude values during each trial were determined and averaged for ten subjects chosen at random. This was done to assess the impact of spurious spikes within the EMG data. Normalization of the EMG data was accomplished by dividing the peak and mean EMG values by the mean EMG of each subject during the concentric contraction. A ratio of the peak to mean EMG (P/M EMG ratio) was also calculated for each trial. This was done for the single peak EMG values (P1/M EMG ratio), as well as for the five peak EMG values (P5/M EMG ratio). The average of the peak, mean, and P/M EMG ratios for the three trials in each condition were calculated for each subject and then used for all comparisons. The differences in the normalized peak EMG, mean EMG, and the P/M EMG ratios between test modes were determined using paired t-tests with Bonferroni corrections to maintain a family wise type I error rate of 5% [28:407].

In addition, peak torque and the torque variability during the CONC and ECC conditions was assessed in the three subjects who trained for three weeks. Elbow flexor torque was obtained from the Kin-Com computer and software. Peak torque was simply recorded as the peak of the torque curve. Torque variability was represented by determining the variation in shape of a torque curve from a single trial relative to a second order polynomial. Averaged torque curves from an isokinetic dynamometer are described well by a second order polynomial. We determined the $R^2$ values for individual torque curves from the three subjects. Since the $R^2$ value represents the degree of variance...
Fig. 1. Raw EMG signal during concentric (A) and eccentric (B) muscle actions for Subject 1. The peak EMG during the concentric movement was 1.47 mV (*) and the mean EMG 0.22 mV producing a P/M ratio of 6.7. In contrast, the peak EMG during the eccentric movement was 1.63 mV (*) and the mean EMG 0.16 mV producing a P/M ratio of 10.2. Peaks used in the calculation of P5/M ratio are shown (+).

3. Results

The single peak EMG was 21% greater \( (P<0.0133) \) during the ECC condition as compared to the CONC condition. The P/M EMG ratio was also significantly larger during the ECC condition as compared to the CONC condition, whether the single peak rectified EMG value was used (P1/M EMG ratio; 29.1% greater; \( P<0.001 \)) or the five peak values within each trial were used (P5/M EMG; 15.9%; \( P<0.015 \); see Figs. 1 and 2 and Table 1).

In the three subjects in which torque was measured, peak torque was greater during the ECC condition, however, torque variability greater for the CONC condition. After three weeks of resistance training, ECC and CONC peak torque and torque variability increased. In contrast, the P/M EMG ratio decreased during both the ECC and CONC testing following training (see Table 2). We did not assess the statistical significance of the peak torque, torque variability, or the training effects due to the small sample size (\( N=3 \)) and the post hoc nature of the data collection.

4. Discussion

Although less integrated EMG during eccentric loading has been observed when maximal concentric and eccentric conditions are compared [3,8,28], greater peak

![Image](image_url)

Table 1
Average EMG values for all subjects. Peak EMG and mean EMG are normalized to mean EMG of the CONC condition. P1/M ratio represents the ratio of the single largest peak EMG amplitude to the mean EMG of that condition. P5/M ratio represents the ratio of the five largest peak EMG amplitudes to the mean EMG of that condition

<table>
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<th>CONC</th>
<th>ECC</th>
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<tr>
<td>Peak EMG mV (SE)</td>
<td>5.02 (0.05)</td>
<td>6.08 (0.56)</td>
</tr>
<tr>
<td>Mean EMG mV (SE)</td>
<td>1.00 (0.00)</td>
<td>0.95 (0.09)</td>
</tr>
<tr>
<td>P1/M ratio mV/mV (SE)</td>
<td>5.02 (0.05)</td>
<td>6.28 (0.12)</td>
</tr>
<tr>
<td>P5/M ratio mV/mV (SE)</td>
<td>5.02 (0.40)</td>
<td>5.82 (0.41)</td>
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EMG was observed during maximal eccentric loading in this investigation. In addition, the P/M EMG ratio was observed to be greater during maximal eccentric loading as compared to maximal concentric loading. These findings suggest that even though the continuous level of muscle activation may be reduced during maximal eccentric loading to prevent excessive muscle force [7], brief spikes in motor unit activation occur which exceed those found during maximum concentric loading. This would be consistent with higher levels of spindle afferent feedback and a more synchronized motor unit activation during eccentric conditions (see ref. 11).

In a recent study by Voigt et al. [29] the soleus EMG
Table 2
Changes following three weeks of training which involved enhanced eccentric loading (N=3). Torque variability values represent percent variation and were calculated using the formula \((1-R^2)\times100\) of the second order polynomial calculated from the torque curve. P1/M ratio represents the ratio of the single largest peak EMG amplitude to the mean EMG of that condition

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<th>Eccentric Pre</th>
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<tbody>
<tr>
<td>Subject 1</td>
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<td>Subject 2</td>
<td>192</td>
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<td>Subject 3</td>
<td>281</td>
<td>313</td>
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<td>359</td>
</tr>
<tr>
<td>Average</td>
<td>194</td>
<td>213</td>
<td>216</td>
<td>234</td>
</tr>
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</table>

**Torque variability**

| Subject 1      | 15             | 19              | 2             | 3             |
| Subject 2      | 35             | 40              | 2             | 5             |
| Subject 3      | 13             | 18              | 2             | 3             |
| Average        | 21.0           | 25.7            | 2.0           | 3.7           |

**P/M ratio (mV/mV)**

| Subject 1      | 5.3            | 4.9             | 6.7           | 6.2           |
| Subject 2      | 4.9            | 4.9             | 6.4           | 6.1           |
| Subject 3      | 5.1            | 4.4             | 6.9           | 6.6           |
| Average        | 5.1            | 4.7             | 6.7           | 6.3           |

was examined during reciprocal hopping, an activity which has an eccentric component upon landing, and compared it to the Achilles tendon reflex at rest. The peak EMG upon landing was observed to have a latency from the initial contact of landing similar to the EMG latency of the Achilles tendon reflex. The authors referred to this peak EMG as a movement induced short latency stretch reflex since it was likely related to the synchronous burst of spindle afferent input upon landing [29]. Recently, our laboratory demonstrated that the peak soleus and lateral gastrocnemius EMGs were higher during reciprocal hopping than during maximal isometric voluntary contractions and concentric hops [17]. Reciprocal hopping involves an eccentric lengthening during the landing phase and a concentric shortening of the muscle during the take off phase (i.e. stretch–shortening cycle), whereas, concentric hops only involve the concentric shortening of the muscle during the take off phase. Again, the findings of these studies and our results suggest that during eccentric loading, the peak EMG is related to stretch evoked muscle activation which can potentially increase the instantaneous level of activation above that seen during maximal isometric and concentric conditions.

A large P/M EMG ratio may also reflect decreased control during a movement. The isokinetic testing used in this study was a novel task for our subjects. Since the subject’s goal was to produce a maximum effort through the range of motion, sudden variations in muscle activation and torque would be counterproductive. The P/M EMG ratio was greater during the ECC condition as compared to the CONC condition. Differences in the way concentric and eccentric muscle activation are controlled may explain this discrepancy. If the P/M ratio is reflective of motor control, it should be related to torque variability decrease with training as subjects improve their ability to control the muscle action with practice. After three weeks of training, however, peak torque on torque variability increased. Thus, the P/M ratio was not related to the torque variability. Torque variability was also greater during the CONC condition (Table 2 and Fig. 3). Therefore, these preliminary findings suggest that the P/M ratio does not represent a measure of motor control.

High force transients in a subset of the muscle may occur during novel tasks and during fatigue when the neural control is not optimal and torque variability is excessive. Transient force spikes may not be reflected in the overall muscle force and therefore would not be
measurable by a dynamometer that measures the torque produced by rotation of the subject’s limb. These force transients, however, could result in injuries to the muscle fibers in which they occur. A high P/M EMG ratio may reflect more synchronous motor unit activation, as well as, the occurrence of transient force spikes within subsets of a muscle.

The mechanisms underlying the differences in the P/M EMG ratio during eccentric and concentric loading likely involve how peripheral afferent feedback is controlled under the two conditions. Golgi tendon organs (GTO’s) monitor muscle tension and provide negative feedback onto alpha motoneurons via a well known disynaptic inhibitory pathway [30:156–8]. A generally accepted function of this pathway is to prevent rapid rises in muscle tension and overloading [30:156–8]. Muscle spindles, on the other hand, detect changes in muscle length, and their primary afferents are facilitatory to the motoneurons along monosynaptic as well as polysynaptic pathways [29]. During rapid changes in muscle length, facilitation from spindles can potentially increase the neural drive [11] more rapidly than the GTOs can exert disynaptic inhibitory control. Therefore, even though the ongoing level of muscle activation may be well controlled and submaximal, rapid changes in muscle length may result in brief periods in which the instantaneous level of muscle activation exceeds the postulated ‘inhibitory zone’ or regulated level of muscle activation [7–9]. Thus, differences in the proportion of neural drive supplied by the spindle afferents, as well as, other peripheral afferents, necessitates a different control strategy during eccentric as compared to isometric and concentric muscle actions [14].

Alternatively, differences in the P/M ratio may reflect differences in the duration of the subject’s effort during the ECC and CONC conditions. As seen in Fig. 1, the subject maintained a near maximal effort and EMG from 10° to 110° during the concentric controlled movement. In contrast, the subject appears to relax during the latter part of the eccentric controlled movement. This could account for a substantially lower mean EMG during the ECC condition and a higher P/M EMG ratio during the ECC condition. However, the mean EMG was only 5% less during the ECC condition while the peak EMG was 21% greater during the ECC condition. Thus, differences in the duration of the subject’s effort unlikely account for the differences in the P/M EMG ratio seen.

In conclusion, the P/M EMG ratio is larger during eccentric muscle actions in comparison to concentric actions when the velocity of movement is controlled. Differences in the P/M EMG ratio may reflect the divergent way eccentric and concentric muscle actions are controlled or the measure may represent a relative measure of variability of muscle activation. There were, however, several limitations to this investigation. We have only assessed the P/M EMG ratio for muscle actions of the elbow flexors. These include a two joint muscle (biceps brachii) that may show activation characteristics different to those of a one joint tonic muscle such as soleus or the vasti muscles. It may be that the peak EMG amplitude is a measure that is too variant and that the average of five peaks provides a more stable result. In this experiment we calculated that P5/M EMG ratio. There was strong evidence of a difference between the concentric and eccentric conditions but not between P/M and P5/M ratios for either condition.

Future directions for this research need to test the reproducibility and robustness of the P/M EMG ratio. Contraction velocity, joint angle and stabilization and subject motivation should be assessed for their impact on this measure to determine its utility. If the P/M ratio is a measure of control then the effect of training should also be investigated with a prospective controlled trial.

References

[14] Enoka RM. Eccentric contractions require unique activation stra-

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