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Variations in the Relationship Between the Frequency Content of EMG Signals and the Rate of Torque Development in Voluntary and Elicited Contractions

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Abstract

Our purpose was to characterize the relationship between EMG mean power frequency (MPF) or median frequency (MF) and rate of torque development in voluntary ballistic and electrically elicited isometric contractions. Twenty-three healthy adults participated in two sets of experiments performed on elbow flexor muscles. For *Experiment 1*, subjects were asked to generate voluntary ballistic contractions by reaching four different target torque levels (20, 40, 60 and 100% of the maximal voluntary contraction (MVC)) as fast as they could. For *Experiment 2*, electrical (M-waves) and mechanical (twitches) responses to electrical stimulation of the nerves supplying the biceps brachii and brachioradialis muscles were recorded with the subjects at rest and with a background isometric contraction of 15% MVC. MPF, MF and rate of torque development (% MVC/s) were calculated for both voluntary and elicited contractions. Significant positive correlations were observed between MPF and rate of torque development for the voluntary contractions, whereas significant negative correlations were observed between the two variables for elicited contractions. This suggests that factors other than muscle fiber composition influence the frequency content of EMG signals and/or the rate of torque development, and that the effect of these factors will vary between voluntary and elicited contractions.

Keywords: Electromyography; Mean power frequency; Rate of torque development; Isometric contraction; Elbow flexor muscles

1. Introduction

Muscle fiber composition has been shown to influence the frequency content of electromyographic (EMG) signals. In studies performed on both humans [10–12,19,27] and animals [17], a significant association is reported between the median frequency (MF) or mean power frequency (MPF) of electromyographic (EMG) signals and the fiber type content (I/II) of the muscle. Significant associations have been reported between both spectral statistics (or their behavior with fatigue or increasing force) and percent fiber type by number of fibers [10–12,27] or relative area [17,19]. Muscles with a higher content/area of type II fibers will show higher MPF or MF values and more pronounced changes with fatigue or increasing force. Such associations most likely reflect the higher conduction velocity of the larger, more fatigable, high threshold type II fibers [20], which would influence the shape of the action potentials and thus the distribution of power in the EMG power spectrum [15].

Muscle fiber composition has also been shown to influence contraction speed (or rate of force/torque development), with muscles containing a higher type II fiber content showing higher rates of torque/force development [6–8,22,26]. However, variations in the results obtained from voluntary compared to electrically-elicited contractions have been reported [18]. In such cases, the confounding effect of the voluntary command to muscles has been suggested as a potential explanation to account for the differences observed.

Therefore, a significant positive relationship should exist between the frequency content of EMG signals (MF, MPF) and the rate of torque development of a muscle. A stronger association could also be expected when the potential influence of the voluntary command is controlled for (e.g., with electrical stimulation). Accord-

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ingly, the purpose of this study was to test these hypotheses and document the association between the MPF and MF and the rate of torque development in elbow flexor muscles during both voluntary (*Experiment 1*) and elicited (*Experiment 2*) contractions.

2. Methods

2.1. Subjects

A total of 23 healthy adults participated in the study. Table 1 gives a detailed description of the demographic data for these subjects. All subjects gave written informed consent prior to participating in the study, which was approved by the Institutional Review Board at the University of Iowa. Thirteen subjects participated in *Experiment 1*, and 14 in *Experiment 2*, with four subjects (no. 1, 3, 7, 12 in Table 1) participating in both sets of experiments.

2.2. Materials

2.2.1. Torque recording

The elbow flexion torque produced voluntarily or with electrical stimulation was recorded with a multiaxial torque/force transducer (JR3 Inc., Woodland, CA, USA). Subjects were seated with their right forearm supported horizontally at shoulder height. The shoulder was kept at about 45° of horizontal adduction (from the frontal plane), the elbow at 90° of flexion, and the forearm in a neutral position midway between pronation and supination. A system of straps minimized unwanted movements at the shoulders. The elbow joint (estimated at the lateral epicondyle) was centered directly underneath the center of the transducer. The wrist of the subject was secured in a padded metal cuff (about 2 cm proximal to the styloid process) attached to a metal bar extending from the transducer. Subjects produced elbow flexion efforts by pulling against the wrist cuff towards them. All contractions in both sets of experiments were isometric.

2.2.2. EMG recordings

EMG signals from the biceps brachii short (BBS) and long heads (BBL), brachioradialis (BR) and triceps brachii were picked up with surface electrodes placed on the respective muscle bellies between the innervation zone and the distal tendon in a direction parallel to the muscle fibers after careful skin preparation. The electrodes had a diameter of 8 mm and a fixed inter-electrode distance of 20 mm. A common reference electrode was placed on the dorsal aspect of the ipsilateral hand. Signals were pre-amplified at the electrode site (X30) and fed into a differential amplifier with adjustable gain settings (X100-100,000; frequency range between 15 and 4000 Hz; CMRR: 87 dB at 60 Hz; Therapeutics Unlimited, Iowa City, IA, USA). EMG gains were adjusted to

Table 1
Demographic characteristics of subjects

Subject no.	Gender	Age (years)	Height (m)	Weight (kg)	Skin BB (mm)	Skin BR (mm)
1	M	30	1.69	67.3	6.0	8.0
2	F	24	1.56	50.0	8.0	6.6
3	M	33	1.75	79.5	3.5	4.8
4	F	25	1.75	59.0	12.7	6.0
5	M	36	1.85	86.4	8.0	4.3
6	F	23	1.75	84.0	9.0	5.6
7	M	35	1.88	79.5	2.3	2.0
8	M	25	1.76	70.0	3.0	3.0
9	F	29	1.70	61.4	5.1	2.4
10	M	23	1.85	77.3	3.8	3.4
11	M	25	1.80	90.9	2.9	3.0
12	F	25	1.68	61.4	8.0	8.0
13	M	25	1.75	72.7	2.5	3.4
14	F	25	1.60	63.6	6.0	8.0
15	F	24	1.65	54.5	11.0	9.0
16	F	38	1.48	50.0	13.0	10.0
17	F	23	1.68	53.2	5.0	7.0
18	M	28	1.75	66.4	3.5	3.5
19	F	30	1.63	59.1	–	–
20	F	26	1.53	47.3	9.0	7.0
21	F	44	1.55	47.7	4.0	4.0
22	F	29	1.70	59.1	4.0	5.0
23	F	28	1.70	67.3	11.0	11.0
mean (std)	–	28.4±5.5	1.70±0.10	65.5±12.8	6.4±3.4	5.7±2.6

maximize the EMG amplitude for each subject without exceeding the capacity of the A/D converter (±10 V).

2.2.3. Electrical stimulation

For *Experiment 2*, single pulses of supramaximal electrical stimulation (1-ms square pulses; 150 V maximum output, Grass 8800 Constant Voltage Stimulator, Astro-Med Inc., West Warwick, RI) were used to elicit electrical (M-waves) and mechanical (twitch torques) responses in both biceps brachii and BR. A supramaximal level of stimulation was obtained by increasing stimulus intensity until no further increase in the size of the M-wave was noted. Biceps brachii responses were obtained by stimulating the musculo-cutaneous nerve just proximal to the innervation zone of this muscle. BR responses were obtained by stimulating the radial nerve on the lateral aspect of the arm, just proximal to the elbow. For both biceps brachii and BR, a transcutaneous bipolar stimulation electrode (8 mm diameter, 29 mm inter-electrode distance) was used.

2.2.4. Skinfold thickness

As a difference in the thickness of the skin layer between different individuals could lead to a corresponding difference in the frequency content of EMG signals [3], skinfold thickness was measured over both the biceps brachii and BR muscles with a skinfold caliper.

2.3. Procedures

2.3.1. Experiment 1

In the first set of experimental sessions, subjects were asked to perform voluntary isometric ballistic contractions at different target torque levels. First, they performed two to three maximum voluntary contractions (MVC) in elbow flexion, each lasting about 3–5 s. A 2-min rest period was allowed between each MVC. The highest torque level recorded during these MVCs was used to calculate the submaximal target torque levels. Subjects were then instructed to perform a series of ballistic contractions, i.e., reach the target torque as fast as possible and then relax completely, at the following target levels: 20, 40, 60 and 100% MVC. The target torque levels (line displayed on an oscilloscope placed in front of the subject) were introduced in a random order. A series of 10 trials was recorded for each target level, from which the fastest trial was chosen for later analysis. Fig. 1 (top panel) shows the EMG and torque signals obtained during a single 60% MVC trial.

2.3.2. Experiment 2

For the second set of experimental sessions, a series of M-waves and twitch torques were elicited, in turn, from both the biceps brachii and BR muscles, with the subject resting and with a 15% MVC background voluntary isometric elbow flexion contraction. The 15% MVC condition was implemented to take up some of the slack in the muscle (series-elastic components) prior to stimulation. For each condition, a series of four to six pulses were delivered to the respective muscles. For a given set of responses, a mean of the two to three best responses was taken and used in the correlation analyses (see below). The criteria used to choose the two to three responses to be averaged were maximal M-wave amplitude and responses without irregular increases in torque. Fig. 1 (bottom panel) shows a single M-wave and twitch torque obtained from the BR muscle of a subject at rest.

2.4. Data analysis

For both experiments, elbow flexion torque was sampled at 2000 Hz and saved on computer for later

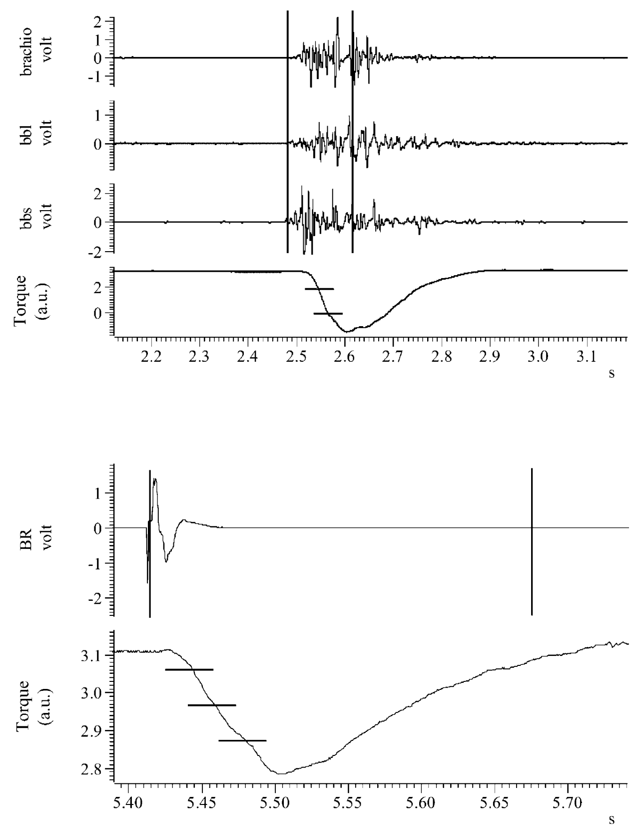

Fig. 1. Typical data set from *Experiment 1* (top panel) and *Experiment 2* (bottom panel). For *Experiment 1*, frequency analysis was performed on a 64-ms window (vertical lines, top panel) taken from the onset of EMG signals from the biceps brachii short (bbs) and long (bbl) heads and brachioradialis (brachio). The rate of rise in torque was calculated as the slope of a regression line fitted through the torque data between 30 and 70% of peak torque for a given trial (horizontal lines on torque trace, top panel). For *Experiment 2*, frequency analysis of EMG signals (biceps brachii long and short heads and brachioradialis (BR, shown) M-waves) was performed on a 0.25-s window (vertical lines, bottom panel). The rate of rise in torque was calculated for segments of 10–40%, 40–70% and 10–70% of peak torque for a given trial. Torque is shown in arbitrary units on both panels.

analysis. EMG signals were sampled at 2000 Hz for *Experiment 1* and 5000 Hz for *Experiment 2*. A higher sampling rate was used for the M-waves in order to have access to more data points when performing frequency analysis on such a short event.

For *Experiment 1*, frequency analysis of EMG signals (256 points, raised cosine window, fast Fourier transform) was performed on a 128-ms window taken from the onset of a given contraction (see Fig. 1, top panel). The MPF and MF were calculated from the obtained power spectrum for each of BBS, BBL and BR. The rate of torque development was calculated between 30 and 70% of the peak torque for a given ballistic contraction to eliminate the slower rising and leveling-off portions of the contraction (Fig. 1, top panel). This was accomplished by fitting a linear regression line through the torque data points and taking the slope of this regression line as the rate variable. To allow comparison of rate between different subjects, the rate of torque development was expressed in % MVC/s.

For *Experiment 2*, frequency analysis of EMG signals (1024 points, raised cosine window, fast Fourier transform) was performed on a 250-ms window taken from the onset of a given M-wave (Fig. 1, bottom panel) from which the MPF and MF were calculated. The rate of torque development for the corresponding twitches was calculated for three different torque segments: 10–40%, 40–70% and 10–70% MVC. This was also accomplished by fitting a linear regression line through the torque data points and taking the slope of this regression line as the rate variable (% MVC/s).

Pearson product-moment correlation analyses were performed to evaluate the association between pairs of variables of interest, but mostly between the MPF or MF and the rate of torque development. Analyses of variance (ANOVAs) for repeated measures were also used to test the significance of differences in MPF/MF and rate of torque development across the different target torque levels in *Experiment 1*. A level of significance of 0.05 was chosen for the statistical analyses, with p values between 0.05 and 0.10 also shown for correlations.

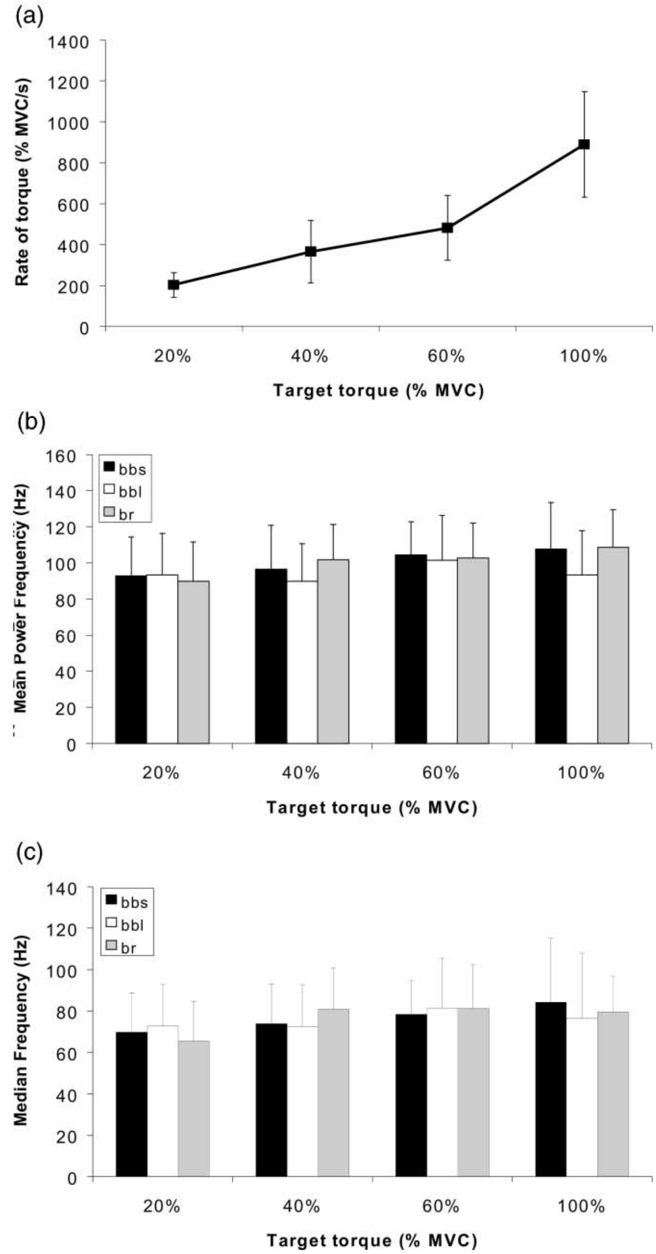

Fig. 2. Mean±standard deviation data ($n = 14$) of the rate of torque development (top panel), mean power frequency (middle panel) and median frequency (bottom panel) plotted against the four target torque levels for *Experiment 1*. Mean power frequency and median frequency data shown for the biceps brachii short (bbs) and long (bbl) heads and for brachioradialis (br).

3. Results

3.1. Experiment 1

The rate of torque development progressively increased across increasing target torque levels ($p < 0.05$; Fig. 2). Both MPF and MF of BR increased with target torque ($p < 0.05$), whereas for the biceps brachii, only the MPF of BBS increased significantly across target torque levels (Fig. 2).

Significant positive associations were observed between MPF or MF and the rate of torque development for all muscles studied (Tables 2 and 3, Fig. 3). Correlation coefficients were lower for the MF in general. Higher correlations were obtained for the biceps brachii at low target torque levels (20–40% MVC), whereas they were obtained at higher target torque levels for the BR (40–60% MVC). No significant correlations were

Table 2
Correlation coefficients obtained between the rate of torque development and the mean power frequency of biceps brachii (short and long heads) and brachioradialis at different target torque levels (*Experiment 1*); $*0.05 < p \leq 0.10$; $**p \leq 0.05$

	20%	40%	60%	100%
bbs	0.53*	0.65**	0.24	0.10
bbl	0.72**	0.25	0.42	0.03
br	−0.43	0.47*	0.56**	0.29

Table 3
Correlation coefficients obtained between the rate of torque development and the median frequency of biceps brachii (short and long heads) and brachioradialis at different target torque levels (*Experiment 1*); $*0.05 < p \leq 0.10$; $**p \leq 0.05$

	20%	40%	60%	100%
bbs	0.47*	0.60**	0.08	0.05
bbl	0.55**	0.28	0.34	0.09
br	−0.44	0.40	0.43	0.11

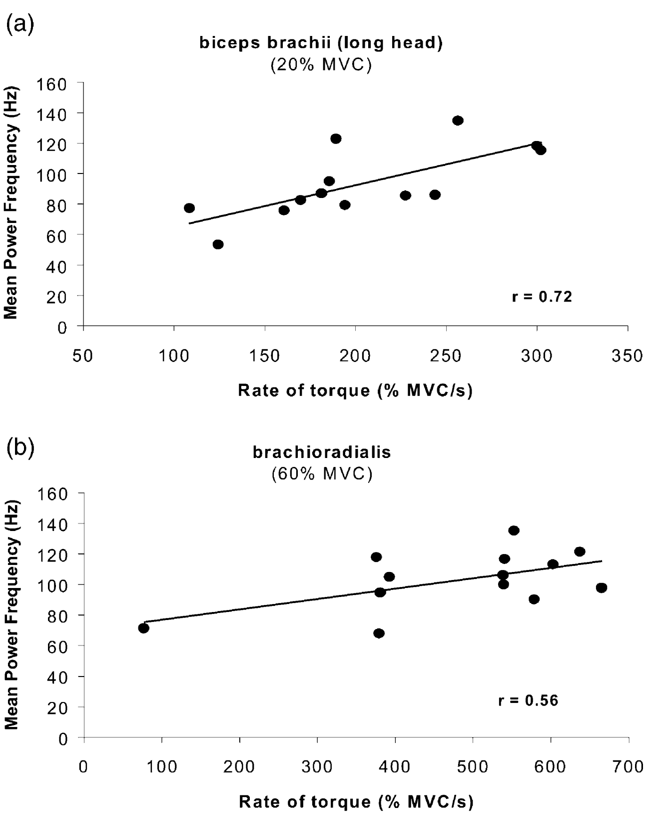

Fig. 3. Scatter plots of the relationship between the rate of torque development and the mean power frequency of the biceps brachii long head (top panel, data obtained for the 20% MVC target torque level) and the brachioradialis (bottom panel, data obtained for the 60% MVC target torque level) obtained in *Experiment 1*.

Table 4
Correlation coefficients obtained between the rate of torque development and the mean power frequency of biceps brachii (short and long heads) and brachioradialis M-waves for the three torque segments analyzed in *Experiment 2*. Data are presented with M-waves and twitches elicited at rest (*rest*) and with a low-force background contraction (*15% MVC*); $*0.05 < p \leq 0.10$; $**p \leq 0.05$

	Rate 10–40% MVC	Rate 40–70% MVC	Rate 10–70% MVC
bbs rest ($n = 10$)	−0.12	−0.03	−0.07
bbs 15% MVC ($n = 8$)	−0.58	−0.64*	−0.61
bbl rest ($n = 10$)	0.05	0.12	0.09
bbl 15% MVC ($n = 8$)	−0.15	−0.20	−0.18
br rest ($n = 12$)	−0.49*	−0.57**	−0.57**
br 15% MVC ($n = 10$)	−0.55*	−0.56*	−0.58*

obtained with the maximal ballistic efforts (100% MVC).

3.2. *Experiment 2*

Tables 4 and 5 present the results of the correlation analysis performed on the elicited contractions. Significant negative associations were observed between the rate of torque development and the MPF of the BBS and BR muscles (Fig. 4). For the BBS, no significant associations were observed with the muscle at rest. No significant correlations were obtained for the MF.

In eight subjects, data were available from both volun-

Table 5
Correlation coefficients obtained between the rate of torque development and the median frequency of biceps brachii (short and long heads) and brachioradialis M-waves for the three torque segments analyzed in *Experiment 2*. Data are presented with M-waves and twitches elicited at rest (*rest*) and with a low-force background contraction (*15% MVC*); $*0.05 < p \leq 0.10$; $**p \leq 0.05$

	Rate 10–40% MVC	Rate 40–70% MVC	Rate 10–70% MVC
bbs rest ($n = 10$)	0.37	0.41	0.40
bbs 15% MVC ($n = 8$)	−0.18	−0.22	−0.20
bbl rest ($n = 10$)	−0.06	0.05	0.01
bbl 15% MVC ($n = 8$)	−0.27	−0.32	−0.30
br rest ($n = 12$)	−0.28	−0.32	−0.36
br 15% MVC ($n = 10$)	−0.37	−0.45	−0.46

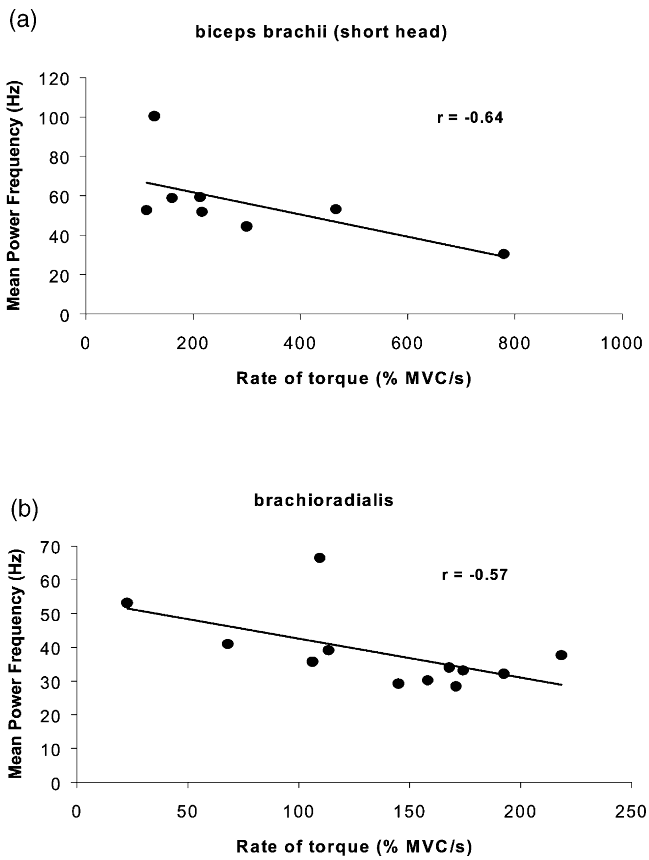

Fig. 4. Scatter plots of the relationship between the rate of torque development and the mean power frequency of the biceps brachii short head (top panel) and the brachioradialis (bottom panel) obtained in *Experiment 2*. Data from the biceps brachii were obtained with a background contraction of 15% MVC and the rate of torque was calculated between 40 and 70% of peak torque. Data from the brachioradialis was obtained with the muscle at rest and the rate of torque was calculated between 10 and 70% of peak torque.

tary ballistic contractions and electrically elicited contractions. Therefore, we performed additional correlation analyses to assess the relationship between the voluntary and elicited contractions for MPF and rate of torque development. In general, stronger positive associations were found between the two contraction types for the rate of torque development compared to the MPF (Fig. 5). However, none of these correlations reached significance.

Because the rate of torque development was expressed as a percentage of the MVC torque, we tested for a potential significant association between MVC torque and MPF or MF. No significant correlation was found between these variables. Also, no significant correlation was found between skinfold thickness and the MPF or MF of either muscle. Skinfold thickness presented with relatively low values and did not vary greatly between subjects (Table 1).

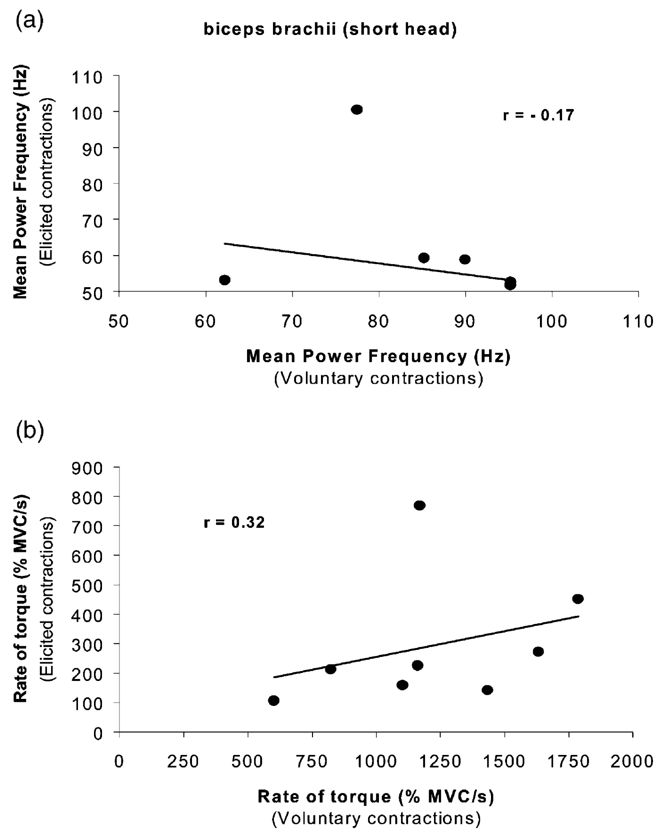

Fig. 5. Top panel: scatter plot of the relationship between the mean power frequency obtained during fast voluntary and electrically elicited contractions in subjects involved in *Experiment 2*. Bottom panel: scatter plot of the relationship between the corresponding rates of torque development during the fast voluntary and electrically elicited contractions (between 10 and 70% of peak torque) in the same subjects.

4. Discussion

The main results of this study were the presence of: (1) significant positive correlations between the MPF of biceps brachii and BR and the rate of torque development in voluntary ballistic isometric contractions; and (2) significant negative correlations between MPF and rate of torque development for electrically elicited isometric contractions.

4.1. Voluntary contractions

For the voluntary contractions, we observed an increase in the rate of torque development with increasing target torque level. Such an increase has been reported by others. For example, Freund and Budingen [9] found a linear increase in the rate of rise in force with the amplitude of the given contraction for three hand muscles. A significant increase with target torque was also observed for the MPF and MF of BR and the MPF of BBS. A shift in the EMG power spectrum towards high frequencies with increasing force/torque has been observed for several muscles [3,4], including elbow flexor muscles [2,24], in slowly increasing contractions. The increase in MPF/MF is thought to reflect the recruitment of larger diameter muscle fibers with increasing force/torque [25].

A positive relationship between MPF (or MF) and the rate of torque development was expected because muscle fiber composition has been shown to influence both the frequency content of EMG signals and the speed of contraction. Muscles with a higher content or larger area of type II fibers are associated with a higher frequency EMG content and thus higher MPF or MF values [10–12,17]. This is most likely due to the higher conduction velocity observed in muscles showing a greater relative area of type II fibers [23]. Several authors also report a significantly greater rate of tension development or a shorter time to peak tension in fast-twitch (comprising type II fibers) compared to slow-twitch (comprising type I fibers) motor units [13,21], or in muscles with a higher type II fiber content [6–8,22,26]. Therefore, the positive association between the MPF and the rate of torque development in the present student could be explained by the simultaneous effect of fiber type composition on EMG and torque rate variables. In general, higher correlations between MPF and rate of torque development were obtained for the biceps brachii muscle at low target levels (20–40% MVC), whereas higher correlations were obtained at higher target levels (40–60%) for the BR muscle. This could reflect a varying contribution of these muscles to elbow flexion torque for the different target levels. Also, the fact that no correlations were obtained for the maximum ballistic contractions could be related to the observation of Desmedt and Godaux [8], who report no difference in contraction speed between the soleus, masseter and first dorsal interosseous muscles for high force voluntary ballistic contractions. However, a shorter time to peak tension for the later two muscles, which is in line with their fiber type composition compared to the slower soleus, was observed for ballistic contractions performed at lower forces. They explained these observations by the potentially greater influence of the central command for the first dorsal interosseous and masseter muscles to produce high versus lower force levels.

4.2. *Electrically elicited contractions*

In contrast, significant negative correlations were obtained between MPF and the rate of torque development for the electrically elicited contractions. This finding was against our initial hypothesis, as a stronger (and positive) association between the electrical and mechanical variables was expected for electrically elicited contractions, because the potential confounding influence of the voluntary command on the rate of torque development [8,9,18] would not be present. The present difference in the data obtained between voluntary and elicited contractions could be due to differences between the two types of contractions in the rate of tension development, the frequency content of EMG signals or a combination of both. As mentioned above, variations in the voluntary command can affect the rate of torque development. Laframboise and Cafarelli [18] report a different range of values in maximal rate of torque development for voluntary versus elicited contractions. Because they found no difference in the maximal rate of torque development between the quadriceps (about 50/50% type I/II fiber composition) and the adductor pollicis (predominance of type I fibers) muscles with elicited contractions, they conclude that in humans, motor units of different types may have the same contractile speed. However, the adductor pollicis was slower than the quadriceps with ballistic voluntary contractions, suggesting a significant role of the central nervous system (central command) in determining the rate of torque development in certain muscles. The potential confounding effect of variations in the rate of torque development across different conditions was also evidenced by the present results obtained with the muscles at rest versus with a 15% MVC background contraction. In this case, it appears that taking up some of the slack in the series-elastic component of the muscle allowed for higher correlations to be observed with the biceps brachii muscle.

The frequency content of EMG signals during elicited contractions will be determined by the shape of the M-wave, which is the sum of action potentials from all muscle fibers in the detection area of a given electrode pair. In the present study, supramaximal levels of stimulation were used and therefore all the fibers of the respective muscles should have been activated. In comparison, even though the shape (and duration) of the recorded action potentials will remain a major determinant with regards to the frequency distribution of the EMG power spectrum [15,25], other factors (e.g., motor unit synchronization) could also influence the value of the MPF or MF. In both types of contraction, differences in the thickness of the skin layer between different subjects could cause differences in the frequency content of EMG signals [3]. However, the skin layer over both biceps brachii and BR was found to be relatively thin and varied only minimally across subjects. In addition, no significant correlations were found between skinfold thickness and the value of the MPF or MF for either muscle. Therefore, we believe that this factor did not contribute significantly to the between-subject variability in MPF/MF values, and that different MPF/MF values most likely reflect differences in fiber composition/size between different individuals. In subjects who had data for both voluntary and electrically elicited contractions (e.g., Fig. 5), no significant correlations were found between both contraction types for either the MPF or the rate of torque development. This suggests that the different (opposite) results obtained in elicited versus voluntary contractions in the present study were most likely due to variations in both MPF and torque rate between the two conditions.

As for the negative correlations between MPF and torque rate found for the elicited contractions, no obvious explanation became apparent. However, such findings point to the contribution of factors other than those related directly to fiber type composition in determining the EMG frequency content and/or speed of contraction of a muscle [1,16], and that the contribution of these factors will vary between voluntary and elicited contractions.

4.3. MPF versus MF

Finally, significant associations between the rate of torque development and EMG variables were obtained mostly for the MPF and to a lesser extent for the MF (Tables 2 and 4 versus 3 and 5). This could reflect the different sensitivity of the two statistics to physiological factors such as muscle fiber conduction velocity [5], which in turn could reflect the differential effect of the high frequency region of the power spectrum on those statistics [3,14].

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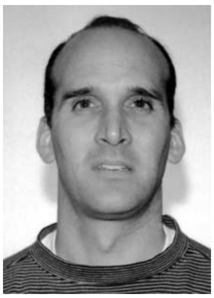

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