Eur J Appl Physiol (2002) 86: 534–540
DOI 10.1007/s00421-001-0563-3

ORIGINAL ARTICLE

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EMG power spectrum and features of the superimposed M-wave during voluntary eccentric and concentric actions at different activation levels

Accepted: 7 November 2001 / Published online: 1 March 2002

Abstract Muscle fiber conduction velocity (CV) may be affected by the level of voluntary activation and by the diameter of the fiber. Both the frequency component of the electromyography (EMG) power spectrum, such the as median frequency (MF) or mean power frequency, and the duration of muscle compound action potential to single supramaximal electrical impulse (maximal M-wave) may be related to CV. The aim of the present study was to examine how changes in the activation level in lengthening and in shortening conditions would affect the EMG power spectrum during voluntary effort, and compare them to changes in M-wave shape in similar conditions. Ten male subjects performed eccentric and concentric knee extensions at force levels of 40%, 60%, 80% and 100% of maximal eccentric and concentric knee extension force (maximum voluntary contraction, MVC) at an angular velocity of 2 rad·s^{-1}. In order to measure the M-wave at each force level and in a relaxed condition, a supramaximal electrical stimulus was given to the femoral nerve. The surface EMG was recorded from the vastus lateralis, vastus medialis, and rectus femoris muscles, and the average EMG (aEMG) and MF were calculated. The results show that although the absolute force was greater, the aEMG was generally lower in eccentric as compared to concentric actions at all of the force levels tested. Although the aEMG increased as force increased, no consistent differences were observed in the amplitude of the maximal M-wave in any of the conditions, or in the duration of the M-wave between eccentric and concentric actions. However, as the force level increased the duration of the M-wave decreased significantly ($P < 0.01$) for both eccentric and concentric actions. On average, no major differences were observed in MF between eccentric and concentric actions or between the force levels in either type of contraction, although rather large variations were observed throughout the motions. In voluntary situations, the recruitment of fast motor units with higher muscle fiber CVs and the increased firing rate of the active units increases the muscle fiber CV as the activation level increases. Even though in conditions of supramaximal electrical nerve stimulation all motor units should be activated simultaneously, the duration of the M-wave in the present study decreased as the force level increased. Possible candidates for the change in the CV may be increased activation of the Na^+/K^+ pump resulting from the activity in the muscle preceding the electrical stimulation and/or changes in the muscle fiber length between different force levels.

Keywords Muscle · Tension · Motor evoked potentials · Electrical conductivity

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Introduction

Although maximal eccentric force is higher than maximal concentric force (e.g., Doss and Karpovich 1965; Komi 1973; Westing et al. 1990), there is evidence that in maximal eccentric actions the muscles may not be utilized to their full capacity (e.g., Westing et al. 1990). The occurrence of a reduction in the amplitude of the average electromyogram (aEMG) observed during a single maximal eccentric action towards the end of the motion, but not during concentric action (Komi et al. 2000) would support the concept of inhibition, as suggested by Westing et al. (1990). The situation may, however, be different in submaximal conditions. Even though the electromyogram (EMG) activity associated with submaximal eccentric actions is lower compared to that associated with concentric actions (e.g., Christensen et al. 1995; Moritani et al. 1988; Muro et al. 1983), there is evidence that with low submaximal eccentric actions the high-threshold fast-twitch motor units may be recruited preferentially before the slow ones (Nardone et al. 1989). Whether this preferential recruitment also occurs at higher force levels is yet to be determined.

In an isometric situation, as the force level increases the smaller and slower units are recruited first, followed then by larger and faster units (Henneman et al. 1965). The additional increase in force observed after all of the motor units have been recruited is accomplished by increasing the firing rate of the active units (e.g., Deluca et al. 1982; Milner-Brown et al. 1973). Since muscle fiber conduction velocity (CV) is higher for fast-twitch fibers than for slow-twitch fibers (Andreassen and Arendt-Nielsen 1987) and the frequency component of the EMG power spectrum is related to the average CV of the active fibers (Arendt-Nielsen and Mills 1985), one would expect an increase in median frequency (MF) or in mean power frequency (MPF) to occur along with an increase in force. In an isometric situation, the results reported on the behavior of the EMG power spectrum with increasing force are, however, somewhat controversial. Some authors report increases in MF or MPF up to 60–80% of maximum voluntary contraction force (MVC; Bilodeau et al. 1990; Moritani and Muro 1987), others up to 25–60% of MVC (e.g., Bernardi et al. 1995; Gerdle et al. 1990), and some report hardly any change at all (e.g, Petrofsky and Lind 1980; Viitasalo and Komi 1978). However, although no change was found in MF, the duration of the maximal M-wave decreased as the isometric force increased (Linnamo et al. 2001). It was suggested that the decreased duration of the M-wave is due to a possible change in the CV, which has been shown to increase as the force increases (e.g., Broman et al. 1985; Zwarts and Arendt-Nielsen 1988). In a voluntary situation this could be due to the recruitment of bigger and faster motor units (DeLuca et al. 1982; Milner-Brown et al. 1973) with higher CVs (Andreassen and Arendt-Nielsen 1987), and/or to increased firing rate of the active units (Morimoto and Masuda 1984; Stålberg 1966). With supramaximal electrical nerve stimulation, all of the motor units should be activated simultaneously so that activation patterns should not play such a major role. On the other hand, there is evidence that the repetitive activation of muscle fibers after the relaxed condition may lead to increased activity of the Na^{+}/K^{+} pump, which may lower the resting membrane potential, resulting in a greater change in voltage across the membrane during an action potential (Enoka et al. 1992; Hicks and McComas 1989). Another possibility that could affect the CV is the change in muscle fiber diameter (Håkansson 1956; Rau et al. 1997). During dynamic actions, muscle fiber diameter may be different depending upon whether the muscle is lengthened or shortened, and lengthening of the fibers may cause a decrease in the CV (Trontelj 1993). This could explain, at least in part, why the MF may be lower for eccentric as compared to concentric actions (Komi et al. 2000; Muro et al. 1983).

It seems that both the EMG power spectrum and M-wave may be sensitive to changes in muscle activation level and muscle length. Therefore, it is of interest to examine whether increased muscle activation in lengthening and in shortening conditions results in similar behavior in the duration of the M-wave and in the MF. The purpose of this study was to examine the EMG power spectrum and maximal M-waves associated with eccentric and concentric actions performed at different force levels.

Methods

Subjects

Ten male subjects volunteered for the study. The mean (SD) values for age, body mass, height and per cent body fat were 21.6 (3.6) years, 77.2 (8.7) kg, 185.0 (6.4) cm and 11.9 (1.6)%, respectively. The subjects were physically fit basketball players. The subjects were fully informed about the possible risks and discomfort associated with this study, and they all gave their written informed consent to participate. The study was conducted according to the Declaration of Helsinki and was approved by the Ethics committee of the University of Jyväskylä.

Experimental design and measurements

The subjects were seated into a specially built dynamometer (Komi et al. 2000) with hip angle at 110°. After a standardized 5-min warm-up on a bicycle ergometer, maximal eccentric and concentric knee extension force (MVC) of the right leg were measured. The movement started with maximal isometric preactivation and the subjects were instructed to maintain maximal force throughout the whole range of motion, which was from 25° to 90° knee angle for the eccentric actions, and from 90° to 25° for the concentric actions (0° = full extension). After that, 40%, 60% and 80% MVC from the isometric preactivation phase was calculated and then shown to the subject on an oscilloscope. The subjects were then asked to maintain the chosen relative submaximal force level all through the dynamic movement. Instant feedback was provided by a computer program that calculated how closely the required force level was kept in relation to the maximal attempt. If there was more than $\pm 10\%$ difference at any point of the movement, the attempt was rejected. The movement velocity was 2 $rad \cdot s^{-1}$ in all conditions. Subjects performed the required force levels in random order with a 1.5-min break between the attempts to avoid fatigue. Several additional attempts were performed in order to measure the maximal M-wave during eccentric and concentric actions at each force level as well as in a relaxed condition.

Surface EMG was recorded from the vastus lateralis (VL), vastus medialis (VM) and rectus femoris (RF) muscles of the right leg using bipolar Beckman miniature-sized electrodes. According to the recommendation of SENIAM (1999), a 20-mm interelectrode distance was employed. A constant interelectrode distance was ensured by using a special plastic housing into which the electrodes were built. Electrodes were placed longitudinally on the muscle approximately halfway between the motor point area and the distal part of the muscle. The skin under the electrodes was abraded to reduce the interelectrode resistance so that it was less than 5.0 kΩ. The sampling frequency of the EMG recordings (Neuropack Four Mini, MEB-5304K) was 2520 Hz. All EMG signals were filtered with a high-pass filter (cut-off frequency 20 Hz) to remove any baseline shift. For aEMG, the signal was fully rectified, the range of motion divided to nine equal sections, and the average amplitude

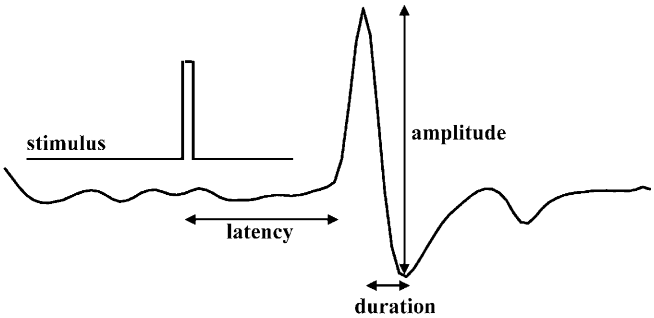

Fig. 1 An example of a maximal M-wave; its latency, amplitude and duration are shown

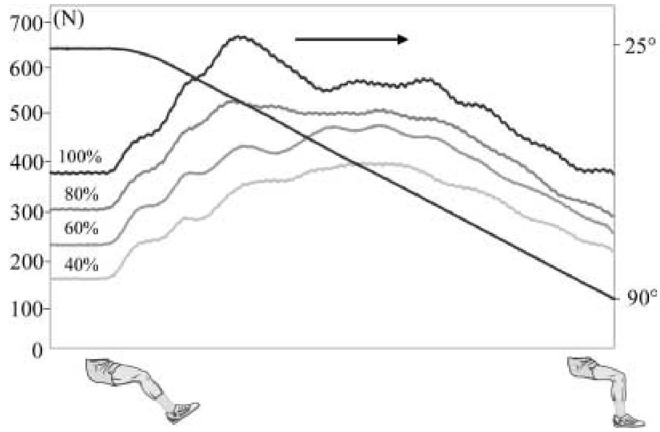

Fig. 2 Force (left ordinate) and joint angle (right ordinate) during eccentric action at different activation levels (mean of ten subjects)

for each section was calculated. The mean value of all nine sections was chosen to represent the aEMG of the whole range of motion. Fast Fourier transform (FFT) analysis was performed for calculation of the MF of the power spectrum. MF was obtained by overlapping the FFT windows (1,024 points) so that a new window was placed over each consecutive data point over the time of angular motion at each force level. The mean value of the calculated 900 MF values for each muscle was used for further analyses. The MF and aEMG were calculated from the attempts without the superimposed M-wave.

For measurement of the M-wave, the subjects performed additional eccentric and concentric actions at similar force levels as in pure voluntary conditions. A supramaximal electrical stimulus was given to the femoral nerve (Neuropack Four Mini, MEB-5304 K) just distal of the inguinal ligament during the steady force phase. The electrical stimulus was 1 ms long and had a square shape. The anode (5×5 cm) was placed over the hip of the stimulated leg, and the cathode (1 cm diameter) was placed over the nerve. Maximal electrical stimulation intensity was defined as the current level when a further increase was not reflected in an M-wave amplitude increase. The actual stimulation intensity was further increased by 50% to secure supramaximal stimulation intensity. The cathode was additionally pressed against the nerve to secure supramaximal stimulation in all conditions. The stimulation was given at a knee angle of 45° in all conditions The maximal M-wave was analyzed for its latency (defined as the time from the start of the electrical stimulus to the first peak of the M-wave), peak-to-peak amplitude and the duration between the negative and positive peaks of the M-wave (Fig. 1).

Data are presented as mean (SD), calculated using conventional statistical methods. The differences in obtained parameters among different voluntary activation levels and between eccentric and concentric actions were analyzed using analysis of variance. When appropriate, comparisons of means between two voluntary activation levels were performed using the Student's paired *t*-test (two-tailed). The level of significance was chosen to be $P < 0.05$.

Results

The absolute average force of the whole range of motion was significantly higher in eccentric than in concentric actions at all of the force levels tested (40% and 60% $P < 0.001$, 80% $P < 0.01$ and 100% $P < 0.05$). Figures 2 and 3 show the force curves at different force levels for eccentric and concentric actions, respectively. aEMG increased as the force level increased ($P < 0.001$) for both type of action (Figs. 4, 5). The aEMG signal for the whole range of motion was significantly higher for concentric actions than for eccentric actions for all the measured muscles at the three highest force levels (60% $P < 0.01$, 80% $P < 0.001$ and 100% $P < 0.05$). In a maximal situation, the difference was most substantial at joint angles corresponding to the beginning of the concentric action and the end of eccentric action (Fig. 6).

No consistent differences were observed in the amplitude and in the latency of the maximal M-wave in any of the conditions. When comparing the duration of the M-wave between eccentric and concentric actions, the only significant differences were found in the relaxed condition and at 40% MVC in the VL muscle, where the duration was shorter ($P < 0.05$) in eccentric action as compared to concentric. However, as the force level increased, the duration of the M-wave decreased significantly ($P < 0.01$) both for eccentric and concentric actions. The differences were greatest for the VL muscle (Fig. 7), but the same trend was also observed in the RF and VM muscles.

In the concentric action, MF tended to be somewhat higher (n.s.) in concentric than in eccentric actions when averaged over all of the overlapping FFT windows. No major differences were observed in MF between the force levels in either type of action in any of the measured muscles except for the VL in the concentric action, for which MF was lower at 40% MVC as compared to the other force levels. These results, however, depend upon which part of the motion is chosen to for inspection (Figs. 8, 9, 10). Table 1 gives representative data for one subject, showing the variation in MF for eccentric and concentric actions.

A similar type of behavior in aEMG and variation in MF was observed in all three muscles. However, since the changes in the M-wave were clearest in the VL, the more detailed results regarding aEMG and MF are also presented only from that particular muscle.

Discussion

The following major findings were observed in the present study: (1) although the absolute force was greater, the aEMG was generally lower for eccentric actions as

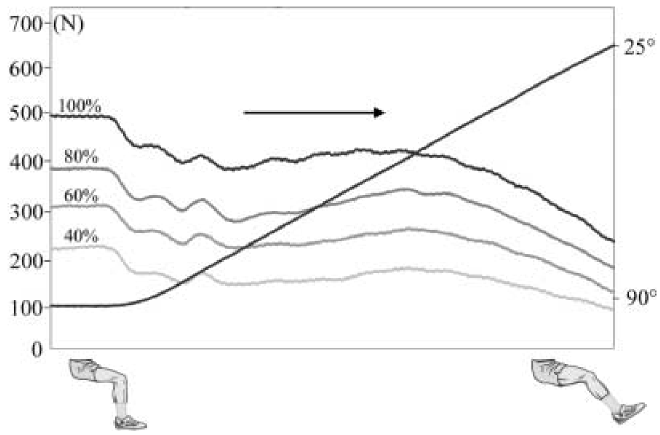

Fig. 3 Force and joint angle during concentric action at different activation levels (i.e., different percentages of maximum voluntary contraction, MVC; mean of ten subjects)

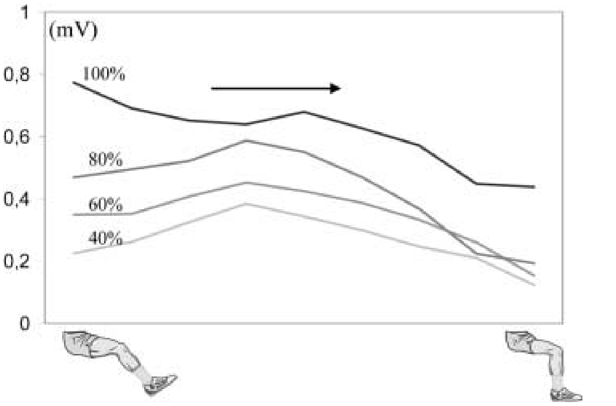

Fig. 4 Average electromyogram (*aEMG*) of the vastus lateralis (*VL*) muscle during eccentric action at different activation levels (mean of 10 subjects)

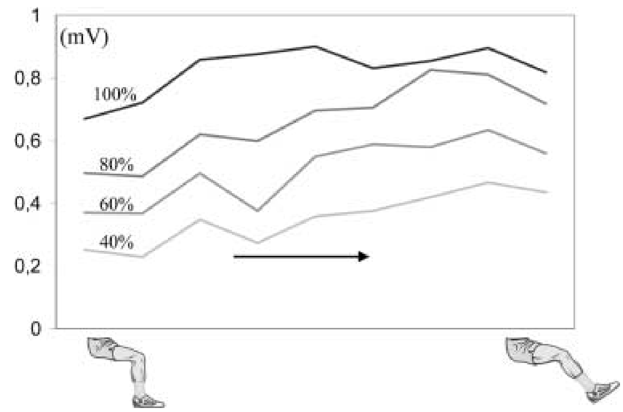

Fig. 5 aEMG of the VL muscle during concentric action at different activation levels (mean of ten subjects)

compared to concentric actions, (2) regardless of the increased aEMG in both conditions, the M-wave amplitude or latency did not change with increases in the activation level or between the action types, (3) the duration of the M-wave decreased with increase in force, but remained similar between the action types, and (4) the power spectrum analysis did not reveal any changes in MF among the force levels or between eccentric and concentric actions.

As in the previous studies (e.g., Doss and Karpovich 1965; Komi 1973; Komi et al. 2000), in the present study the average force level associated with concentric actions was lower than that associated with eccentric force. Although the forces are greater in the eccentric mode, it seems that there is some neural inhibition, and it may be difficult to fully activate the muscles during eccentric actions (Westing et al. 1990). The shape of the force curve for the eccentric action in the present study supports this concept of possible inhibition. At the highest force levels there is a rather rapid decline in force in the middle part of the movement (Fig. 2). In the present study, the aEMG was, as expected, lower for eccentric than for concentric actions at almost all of the force levels studied. In the maximal situation, however, the EMG has been reported to be higher for concentric actions (Eloranta and Komi 1980; Tesch et al. 1990; Westing et al. 1991), for eccentric actions (unpublished observations), or to remain at the same level (Komi 1973; Komi et al. 2000), depending upon the muscles, joint angles and protocols used. In our previous study (Komi et al. 2000), in which the protocol was similar and using the same dynamometer but with forearm flexors, it was found that in the maximal situation the aEMG was similar for eccentric and concentric actions at smaller joint angles, which correspond to the beginning of the eccentric and the end part of the concentric actions. However, towards the end of the eccentric movement, at greater joint angles the eccentric aEMG decreased below the concentric aEMG. The same phenomenon was also observed in the present study, supporting the concept that maintaining the maximal force throughout the motion is difficult in eccentric actions. In both studies, the separately measured maximal isometric force exceeded the maximal eccentric force when the forces were compared at the joint angles in the middle part of the motion. For the elbow flexors the isometric force was 7% higher than the eccentric force, and for the knee extensors the isometric force was 17% higher than eccentric force at a corresponding joint angle, thus suggesting that inhibition may be greater with the knee extensors. The reduction observed in maximal EMG during eccentric actions may not have much practical relevance. In natural locomotion the eccentric action precedes the concentric one in a stretch-shortening cycle (SSC) fashion. Since the duration of the eccentric phase is usually very short (e.g., Komi 2000), the inhibitory mechanism may not have time to be functionally meaningful. This hypothesis, however, needs careful testing.

Although the aEMG increased as the force increased, no major changes were observed in the amplitude of the maximal M-wave at different force levels or between the action types. This could be due to supramaximal

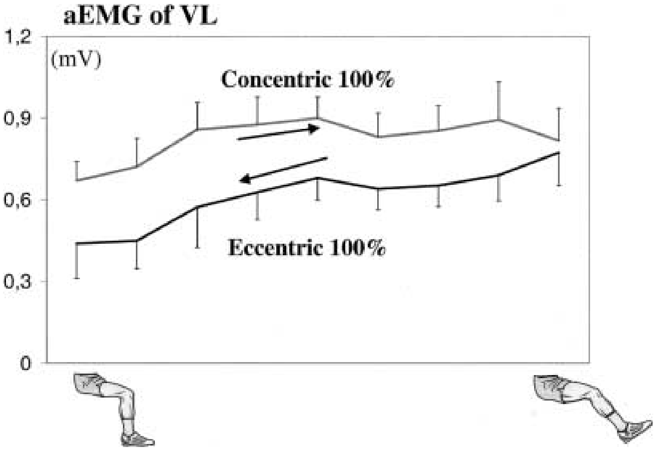

Fig. 6 aEMG of the VL muscle during eccentric and concentric action at 100% force level (mean of ten subjects)

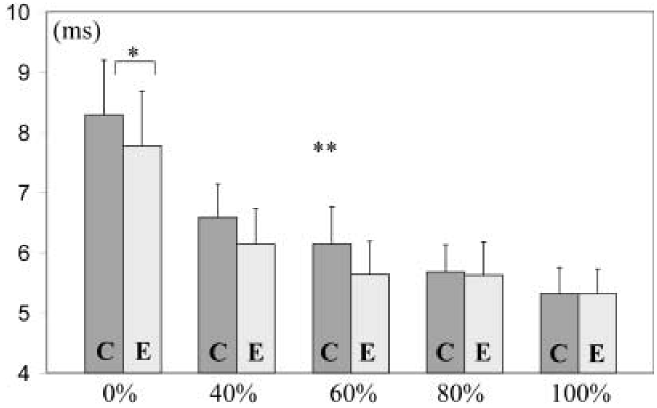

Fig. 7 Duration (±SD) of the M-wave of the VL muscle at different force levels in eccentric and concentric action

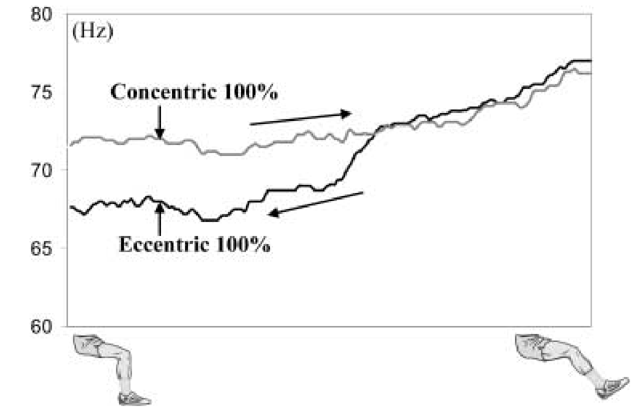

Fig. 8 The MF of the VL muscle during eccentric and concentric action at the 100% force level (mean of ten subjects)

stimulation of the nerve that, regardless of the level of voluntary activation, activates all of the motor units connected to the stimulated nerve, except those that are in the absolute refractory phase. No real differences were observed in the latencies, so it seems that the axonal conduction velocity remained the same regardless of the force level or the action type.

On the other hand, the duration of the M-wave became shorter as the force increased, which could imply an increased CV. As the force level increases in voluntary isometric action, bigger and faster motor units are being recruited up to 50–80% MVC depending upon the muscle (DeLuca et al. 1982; Kukulka and Clamann 1981; Milner-Brown et al. 1973), after which the additional increase in force is accomplished by increasing the firing rate of the active units (DeLuca et al. 1982; Milner-Brown et al. 1973). If during supramaximal electrical stimulation all of the motor units are activated simultaneously, the recruitment and firing rate should then not affect the duration of the M-wave. However, in the present study the duration of the M-wave decreased as the force level increased, even at the highest force levels between 80% and 100% MVC, which would be in line with previous studies showing that in a voluntary situation the CV continues to increase up to 100% MVC (e.g., Broman et al. 1985; Zwarts and Arendt-Nielsen 1988). In addition, the duration of the M-wave was in some cases shorter at the lower force levels for eccentric actions than for concentric actions, which would support the idea that the CV would be higher in eccentric situations. There is some evidence that in submaximal eccentric actions the fast-twitch fibers may be selectively recruited (Nardone et al. 1989), as opposed to the size principle of Henneman et al. (1965). It has been suggested that the excitability of muscle membranes may be affected by the preceding action potential (Morimoto and Masuda 1984) and the activity of the Na^+/K^+ pump can increase due to the repetitive activation of muscle fibers (Hicks and McComas 1989). This may partly explain why during supramaximal electrical stimulation the voluntary activation level may affect the duration of the M-wave, even though all of the motor units should be activated simultaneously. Fast (phasic) motor units may increase their firing frequency almost linearly up to 100% MVC, while slow (tonic) motor units reach a saturation frequency of discharge at lower force levels of approximately 60–80% MVC (Gydikov and Kosarov 1973). An increase in the firing rate of fast motor units affecting the activity of the Na^+/K^+ pump could thus play a role in the increased CV. The reason why the amplitude of the M-wave did not change could be related to the absolute refractory period of the action potential during which another potential cannot be elicited by electrical stimulation (Farmer et al. 1960). At higher force levels it is more likely that more motor units are in this refractory phase than at lower force levels.

Another possibility affecting the CV is the change in muscle fiber length. It has been shown that the CV is higher at shorter muscle lengths (Rau et al. 1997). In an isometric situation, the fascicle length of the VL muscle may shorten by 10–35% from rest to MVC depending on the joint angle (Ichinose et al. 1997). With the exception of low force levels, no consistent changes were observed in the duration of the M-wave between the

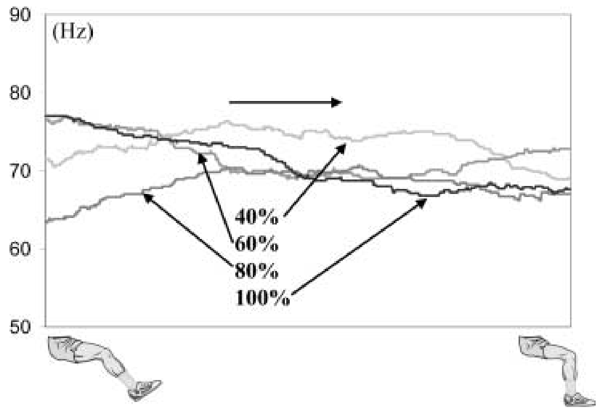

Fig. 9 MF of the VL muscle during eccentric action at different activation levels (mean of ten subjects)

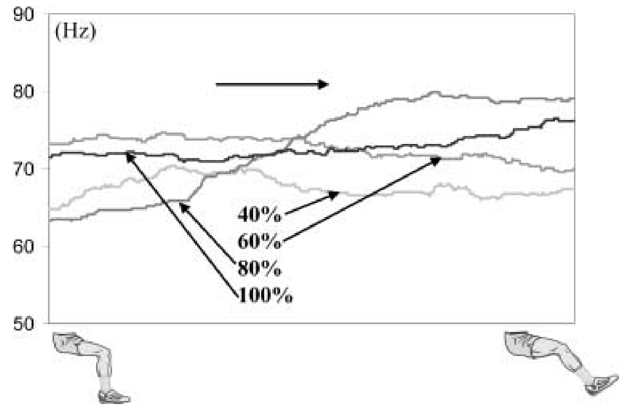

Fig. 10 MF of the VL muscle during eccentric action at different activation levels (mean of ten subjects)

action types. If the muscle fiber length is different during concentric and eccentric actions, it would seem likely that changes in the muscle fiber excitability would be the major factors affecting the duration of the M-wave and thus the CV, whereas changes in the fiber length do not seem to be so important. On the other hand, recent experiments from our laboratory indicate that whether the fascicle length in the eccentric situation is greater as compared to the concentric situation depends upon which part of the motion is chosen for the analysis, and upon the movement velocity. The greatest fascicle length differences in the VL muscle between eccentric and concentric actions appear to be toward the end of eccentric action at the flexed position of the knee (Finni et al. 2001). Since we chose the middle part of the motion, it is possible that in the case of the eccentric action the fascicle length may not have been much different from that of the concentric action.

The frequency component of the EMG power spectrum is related to CV (Arendt-Nielsen and Mills 1985; Stulen and De Luca 1981). Therefore, an increase in MF along with an increase in force was expected to occur. Instead, no major differences in MF were observed either in eccentric or in concentric actions between the force levels. The average MF of the whole range of motion tended to be somewhat lower for the eccentric action than for the concentric action, which is in line with some of the previous studies (Komi et al. 2000; Muro et al. 1983). However, as seen in Figs.9 and 10, the result may depend upon which part of the motion is chosen for the inspection. At the extended position, with shorter muscle lengths, the MF was higher than at the flexed position, with longer muscle lengths, for both the eccentric and concentric actions. This could be due to changes in the CV at different muscle lengths (Rau et al. 1997) or simply due to changes in the electrode position in relation to the innervation zone area (Roy et al. 1986). With shorter interelectrode distances, the frequency content of the EMG signals could have been more sensitive to changes in force; if the interelectrode distance is too long the high-frequency content of the signal may be suppressed (Bilodeau et al. 1990; Moritani and Muro 1987). Even more important to the behavior of MF may be the role of the FFT window placement. As was shown in an isometric situation with the overlapping FFT window technique, there may be rather large variations in MF even during a short (1 s) time interval of a relatively stable contraction (Linnamo et al. 2001). Similar variations were also observed in the present study in a dynamic situation, and therefore the interpretation of the behavior of MF should be treated with caution.

Table 1 Variation of median frequency (*MF*) in the vastus lateralis muscle throughout the whole range of motion (65°) at different eccentric (*Ecc*) and concentric (*Con*) force levels (i.e., percentage of maximum voluntary contraction; one subject). (*MVC* Maximum voluntary contraction force, *Min* minimum value, *Max* maximum value)

Parameter		40% MVC		60% MVC		80% MVC		100% MVC	
		Ecc	Con	Ecc	Con	Ecc	Con	Ecc	Con
MF	Mean	72.8	64.8	70.0	72.2	69.1	63.9	57.4	69.6
(Hz)	Min	66	54	64	66	62	57	42	66
	Max	81	81	81	81	76	71	74	84

In conclusion, while the force and aEMG curves followed similar patterns in both eccentric (40–80% MVC) and concentric (40–100% MVC) actions, during the maximal eccentric action the force and the aEMG decreased substantially toward the end of the motion. This would suggest that with the present protocol it is possible that inhibition would occur only during maximal effort in eccentric actions. Muscle fiber CV, as indicated by the decreased duration of the M-wave, appears to increase along with increasing force level. Based on the present data, it is difficult, however, to establish whether the duration of the M-wave is affected by the increased excitability of muscle membranes (possibly due to the recruitment of fast motor units with higher firing rates), and the role of possible changes in the muscle fiber length. Increased CV was not, however, seen as changes in the MF, although the result seemed to depend upon what part of motion was chosen for the analysis.

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