Neuromuscular responses to explosive and heavy resistance loading

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Abstract

The EMG power spectrum may shift towards higher frequencies with higher movement velocities. Fatigue, on the other hand, can cause a decrease in the frequency components. The purpose of this study was to examine acute effects of explosive (EE) and heavy resistance (HRE) concentric leg press exercise on muscle force, EMG and blood lactate. The EE included five sets of ten repetitions with $40\pm6\%$ of the isometric maximum at a $100°$ knee angle performed as explosively as possible. The same number of repetitions was performed in HRE but with a heavier load ($67\pm7\%$ of the isometric maximum at a $100°$ knee angle). Maximal isometric and single concentric actions of different loads, and an isometric fatigue test were measured before and after both exercises. Surface EMG was recorded from the vastus medialis muscles for analyses of average EMG (aEMG) and EMG power spectrum. Muscle fiber composition of the vastus lateralis was determined and blood lactate measured throughout the exercises. Mean power frequency and median frequency were higher during EE than during HRE ($P<0.05$). They increased during EE ($P<0.05$) as the exercise progressed, whereas during HRE no change or even slight decreases were observed. Signs of fatigue after pure concentric work were not observed after EE, and even after HRE, possibly due to the relatively small range of motion and short duration of action time, the fatigue was not that extensive. The relative number of fast twitch fibers was correlated ($r=0.87$, $P<0.05$) with the change in blood lactate in HRE. It was concluded that there may be a greater use of fast twitch motor units in explosive movements and that instead of fatigue, the present number of concentric actions in explosive exercise seems to have facilitated the neuromuscular system. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Intensive muscular work leads to fatigue which can depend on the type of the loading [18,21], the amount and intensity of the load [17,24], the fast/slow fiber composition of the exercised muscle [40], and the specificity of the athletic background [16]. Exercise-induced fatigue leads to decreased strength output accompanied by decreases in electromyographic activity measured from the muscles in maximal voluntary conditions [17,18,24], although momentary increases in maximal EMG activity during the very first repeated maximal contractions are also possible in some situations [4]. Fatigue also leads to a shift in the EMG power spectrum towards lower frequencies [2,19]. Frequencies of the EMG power spectrum are related to the average conduction velocity of the active muscle fibers [2] and muscle fiber conduction velocity is higher for fast twitch fibers [1]. There is evidence that a high relative number of fast twitch fibers results in higher frequency values of the EMG power spectrum [11,26] and that the shift during fatigue is generally greater with subjects possessing a greater relative number of fast twitch fibers [19,42]. Increased post exercise blood lactate concentration seems to be related to the type and the amount of loading [15,17,24], to the duration of work and rest periods [31], as well as to the relative number of fast twitch fibers [38,43]. During explosive exercise with short working periods and maximal movement velocity fatigue may be more of central

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origin, whereas during heavy resistance exercise fatigue may be both central and peripheral [24].

Besides fatigue studies, the EMG power spectrum has also been used to study changes in muscle activation at different movement velocities. The shift of the EMG power spectrum towards higher frequencies with higher movement velocities has been suggested to be due to a difference in activation pattern with greater use of fast units [29,37]. However, when comparing dynamic actions with different intensities, changes in mean power frequencies and median frequencies varied between subjects [10]. Besides movement velocity, the type of action may have an effect on the activation pattern. In the submaximal situation during eccentric actions the fast motor units could be preferentially recruited, whereas in concentric actions the slow units may be recruited first then followed by the fast ones [30].

To examine if more intensive concentric actions would cause any changes in activation pattern two strenuous but different type leg exercises were chosen. Besides looking at different movement velocities it was also of interest to study the fatiguing effects of the two exercises. High movement velocities, as used in explosive exercises, could cause a shift of the EMG power spectrum towards higher frequencies as compared to lower movement velocities if the fast motor units are being preferentially recruited. Should this be the case then during fatigue in the explosive exercise in which a decrease in the median frequency is to expected because fast units also fatigue more easily. On the other hand more substantial peripheral fatigue in heavy resistance exercise may lead to a decrease in the muscle fiber conduction velocity thus causing a decrease in the median frequency.

The purpose of this study was to examine (1) the acute effects of explosive and heavy resistance concentric leg press exercise on the EMG power spectrum, aEMG, force production, and on the blood lactate concentration and (2) to see how these changes are related to fiber type distribution.

2. Methods

2.1. Subjects

Eight young adult men volunteered as subjects for the study. The mean (±SE) age, weight and body mass were 27.1±0.7 yr, 74.4±3.2 kg, and 181.3±1.1. The subjects were physically fit and actively took part in various physical activities but had no background in regular strength training or competitive sports of any kind. Full advice about possible risks and discomfort was given to the subjects and all the subjects gave their written informed consent to participate. The study was conducted according to declaration of Helsinki and was approved by the Ethics Committee of the Southern Cross University.

2.2. Experimental design

The experiment was cross-over in design to assess two different leg press exercises: 1, Explosive Exercise (EE) and 2, Heavy Resistance Exercise (HRE). The two exercises were performed separately so that there was a recovery period of at least two weeks after the explosive exercise, which was administered first. The subjects were allowed to continue their normal physical activities throughout the experimental period but were instructed to have a full day of rest preceding the testing sessions.

2.3. Explosive exercise (EE)

The EE protocol consisted of 5×10 repetitions of bilateral concentric leg extensions on an inclined leg press machine (Kolossal, Sydney) with a hip angle of 110°. The subjects extended their legs from a starting position of a 100° knee angle to full extension as fast as possible. The computer controlled braking system caught the press and lowered it [44] so that the subjects did not perform any eccentric work. During EE the weight corresponded to 40±6% of the isometric maximum at a 100° knee angle. A rather large starting knee angle was chosen so that the subjects were able to perform explosive actions effectively. The recovery period between the sets was one minute.

2.4. Heavy resistance exercise (HRE)

The HRE was performed using the same protocol and apparatus as EE and the number of sets and repetitions was the same in both exercises. However, in HRE extra weights were added so that the loads for the first set corresponded to about 70% (67±7%) of the isometric maximum at a 100° knee angle. During HRE weights were either added or removed so that the subject was always able to just finish the required ten repetitions.

2.5. Measurements

Maximal isometric force and the forces during the concentric actions were determined using a Kistler force platform (Type 9287, Kistler, Switzerland) which was fixed to the leg press. One maximal bilateral isometric leg extension followed by three single concentric actions with submaximal loads of 40%, 55% and 70% of the isometric maximum at a 100° knee angle were performed. An isometric fatigue test was administered before and after the actual exercise. In the isometric fatigue test subjects started at the force level of 10% MVC holding the force on the required target which was displayed on the computer screen. The target force was increased after

every tenth second by increments of 10% until the subject was no longer able to maintain the required force level. A ten second work period was always followed by a five second rest period. All the isometric actions were performed with a knee angle of 120°.

The force was recorded on a computer system (Amlab software, Amlab International, Australia) with a sampling frequency of 1 kHz. Maximal peak force (N), average force (N) and the maximal rate of rise of force production (N/s) were calculated both in isometric and in dynamic actions.

A rotary encoder (Omron Corporation, Japan) which was attached to the press and interfaced with the computer measured the position of the leg press apparatus. This allowed us to calculate the time of the movement.

Electromyographic activity (EMG) was recorded from the vastus medialis (VM) muscles of both legs with silver/silver chloride surface electrode modules. Each electrode module consisted of two active electrodes and a third reference electrode, all equidistant at 2 cm. The active electrodes were aligned parallel with the fibers halfway between the estimated center of the innervation zone and the distal tendon. The position of the electrodes was then marked carefully on the skin to ensure the same electrode location in both exercises Before electrode application, each site was shaved, abraded and cleansed with alcohol to reduce the impedance between each electrode pair. Preamplifiers (Quantec, Brisbane, Australia) were incorporated into the electrode modules with the signal being further amplified with amplifiers (Quantec, Brisbane, Australia) at a low-pass filter setting of 1 kHz and a high-pass at 3 Hz. EMG signals were recorded with the Amlab software system at a sampling frequency of 1 kHz. To calculate average EMG (aEMG) the signal was fully rectified and average amplitude of the signal was calculated over the chosen time period. In both conditions (isometric and concentric) the comparison was made only with the action used in the exercise. Thus the condition itself was its own control and reference and always for the same joint angle (isometric) or range of motion (concentric). This was to avoid the effects that electrode movement in relation to innervation zone may cause to the signal. For the EMG power spectrum to analyze the same range of motion, windows of 128 and 256 points were used in explosive and heavy resistance concentric actions, respectively, and a window of 1024 points in isometric actions for fast Fourier transformation (FFT) to obtain median frequency (MF) and mean power frequency (MPF) (Mega Electronics, Kuopio, Finland). In dynamic actions the window was placed at the start of the movement, and in maximal isometric actions the window was placed at the plateau phase of the peak force. During the isometric fatigue test the window was placed at the midpoint of each ten second work period.

A canula was inserted into the antecubital vein of each

subject before the exercise. Blood was subsequently drawn before the exercises, and after the second, fourth and last sets in both exercises and analyzed using a YSI 1500 Sport L-lactate Analyser (Yellow Springs Instrument Co, Ohio, USA)

Muscle biopsies were obtained from the vastus lateralis muscle from six subjects by a standard procedure involving a double-chop and suction method [3,9]. Muscle fibers were then aligned, mounted on small pieces of cork, frozen in isopentane pre-cooled in liquid nitrogen, and stored at −80°C for later analysis. Standard histochemical analysis was performed to determine fiber type distribution [6,12]. Muscle samples were serially cross-sectioned (10 μm) and mounted on cover slips. Samples were assayed for mATPase activity after pre-incubation either at pH 4.34 (1.5–2 minutes, 25°C) or pH 10.3 (5–7 minutes, 37°C). In addition, other samples were also stained for NADH-tetrazolium reductase [13]. Samples were then mounted on slides (Aquamount, BDH Laboratories, Poole, England) and photographed (Olympus BH-2 Imaging System, Olympus America Inc., Melville, USA). Fiber typing was performed by manually counting approximately 100 (90–153) fibers for each sample and then cross-referencing the pH 4.34, pH 10.3 and NADH stained samples to determine the proportion of type I to type II fibers.

2.6. Statistical methods

Conventional statistical methods were used for calculation of means, standard errors (SE) and coefficient of correlation. In concentric actions the average of the 2nd, 3rd and 4th repetitions of the first set, and the average of the 4th, 5th and 6th repetitions of the 2nd, 3rd and 4th sets and the average of the 7th, 8th and 9th repetitions of the fifth set were used for further analyses. The data were then analyzed utilizing multiple analysis of variance (MANOVA). When appropriate, comparisons of means were performed by Student's paired t-test.

3. Results

The average time of one concentric repetition was 347 ms in EE and 670 ms in HRE, and corresponding average forces were 1121 N and 1556 N, respectively. The average power was approximately 39% higher during EE than during HRE. During HRE the average time of one concentric repetition increased by 11.6±4.4% ($P<0.05$) from the first set to the last set, while there was no change during EE (Table 1). No significant changes were observed in peak force, maximal rate of force production or average force from a 100° to 180° knee angle during concentric actions of either exercise (Table 1).

During concentric actions of EE, as the exercise progressed, there was a shift of the EMG power spectrum

Table 1
Force characteristics (±SE) during concentric actions of explosive exercise (EE) and heavy resistance exercise (HRE) and their relative changes (Δ%)

		Maximal peak force	Maximal rate of force production	Average force 100°–180°	Repetition time 100°–180°
EE	1st set	1307±41 N	11485±905 N/s	1118±27 N	345±111 ms
	5th set	1266±47 N	11575±877 N/s	1125±28 N	350+117 ms
	Δ%	−3.2±1.7%	3.0±7.7%	0.8±1.8%	1.4±1.8%
HRE	1st set	1790±89 N	9529±1221 N/s	1595±72 N	638±129 ms
	5th set	1703±90 N	8972±823 N/s	1517±76 N	704±119 ms
	Δ%	−4.5±3.3%	1.4±12.9%	−4.6±3.7%	11.6±4.4%*
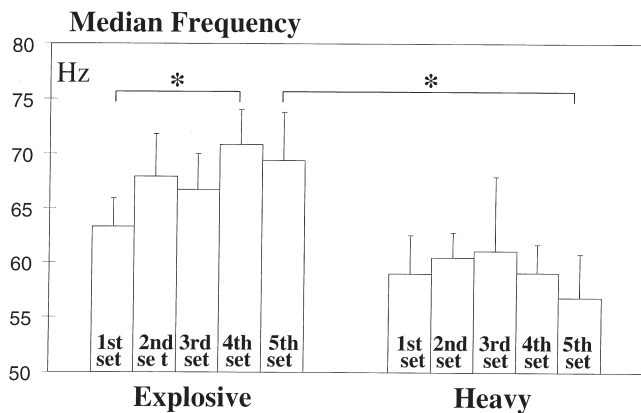
Median Frequency

Fig. 1. Median frequency (±SE) during explosive and heavy resistance exercise.

towards higher frequencies. Compared to the first set the highest MF value in EE was found in the fourth set ($P<0.05$), whereafter it decreased slightly (Fig. 1). During HRE, MF was lower compared to EE and decreased slightly (NS) towards the end of the exercise so that the difference compared to the fifth set of EE was significant ($P<.005$) (Fig. 1). No significant changes were found in aEMG between any sets either from a 100° to 120° or from a 100° to 180° knee angle (Fig. 2).
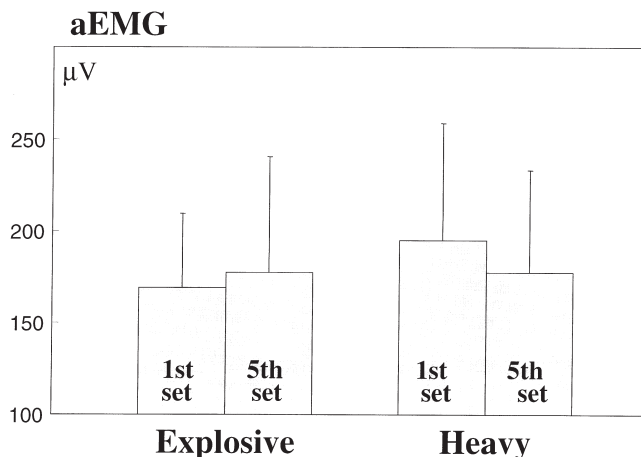
aEMG

Fig. 2. aEMG (±SE) during the first and the fifth set of explosive and heavy resistance exercise.

No significant differences were found in either single submaximal concentric actions or the maximal isometric action for peak force, maximal rate of force production, aEMG, MF and MPF in either exercise or between the exercises. Table 2 summarizes the changes in isometric actions. In the isometric fatigue test aEMG and MF were almost the same before and after the exercise in each percentage level of MVC during EE. The same was true for HRE, although an increasing (NS) trend was observed (Fig. 3 and Fig. 4).

Blood lactate increased from 1.00±0.22 to 3.09±0.55 mmol/l during EE ($P<0.05$) and from 0.79±0.09 to 4.95±0.81 mmol/l during HRE ($P<0.01$). The increase during HRE was significantly greater ($P<0.05$) than that of EE (Fig. 5) and was correlated significantly with the change in MPF in HRE ($r=-0.73$, $P<0.05$).

The percentage of fast twitch fibers ranged from 34.4% to 64.9% (Table 3). The relative number of fast twitch fibers was correlated significantly with the change in blood lactate in HRE ($r=0.87$, $P<0.05$), while in EE it was not significant ($r=0.70$, $P=0.118$). No significant correlations between the relative number of fast twitch fibers and MF or MPF were found before or after either exercise, although MF was somewhat lower after HRE ($r=-0.72$, $P=0.105$)

4. Discussion

The present data showed that the signs of fatigue in both loadings were much smaller than could be expected based on another study between heavy resistance and explosive leg extension exercise with the same number of sets and repetitions [24]. During EE there was hardly any change or in some occasions a small increase in the force parameters, and even during HRE the decreases were not that large. The same can also be seen in the increase in blood lactate concentration in HRE which was extremely low as compared to previous studies of heavy resistance protocols [15,22,24,39]. Although 5×10 RM was used as previously [24], the small changes in HRE may be explained by (1) a small range of motion and consequently short duration of action time, (2) lack

Table 2
Force characteristics, aEMG (500–1500 ms) and MF in maximal isometric actions (±SE) before and after explosive exercise (EE) and heavy resistance exercise (HRE) and their relative changes (Δ%)

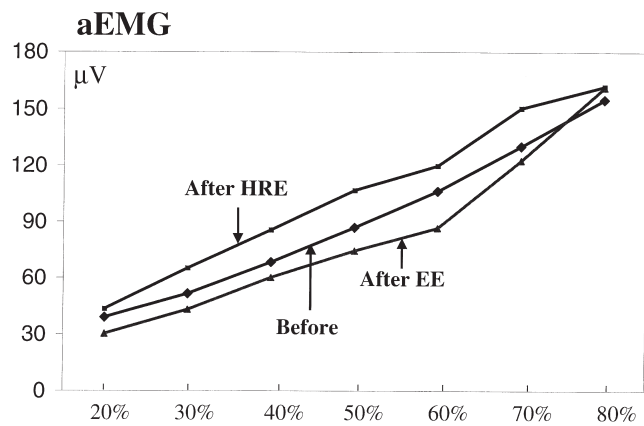|		Maximal peak force	Maximal rate of force production	aEMG 500–1500 ms	Median frequency
EE	Before	2630±228 N	18440±2779 N/s	128±35 μV	55.7±4.6 Hz
	After	2479±184 N	17942±2167 N/s	119±37 μV	58.0±2.8 Hz
	Δ%	−4.2±3.9%	−4.2±13.4%	−5.6±10.1%	4.2±5.5%
HRE	Before	2660±215 N	20270±3233 N/s	139±43 μV	54.0±2.8 Hz
	After	2482±197 N	15930±1698 N/s	134±46 μV	57.2±2.9 Hz
	Δ%	−5.7±4.1%	−11.9±12.2%	−8.3±10.5%	6.8±5.8%

Fig. 3. aEMG during the isometric fatigue test before and after explosive and heavy resistance exercise. The before curve represents the average of both EE and HRE curves, which were not significantly different from each other.
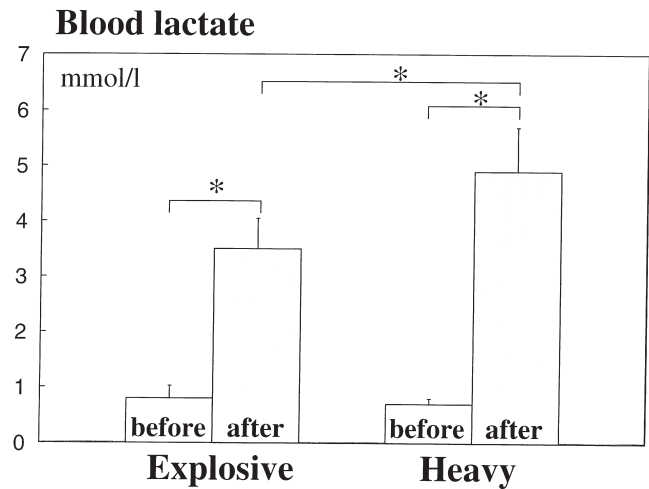

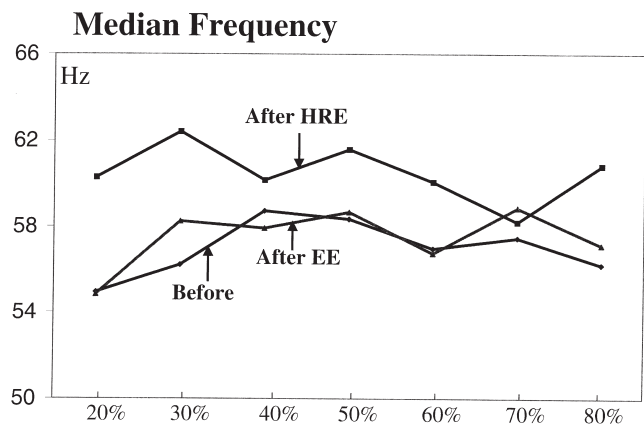Fig. 5. Blood lactate (±SE) before and after explosive and heavy resistance exercise.

Fig. 4. Median frequency during the isometric fatigue test before and after explosive and heavy resistance exercise. The before curve represents the average of both EE and HRE curves, which were not significantly different from each other.

Table 3
Percentage of fast twitch fibers in each subject

Subject	Fast twitch fibers
1	64.0%
2	39.3%
3	64.9%
4	34.4%
5	40.2%
6	34.6%

of eccentric work and (3) by a constant resistance leg press that was used in this study.

During fatigue a shift of the EMG power spectrum towards lower frequencies has been observed both in isometric (e.g. [2]) and in dynamic situation (e.g. [19]). The data during HRE support these findings, while during EE instead of decreasing, MF and MPF actually increased. The frequency component of the power spectrum has been found to be well correlated with the muscle fiber conduction velocity [2], which is higher in fast units [1]. Previously it has been suggested that a decrease in conduction velocity is related to proton [H$^+$] accumulation [23] and it has been shown that lactate concentration is correlated to the mean power frequency [38,43]. A negative correlation with the change in MPF and blood lactate was also found in the present study during HRE. It seems possible, however, that proton or

blood lactate accumulation is not primarily responsible for the spectral changes of surface EMG. Instead, an impairment of the excitation–contraction coupling has been suggested as a cause of the change [41]. During the isometric situation the change in conduction velocity to generate equal changes in the EMG power spectrum was much greater in the absence of fatigue than during fatigue and it was suggested that changes in the waveform of individual muscle fibers are not the sole contributor to the shift of the surface EMG frequency components [5].

Increased muscle temperature has been shown to affect the frequency component of the power spectrum [32]. The effect of increased temperature on maximal power was found to be the greatest at the highest pedaling rates in an isokinetic cycle ergometer [34], although it has been shown that MPF decreased due to cooling but remained unchanged with heating [14]. The total working time with the same rest periods was greater in HRE so muscle temperature could have increased even more during HRE than during EE. However, in HRE no increase in MF or MPF was observed but rather a trend to decrease. It may be possible that, besides increased temperature, there was also a learning effect. If the subjects were able to activate additional fast units in the course of the exercise, MPF and MF would also increase. Since no changes in aEMG were observed throughout either exercise, increase in muscle temperature may be a more likely explanation of why the decrease in MF and MPF during HRE was not more substantial and they actually increased during EE. Since MF was somewhat higher during the fourth set than during the fifth set in both exercises, it is likely that it would have decreased even more if additional sets had been used.

Higher movement velocity can be accompanied by changes in activation from slow muscle to fast muscle [27,35], and a shift of the EMG power spectrum towards higher frequencies [29,37]. Some previous studies have shown that a high relative number of fast twitch fibers may be related to high frequency values of the EMG power spectrum [11,26]. In the present study this relation could not be demonstrated, possibly due to the low number of subjects or to differences in electrode placement between subjects. The electrodes were placed halfway between the estimated center of the innervation zone and the distal tendon for all the subjects, but estimation was not based on electrical stimulation. Therefore it is possible that the distance between the innervation zone and the electrode was not the same in all the subjects which could affect the EMG power spectrum [33]. During concentric actions, although the forces were higher in HRE than in EE, MF and MPF were higher during EE. This could be due to a greater usage of fast units in the explosive situation, as speculated in some previous studies of different movement velocities [7,29,37]. In dynamic actions it is possible that the electrode may

change its location in relation to the innervation zone, which may affect the EMG power spectrum [33]. In the present study the range of motion was similar at all the velocities so the possible effects should be similar in both exercises. Another problem may be the low number of data points used for the FFT window, especially in EE, which can cause problems with the signal stationarity. Coefficient of variation expressed as percentages [CV%] [25] between the second and third repetitions of the first set was 8.7% for MF and 6.8% for MPF in EE, and 9.9% for MF and 7.0% for MPF in HRE. The low CV% for MF and MPF would indicate that even shorter FFT windows can be used in analyzing fast movements. It should be, however, carefully tested with larger numbers of subjects in the future.

The purpose of the single concentric actions with submaximal loads was also to examine the effect of movement velocity on MF and MPF. Possibly the single repetitions were not sufficient to fully activate the neuromuscular system since no changes in MF and MPF were observed. When comparing MF and MPF of single concentric actions between the two exercises no significant differences were observed, suggesting that the EMG power spectrum can be used even in measurements separated by several weeks. The idea of the isometric fatigue test was to examine whether a neuromuscular fatigue threshold as found in cycling [28] could be determined also in the isometric situation, and how it would be affected by two different loadings. No clear threshold could be determined in the isometric fatigue test and no remarkable changes before and after the loadings were observed. In EE there was not much change either in aEMG or in MF and MPF before and after the loading. In HRE, however, a trend to increase of both aEMG and frequency components of the power spectrum at submaximal levels was observed suggesting that after fatigue more muscle activation was needed to achieve the same relative force level as before fatigue [4]. In previous studies during stepwise increasing levels of force, an increase of MPF and MF of the power spectrum has been found [20,33], while there are also studies with no increase with the level of force [32,42]. In the present study there were no significant differences in MF and MPF between the force levels, but a trend of increase up to 40% MVC could be seen. According to De Luca et al. [8] when all the motor units have been recruited at some submaximal level the firing rate continues to produce the maximal force. Thereafter, since the average conduction velocity does not increase, further changes in the spectral frequencies may not be so pronounced [36]. Choosing a rather long period of work (10 s) for the determination of the neuromuscular threshold may have caused fatigue effects within each force step thus conflicting the results concerning the possible increase of MF and MPF with increasing force.

In conclusion, the present heavy resistance exercise

induced fatigue changes support the findings of the previous studies. However, fatigue effect as measured by changes in force, blood lactate and aEMG, was not that obvious, possibly due to a small range of motion and a relatively short action time, a lack of eccentric work and a constant resistance leg press used in this study. Explosive exercise, on the other hand, seemed to have facilitated the function of the neuromuscular system rather than producing fatigue. Median and mean power frequency increased during explosive exercise and were higher during rapid movements compared to slower movements. Therefore, it seems that during rapid movements an increased activation of fast motor units or decreased activation of the slow ones may occur.

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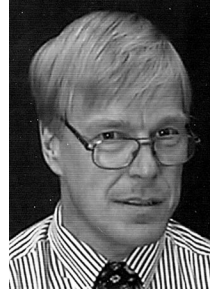

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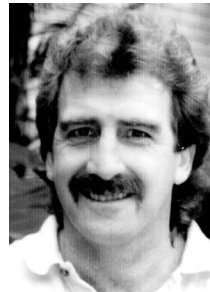
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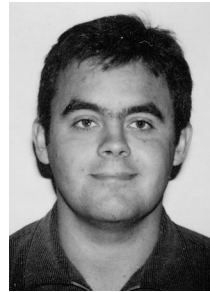
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