Neuromuscular Fatigue After a Ski Skating Marathon

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Abstract/Résumé

The aim of this study was to characterize neuromuscular fatigue in knee extensor muscles after a marathon skiing race (mean ± SD duration = 159.7 ± 17.9 min). During the 2 days preceding the event and immediately after, maximal percutaneous electrical stimulations (single twitch, 0.5-s tetanus at 20 and 80 Hz) were applied to the femoral nerve of 11 trained skiers. Superimposed twitches were also delivered during maximal voluntary contraction (MVC) to determine maximal voluntary activation (%VA). EMG was recorded from the vastus lateralis muscle. MVC decreased with fatigue from 171.7 ± 33.7 to 157.3 ± 35.2 Nm (–8.4%; $p < 0.005$) while %VA did not change significantly. The RMS measured during MVC and peak-to-peak amplitude of the compound muscle action potential (PPA) from the vastus lateralis decreased with fatigue by about 30% ($p < 0.01$), but $RMS \cdot PPA^{-1}$ was similar before and after the ski marathon. Peak tetanus tension at 20 Hz and 80 Hz ($P_0 20$ and $P_0 80$, respectively) did not change significantly, but $P_0 20 \cdot P_0 80^{-1}$ increased ($p < 0.05$) after the ski marathon. Data from electrically evoked single twitches showed greater peak mechanical response, faster rate of force development, and shorter contraction time in the fatigued state. From these results it can be concluded that a ski skating marathon (a) alters slightly but significantly maximal voluntary strength of the knee extensors without affecting central activation, and (b) induces both potentiation and fatigue.

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Le but de cette étude était de caractériser la fatigue neuromusculaire des muscles extenseurs du genou après un marathon en ski de fond (durée moyenne ± ET = 159,7 ± 17,9 mn). Au cours des 2 jours précédent la compétition et immédiatement après, des stimulations électriques percutanées maximales (secousse isolée, tétanos de 0,5 s à 20 et 80 Hz) ont été appliquées sur le nerf fémoral de 11 skieurs de fond. Des secousses ont aussi été délivrées pendant des contractions maximales volontaires (CMV) isométriques afin de déterminer le niveau d'activation maximale (%AV). L'EMG du muscle vastus lateralis a été enregistré. CMV diminuait avec la fatigue de 171,7 ± 33,7 à 157,3 ± 35,2 Nm (–8,4%; p < 0,005) alors que %AV n'était pas modifié significativement. La RMS mesurée pendant CMV et l'amplitude pic-à-pic de l'onde M (PPA) du vastus lateralis diminuaient avec la fatigue d'environ 30% (p < 0,01), mais $RMS \cdot PPA^{-1}$ était similaire entre avant et après la compétition. Les pics de force durant les tétanos à 20 Hz et 80 Hz (respectivement, $P_0 20$ et $P_0 80$) ne changeaient pas significativement, mais $P_0 20 \cdot P_0 80^{-1}$ augmentait (p < 0,05) après le marathon en ski de fond. Enfin, les données issues des secousses isolées montraient un pic de tension supérieur, une vitesse de montée en force plus élevée, et un temps de contraction plus court en situation de fatigue. D'après ces résultats, il peut être conclu qu'un marathon en ski de fond (a) altère faiblement mais significativement la force maximale volontaire des extenseurs du genou sans modifier le niveau d'activation maximale, et (b) induit à la fois des phénomènes de potentiation et de fatigue.

Introduction

It is well known that loss of strength with fatigue depends on both the intensity and duration of exercise and on the type of muscular contraction (e.g., Pasquet et al., 2000). The stretch-shortening cycle (SSC), defined as stretch of an active muscle immediately followed by concentric contraction (Komi, 1984), is often used in human movements such as running, jumping, or throwing. Several experiments have studied the effects of intense SSC contractions on neuromuscular function with exercise lasting 1 to 8 min (Gollhofer, 1987; Hortobagyi et al., 1991; Strojnik and Komi, 1998, 2000). It was reported that while this type of fatigue systematically impaired the rate of force development, maximal voluntary force was often (Gollhofer, 1987; Hortobagyi et al., 1991; Strojnik and Komi, 2000) but not always (Strojnik and Komi, 1998) reduced.

Electrical stimulation at different frequencies has been used to enable a better understanding of the mechanisms underlying peripheral fatigue. Low-frequency fatigue, which has been connected to excitation/contraction coupling failure (e.g., MacIntosh and Rassier, 2002), was observed following submaximal intense exercise (Skurvydas et al., 2000; Strojnik and Komi, 2000), but not following maximal SSC exercise (Strojnik and Komi, 1998). Only a few experiments have studied fatigue induced by long-duration SSC exercise.

When such studies were conducted, the protocols used marathon running as the model (Kyröläinen et al., 2000; Nicol et al., 1991a). Marathon running causes muscular damage in the extensor muscles of the lower limbs (Kyröläinen et al., 2000), due not only to the eccentric phase of the SSC but also to the shock wave induced by heel strike. In addition, fatigue was recently shown to cause an increase of approximately 50% in the impact acceleration (Mizrahi et al., 2001), likely leading to greater muscular damage and thus greater loss of strength. We have previously shown that lower limb extensor muscles perform SSC regardless of the skating technique used (Millet et al., 1998; Perrey et al., 1998). Therefore, the study of ski skating should permit a better understanding of the effects of a long-term, no-shock-wave SSC exercise on neuromuscular function. The aim of the present experiment was then to examine neuromuscular alterations following a ski skating marathon.

Methods

SUBJECTS

Eleven trained male cross-country skiers (age 30.6 ± 6.5 yrs; mass 71.1 ± 7.9 kg; height 179.6 ± 8.1 cm; body fat 10.2 ± 2.9%) of regional to national level completed the study. All subjects were familiar with ski marathons. The ski marathon used in the study was a national level race with a mass start and an altitude difference of 616 m. Written informed consent was obtained from the subjects. The study was conducted according to the Declaration of Helsinki. Approval for the project was obtained from the local committee on human research.

Two testing sessions were conducted. The first one, in the nonfatigued state, was conducted during the 2 days preceding the race and started with a 10-min warm-up of skiing at a self-selected pace. The second session, in the fatigued state, started less than 5 minutes after the ski marathon, i.e., the time taken for the experimental set-up. A researcher was positioned at the finish line to remind the skiers to continue at race pace to the testing site, which was located about 800 m from the finish line. The testing session in the fatigued state lasted 7 to 10 minutes. Because the fatiguing exercise was a race, each subject was well motivated to perform maximally over the distance.

During the race, skiers skated over the whole course with the exception of long steep downhills where they used the closed slide-down position. It has been shown that ski skating implies the use of SSC for lower limb extensor muscles, regardless of the skating technique used, i.e., V1 skate, V2 skate, or V2-alternate technique (Candau et al., 1994; Perrey et al., 1998). Thus, it can be considered that the SSC type of contraction was performed during about 95% of the ski marathon, with the other 5% being isometric contractions.

MEASUREMENTS OF MUSCLE CONTRACTILE FUNCTION

All muscle contractile measurements were conducted in isometric conditions on the right knee extensor muscles (KE) with the subjects seated in a strength training device (leg extension machine) with the knee angle fixed at 90° (0° = knee fully extended). Velcro straps were used to stabilize the subject, and the mechanical response was recorded by a strain gauge (SBB 200 kg, Tempo Technologies, Taipei, Taiwan).

Maximal voluntary contraction (MVC) measurement involved two trials. The subjects were strongly encouraged and the best result was used for further analysis. KE maximal voluntary activation (%VA) was estimated using a technique based on the interpolated-twitch method. Briefly, an electrically evoked twitch was superimposed during the plateau. The ratio of the amplitude of the superimposed twitch to the size of the twitch in the relaxed muscle (control twitch) was then calculated to obtain %VA as follows:

$$\%VA = (1 - \text{superimposed twitch} \cdot \text{mean control twitch}^{-1}) \cdot 100$$

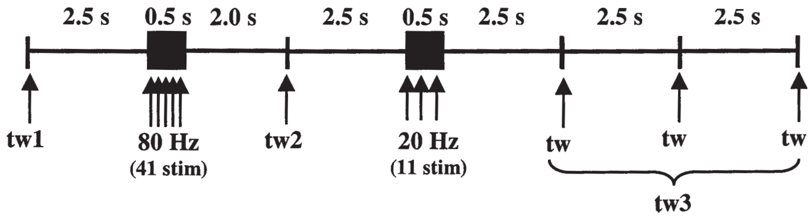


Figure 1. Schematic view of the electrically induced contractions.

The mean control twitch was a potentiated twitch (tw3, see Figure 1) that was measured as explained below.

Electrical stimulation was delivered using a high-voltage stimulator (Model DS-7, Digitimer Stimulator, Herthfordshire, UK). During the tests performed in the nonfatigued condition, the amperage of a 400-V maximal rectangular pulse (500 μs) was progressively increased. It was considered that optimal intensity, i.e., that which recruited all motor units of the KE, was reached when an increase in intensity did not increase the twitch response of the KE or the peak-to-peak amplitude of the vastus lateralis compound muscle action potential (M-wave, see below). This individual optimal intensity was also used for the fatigued condition. The femoral nerve was stimulated using a monopolar cathodal electrode (0.5-cm diameter) situated over the femoral triangle. The anode was a 10- by 5-cm rectangular electrode (Compex SA, Ecublens, Switzerland) located in the gluteal fold opposite the cathode. The electrically evoked force measurements comprised five single twitches and two 0.5-s tetanus at a frequency of 80 Hz and 20 Hz (i.e., 41 and 11 stimuli, respectively). The stimulations were done in the order shown in Figure 1. The last three twitches were averaged and this averaged twitch (tw3) was considered as the control twitch for calculating %VA and for the comparison before and after the ski marathon.

The following parameters were measured from the mechanical response of the evoked twitch: (a) peak twitch tension (P_t, see Figure 2), the highest value of twitch tension production; (b) twitch contraction time (CT), the time from the origin of the mechanical response to P_t; (c) maximal rate of twitch tension development (MRFDt), the maximal value of the first derivative of the force signal; (d) half relaxation time (HRT), the time to obtain half of the decline in twitch maximal force; and (e) maximal rate of twitch tension relaxation (MRFRt), the lowest value of the first derivative of the force signal. The following parameters were obtained from the mechanical response of the evoked tetanus: (a) peak tension ($P_0$80 and $P_0$20, see Figure 2), the highest value of tetanus tension production; and (b) maximal rate of tetanus tension development (MRFD80 and MRFD20), the maximal value of the first derivative of the force signal.

The post-tetanic potentiation (PTP) was calculated as P_t of tw2 divided by P_t of tw1 (see Figure 1).

EMG RECORDING

The EMG signals of the right vastus lateralis were recorded using bipolar silver chloride surface electrodes during MVC and percutaneous electrical stimulation.

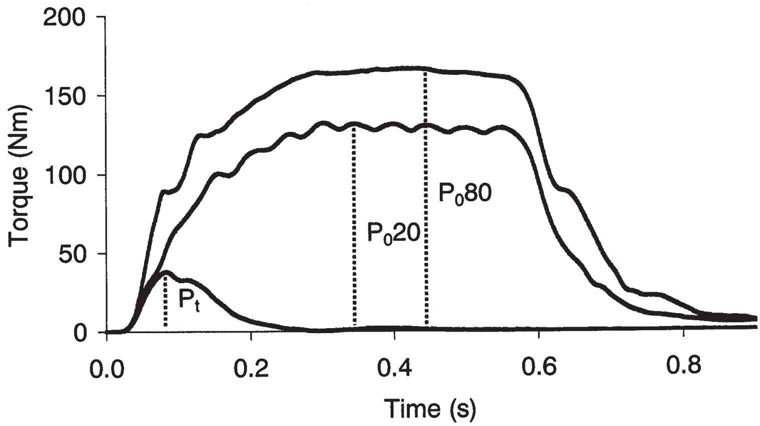


Figure 2. Typical trace of a single twitch (Pt) and the two 0.5-s tetanus at a frequency of 20 Hz and 80 Hz ($P_0$20 and $P_0$80, respectively).

The recording electrodes were fixed lengthwise over the middle of the muscle belly with an interelectrode distance of 20 mm. The reference electrode was attached to the wrist of the opposite arm. Low impedance at the skin-electrode surface was obtained ($Z < 5$ kΩ) by abrading the skin with emery paper and cleaning with alcohol. Myoelectrical signals were amplified with a bandwidth frequency ranging from 1.5 to 2 kHz and simultaneously digitized on-line (sampling frequency 2000 Hz). Peak-to-peak amplitude (PPA) and duration (peak-to-peak time; PPT) of the M-wave were determined during the maximal twitches. In addition, the root mean square (RMS) value was calculated during the MVC trials over a 0.5-s period after the torque had reached a plateau. All mechanical and EMG data were stored with commercially available software (Tida, Heka Elektronik, Lambrecht/Pfalz, Germany).

STATISTICAL ANALYSIS

Each study variable was compared between the nonfatigued and the fatigued state with a Student's paired *t*-test (single-tailed). For all statistical analyses, a *p* value of 0.05 was accepted as the level of significance.

Results

The winner's time for the ski marathon was 131.9 min. The average (±*SD*) time of the subjects participating in the study was 159.7 ± 17.9 min, i.e., 121 ± 14% of the winning time. One participant placed first and one placed fifth in the competition.

MUSCULAR PROPERTIES

The KE MVC decreased significantly with fatigue from 171.7 ± 33.7 to 157.3 ± 35.2 Nm (–8.4%; $p < 0.005$). Maximal voluntary activation did not change significantly

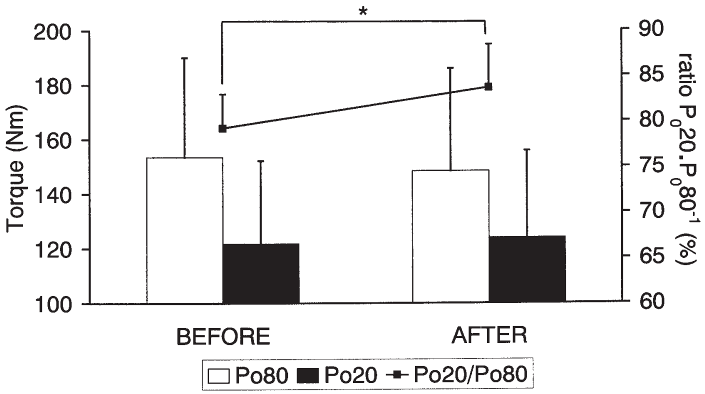


Figure 3. Mean (±*SD*) values of maximal mechanical response of 80-Hz tetanus ($P_0 80$), 20-Hz tetanus ($P_0 20$), and ratio $P_0 20 \cdot P_0 80^{-1}$ before and after marathon skiing. Significant difference between nonfatigued (before) and fatigued condition (after), $*p < 0.05$.

(99.4 ± 1.1% and 98.4 ± 2.9% before and after the race, respectively). Figure 3 shows that the ratio $P_0 20 \cdot P_0 80^{-1}$ increased significantly, $p < 0.05$, after the race but neither $P_0 80$ nor $P_0 20$ changed significantly between the nonfatigued and the fatigued state (–3.1%, $p = 0.18$, and +2.1%, $p = 0.27$, respectively, Figure 3). MRFD80 did not change with fatigue (2,737 ± 648 vs. 2,712 ± 854 $Nm \cdot s^{-1}$, n.s.) but MRFD20 increased significantly from 1,764 ± 461 to 1,943 ± 667 $Nm \cdot s^{-1}$, $p < 0.05$.

Table 1 displays the changes in the mechanical response of the electrically evoked twitch. Greater P_t, faster rate of force development, and shorter CT were observed in the fatigued state, $p < 0.05$. Figure 4 presents the changes of tw1 and tw2 with fatigue. The PTP decreased significantly with fatigue from 105.2 ± 3.1% to 101.3 ± 4.5%, $p < 0.05$. There was no significant difference between the P_t of tw2 and the P_t of tw3 in the rested state and the fatigued state.

EMG ACTIVITY

As shown in Figure 5, RMS decreased by 30. ± 16.2% between the nonfatigued state and the fatigued state, $p < 0.01$. The PPA was also lower after the race than before, $p < 0.01$, while the ratio between RMS and PPA did not change significantly (see Figure 5). The PPT was not affected by the type of fatigue induced in this experiment (6.9 ± 1.3 vs. 7. 5 ± 2.6 ms, n.s.).

Discussion

MVC CHANGES: COMPARISON WITH THE LITERATURE

To the best of our knowledge, only two studies have measured the reduction of force production after a cross-country ski race. In both cases the race was the 85-km Vasa ski race performed in classical style (Forsberg et al., 1979; Viitasalo et al., 1982). The large differences in strength decreases that were measured (–28% and

Table 1 Main Mechanical Characteristics (mean ± *SD*) of Evoked Twitch (tw3, see Figure 1) Before and After Fatiguing Exercise

	Before	After
P_t (Nm)	52.2 ± 12.7	56.1 ± 14.3 *
CT (ms)	94.8 ± 3.8	92.1 ± 4.0 **
MRFDt ($Nm \cdot s^{-1}$)	1,795 ± 473	1,971 ± 598 *
HRT (ms)	54.3 ± 22.5	55.1 ± 20.0
MRFRt ($Nm \cdot s^{-1}$)	710 ± 175	752 ± 256

Note: P_t = peak twitch; CT = contraction time; MRFDt = peak rate of force development; HRT= half-relaxation time; MRFRt = peak rate of force relaxation.
Significant difference between nonfatigued (before) and fatigued condition (after), *$p < 0.05$; **$p < 0.01$.

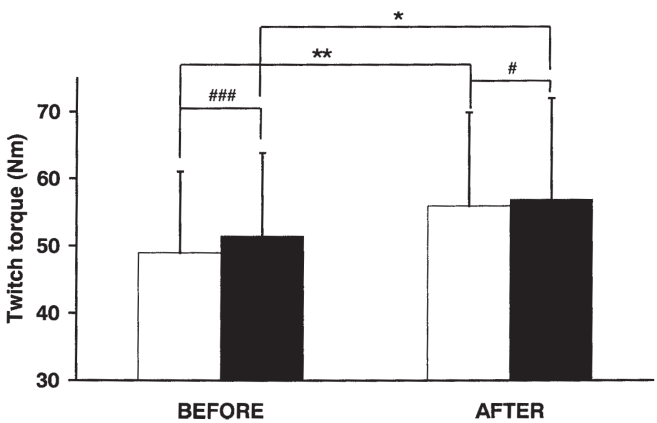
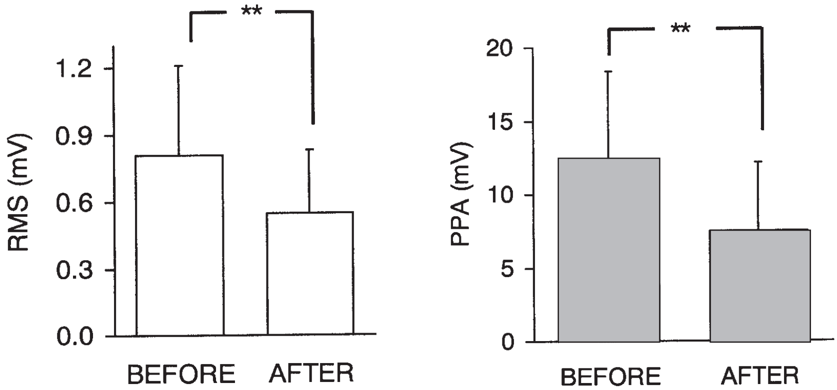


Figure 4. Mean (±*SD*) values of maximal mechanical response to nonpotentiated twitch (tw1, white bar) and potentiated twitch (tw2, black bar) before and after marathon skiing. Significant difference between nonfatigued (before) and fatigued condition (after), *$p < 0.05$; **$p < 0.01$. Significant difference between tw1 and tw2, $^{\#}p < 0.05$; $^{\#\#\#}p < 0.001$.

–10%, respectively) can be explained by the protocols of these two studies. Forsberg et al. (1979) tested the subjects immediately after the race, while Viitasalo et al. (1982) allowed a 1- to 2-hr delay between the end of the race and the tests. Thus, because the race distance (85 vs. 42 km), the testing protocols (isokinetic vs. isometric), and the style (classical vs. skating) differed between these two studies and the present one, any comparisons are only anecdotal.



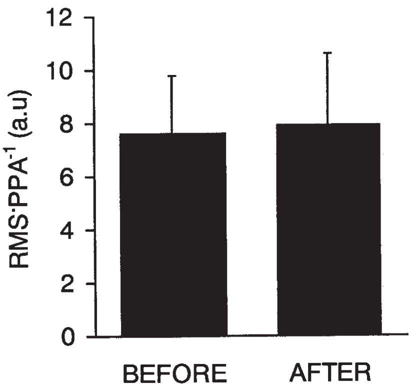


Figure 5. Mean (±*SD*) values of RMS (top left panel), peak-to-peak amplitude of compound muscle action potential (PPA) (top right), and RMS·PPA^{-1} ratio (lower panel) for vastus lateralis before and after marathon skiing. Significant difference between nonfatigued (before) and fatigued condition (after), $^{**}p < 0.01$.

It is difficult to compare fatigue after marathon running and marathon skiing because the courses are somewhat different, i.e., running marathon courses are often flat while the total altitude difference was 616 m in the present study. Nevertheless, the duration of the ski marathon was similar to the duration of the marathon runs previously studied (Kyröläinen et al., 2000; Nicol et al., 1991a; Sherman et al., 1984), so it is interesting to compare our results with those of studies that have focused on fatigue after marathon running. Maximal isometric knee extension force has been shown to decrease on average by 26% following a marathon (Nicol et al., 1991a), which is three times higher than in the present study. The isokinetic torque measured at a slow angular velocity (1.1 rad·s^{-1}) was also found to decrease by 35% in another study (Sherman et al., 1984). Thus, while exercise duration is similar in marathon skiing and running, there are large differences in strength loss between the fatigue induced by these two SSC activities. Further experiments on long-term fatigue induced by running are needed in order to shed light on the origins of this difference in strength loss, i.e. the relative contributions of peripheral factors and motor unit activation.

MAXIMAL VOLUNTARY ACTIVATION

A 30% decrease in maximal vastus lateralis RMS was measured in the present study after the ski marathon. This result is in good agreement with the findings of Viitasalo et al. (1982), who found a 35% lower vastus lateralis iEMG during maximal isometric contraction following a 85-km ski race. A decrease of iEMG or RMS does not necessarily imply a greater activation deficit. In the present study, the PPA of the M-wave and the RMS of the vastus lateralis decreased with fatigue to a similar extent, so that their ratio was unchanged. Previous studies have also shown a decrease in M-wave PPA with long-term fatigue (e.g., Lepers et al., 2000). The lower M-wave PPA has been attributed to modifications at the neuromuscular junction and/or modifications of sarcolemmal excitability because of a K^+ shift in the extracellular space (Jones, 1996). Interestingly, while large differences in force reduction were found between the present study and a marathon running study (Nicol et al., 1991b), iEMG measured during MVC decreased nearly as much with skiing as with running.

In the present experiment, neither the interpolated-twitch response nor the ratio of the voluntary EMG to the amplitude of the M-wave was affected by the ski marathon. It can be concluded that low intensity SSC exercise, such as a cross-country ski marathon, does not alter maximal voluntary activation. As a consequence, one would expect the same decrease for $P_0$80 and MVC. Even though a tendency for lower $P_0$80 in fatiguing conditions was noted, it was not the case since $P_0$80 decreased by –3.1% vs. –8.4% for the MVC. This can be due to a higher coactivation in postrace conditions or to the fact that the twitch interpolation method is not sensitive enough to detect low activation deficit (Miller et al., 1985). In fact, it has been argued that high-frequency maximal trains of stimuli may improve the detection of central activation failure (Miller et al., 1999) so that even though the conventional twitch interpolation technique indicates no central fatigue, a small difference in %VA may be present.

HIGH- AND LOW-FREQUENCY FATIGUE

P_t and MRFDt increased significantly after the ski marathon despite a lower PPA, and despite the fact that the reference twitch in the nonfatigued condition was a potentiated twitch, i.e., measured after an 80-Hz and a 20-Hz evoked tetanus (tw 3, see Figure 1). Decreases in twitch mechanical response have generally been observed after exercises lasting 1 to 2 hours (Booth et al., 1997; Lepers et al., 2000). While we studied alteration of neuromuscular function after an ultra-marathon (Millet et al., 2002), the present experiment was the first to measure the effects of fatigue induced by 2 to 3 hours of SSC exercise on twitch parameters.

The net result of an evoked twitch depends on the sum of potentiation- and fatigue-associated effects (MacIntosh and Rassier, 2002). Among the hypotheses that could be suggested to explain the potentiated P_t in the fatigued state is the possibly higher muscle temperature after the race. However, Davies et al. (1982) have shown that heating enhanced twitch tension at submaximal stimulation voltage but had no effect on supramaximal twitch force such as was measured in the present study. Stiffness changes could also be suggested as an explanation for the larger mechanical twitch response, but maximal rate of force development should have also increased during high-frequency stimulation. This was not observed in the present study.

During low-frequency stimulation, a potentiation phenomenon called the staircase effect has been previously observed and is thought to occur primarily as a result of phosphorylation of the regulatory light chains of myosin (MacIntosh and Rassier, 2002). This phenomenon could represent a valid explanation for the higher twitch tension and faster rate of force development found in the present study. The fact that the posttetanic potentiation decreased significantly may seem to contradict this hypothesis. However, it must be considered that the lower PTP found after the race was not due to the potentiated twitch (tw2) being lower in the fatigued state, but rather to the higher pretetanus twitch after the marathon than before (tw1). Indeed, the P_t of tw1 after the race was found to be $15.2 \pm 16.7\%$ higher than it was before the race.

It must be emphasized that the higher P_t found in the fatigued state does not imply that contractile function was improved by such long-term exercise. It is known that a twitch can be enhanced with depressed tetanus force (Rassier and MacIntosh, 2000; Shield et al., 1997). In the present study $P_0 80$ tended to be lower (–3.1%; n.s.) and the ratio $P_0 20 \cdot P_0 80^{-1}$ was significantly higher after the ski marathon, suggesting the existence of high-frequency fatigue. The lower M-wave PPA found here is in good agreement with high-frequency fatigue since this type of fatigue has been linked to depressed conduction of the action potential along the sarcolemma and/or into the transverse tubule (Jones, 1996; Metzger and Fitts, 1987).

Low-frequency fatigue (LFF), also called long-lasting fatigue, is generally viewed as involving impaired excitation/contraction coupling and structural damage (Metzger and Fitts, 1987). Eccentric exercise and intense SSC contractions are known to induce LFF (Jones et al., 1989; Skurvydas et al., 2000; Strojnik and Komi, 2000). Despite the existence of an eccentric phase in each stride during ski skating (Millet et al., 1998; Perrey et al., 1998), no LFF was detected in the present study. On the contrary, in line with the higher P_t, the ratio $P_0 20 \cdot P_0 80^{-1}$ increased significantly.

To our knowledge, no study has attempted to quantify the effects of cross-country skiing on muscle damage. However, delayed onset muscle soreness (DOMS) is much lower after a ski marathon than after marathon running so that some skiers are able to win several marathons in the same month while runners cannot. In addition, it has been shown that LFF and DOMS are greater when a muscle is in a stretched position (Jones et al., 1989), which is not the case in ski skating (Perrey et al., 1998). Thus, low-frequency fatigue was not necessarily expected after a ski skating marathon as it would be after marathon running. However, potentiation of the low-frequency tetanus cannot be ruled out because the postrace tests were conducted 5 to 10 min after the exercise. This may have hidden any low-frequency fatigue. As a consequence, the lack of LFF does not prove that there was no failure of the excitation/contraction coupling.

It is worth noting that the type of frequency-dependent alteration found in the present study has been reported in previous studies. For instance, Rankin et al. (1988) have shown that a substantial number of the motor units in the extensor digitorum longus muscle exhibited an enhanced twitch response after a fatiguing protocol while their tetanic contraction was depressed. This is generally considered as evidence for the coexistence of potentiation and high-frequency fatigue (Rankin et al., 1988; Rassier and MacIntosh, 2000).

In conclusion, the following were observed in knee extensor muscles after a ski marathon: (a) a small but significant loss of maximal voluntary isometric strength; (b) no change in maximal activation level; (c) potentiation of electrically evoked single twitch and low-frequency stimulation; and (d) a significant increase in the ratio between low-frequency and high-frequency tetanus. From these results it can be suggested that 2 to 3 hours of SSC exercise with no shock wave alters the capacity of force production without affecting voluntary activation during maximal isometric contractions. Also, it can be concluded that this type of long-duration exercise induces both potentiation and fatigue.

Acknowledgments

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