Fatigue and Recovery After High-Intensity Exercise Part I: Neuromuscular Fatigue

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Fatigue and Recovery After High-Intensity Exercise Part I: Neuromuscular Fatigue

G. Lattier
G. Y. Millet
A. Martin
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Abstract

The contribution of central and peripheral factors to muscle fatigue were quantified following a high-intensity uphill running exercise. Eight male volunteers performed an intermittent exercise at 120% of maximal aerobic speed on a treadmill with an 18% grade. Electrically evoked and voluntary contractions of the knee extensors and EMG of the two vastii were analyzed before and immediately after the high-intensity exercise. Isometric maximal voluntary contraction decreased slightly (– 7 ± 8%; $p < 0.05$) after exercise but no changes were found in the level of maximal activation or in the torque produced by a 80 Hz maximal stimulation applied to the femoral nerve. Following exercise, the single twitch was characterized by lower peak torque, maximal rate of force development, and relaxation (– 28 ± 11%, – 25 ± 12%, – 31 ± 15% respectively, $p < 0.001$), and higher surface of the M-wave for both vastii. The ratio between the torques evoked by 20 Hz and 80 Hz stimulation declined significantly (– 22 ± 10%, $p < 0.01$) after exercise. These findings indicate that muscle fatigue after high-intensity running exercise is due to significant alteration in excitation-contraction coupling and that this type of exercise does not induce significant central fatigue or changes at the crossbridge level.

Key words
Intermittent exercise · maximal voluntary contraction · low-frequency fatigue · EMG · electrical stimulation

Introduction

Muscle fatigue can be characterized by a reduction in maximal voluntary muscle force. This phenomenon may arise not only because of peripheral changes at the muscle level, but also because the central nervous system fails to drive the motoneurons adequately. The metabolic changes that accompany fatigue directly affect the contractile machinery [1] and activate afferents which may induce a reduction in force [10]. Historically, by far the most popular hypothesis to explain force reduction after high-intensity exercise has been that intracellular acidosis associated with lactic acid is the major cause of fatigue acting through mechanisms including Ca^{2+} movements, sensitivity of the myofilaments to Ca^{2+}, and force produced by the crossbridges [1,8,19]. However, recent studies in mammalian muscle have shown that acidification has only a modest effect on isometric force production at physiological temperatures [2], and even that acidosis might protect against fatigue [22]. It is likely that increased concentrations of inorganic phosphate (Pi), not hydrogen ions, is a major causative factor in skeletal muscle at the crossbridge level [27]. In fact, it has been demonstrated that high Pi inhibits the maximal force of skinned fiber by reducing, (i) sarcoplasmic reticulum (SR) Ca^{2+} release with Ca^{2+}-Pi precipitation, (ii) the number of active crossbridges, and (iii) myofibrillar sensitivity to Ca^{2+}. In addition, Pi decreases twitch relaxation velocity by reducing the rate of isometric crossbridge detachment, due to a slow myofibrillar ATPase [1]. The integrative studies conducted in humans raise the same debate about H^+ effects. For instance, Kent-Braun [16] and Miller et al. [20] have shown that changes in force and pH are closely related during fatigue, while Sahlin

Affiliation
Faculty of Sport Sciences, University of Burgundy, Dijon, France

Correspondence
G. Lattier · Faculty of Sports Sciences · University of Burgundy · BP 27877 · 21078 Dijon Cedex · France · Phone: + 33 3 80 39 67 62 · Fax: + 33 3 80 39 67 02 · E-mail: Gregory.Lattier@u-bourgogne.fr

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and Ren [24] have suggested that high intracellular H^+ concentrations do not limit capacity to generate force *in vivo*.

During intense exercise, intracellular potassium ion concentration ($[K^+]$) declines, while extracellular $[K^+]$ increases [25]. These large and rapid K^+ fluxes may contribute to muscular fatigue. In fact, disrupted $[K^+]$ homeostasis results in sustained t-tubular and sarcolemmal membrane depolarisation, which slows the action potential conduction velocity of the muscle fiber upon which the initiation of muscle contraction depends [25]. Thus, metabolite accumulation may induce peripheral fatigue through impaired neuromuscular propagation and depressed contractile function.

Central fatigue, i.e. the decrease in muscle force attributable to a decline in motoneuronal output, can be due to spinal and/or supraspinal factors [10]. One of the mechanisms potentially responsible for declining motoneuronal output is a reflex inhibitory system active during fatigue, mediated by small-diameter afferents from within the fatigued muscle [11]. During muscle fatigue the discharge of small-diameter muscle afferents (group III and IV) increases according to the temperature, chemical modifications like lactic acid accumulation [23] and the mechanical changes in the environment of their free nerve endings.

To our knowledge, only a few studies conducted in humans have focussed on the relative roles of potential factors of fatigue following high-intensity exercise. Strojnik and Komi [28] have performed experiments after intensive stretch-shortening cycle exercise but this type of exercise is known to induce muscle damage. For this reason, an uphill running exercise, known to imply large muscle masses [26] and to involve essentially concentric contraction, was chosen for the present experiment.

Therefore, the aim of this study was to investigate the neuromuscular alterations resulting from whole-body exercise designed to elicit anaerobic glycolysis in lower limbs extensor muscles. To distinguish the different pathways of fatigue, we studied the mechanical and electrophysiological responses of electrically evoked and voluntary contractions.

Methods

Subjects

Eight well trained male subjects, from regional to national level, volunteered to participate in the study. The subjects' physical characteristics and maximal aerobic velocity are presented in Table **1**. After being informed of the nature of the experiment, the subjects provided their written informed consent. The study was conducted in compliance with the Declaration of Helsinki and was approved by the local Committee on Human Research.

Experimental design

Subjects performed five sessions. All sessions were separated by at least one week and were performed on a treadmill (EF 1800, Medical Development, Tecmachine, Andrézieux-Bouthéon, France). The day before the sessions, subjects were requested to perform no intense physical activities.

Table **1** Physical characteristics of the subjects and maximal aerobic velocity

Age (yr)	*Body mass (kg)*	*Height (cm)*	*$MAV_{3\%}$ ($km \cdot h^{-1}$)*	*$MAV_{18\%}$ ($km \cdot h^{-1}$)*
25.0 ± 4.4	72.5 ± 5.5	176.6 ± 4.4	17.8 ± 1.4	9.4 ± 0.9

Values are means ± SD. $MAV_{3\%}$ maximal aerobic velocity with 3% grade. $MAV_{18\%}$ maximal aerobic velocity with 18% grade

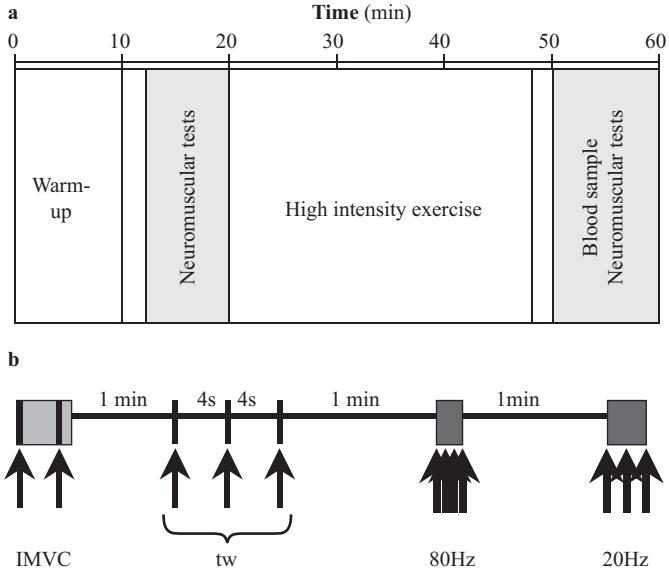

Fig. **1 a** and **b** **a** Experimental design. **b** Neuromuscular tests. IMVC: isometric maximal voluntary contraction; tw: twitch; 80 Hz: 0.5 s tetanus evoked at high frequency; 20 Hz: 0.75 s tetanus evoked at low frequency. Arrows designate maximal electrical stimulations of the femoral nerve.

The first two sessions consisted of determining the maximal aerobic velocity with the treadmill set at 18% and 3% grade (i.e. $MAV_{18\%}$ and $MAV_{3\%}$ respectively). The measurement of $MAV_{3\%}$ was performed to determine the intensity of the warm-up (60% of $MAV_{3\%}$) as well as the intensity of the active recovery (50% of $MAV_{3\%}$) in the companion article [18]. The initial speed was set at 5 $km \cdot h^{-1}$ for 18% grade and at 10 $km \cdot h^{-1}$ for 3% grade, and increased by 1 $km \cdot h^{-1}$ every 2 min until volitional exhaustion. The session designed to evaluate neuromuscular fatigue was then repeated three times because the present paper is followed by an article about comparison of three modes of recovery. Data on neuromuscular alterations collected after high-intensity exercise are presented here. The effects of different recovery interventions following this type of exercise are presented in the companion article [18]. As shown in Fig. **3**, no difference existed between the sessions in terms of strength loss. This was true for all parameters studied in the present experiment. The experimental design is depicted in Fig. **1**. Each session started by a warm-up which consisted of 10 min running on a treadmill at a speed corresponding to 60% of $MAV_{3\%}$.

High-intensity exercise

The fatiguing exercise was performed on a treadmill with a 18% grade. The subjects were asked to repeat 10 runs lasting one minute each at 120% $MAV_{18\%}$ with a two-minute rest period between repetitions. During the two-minute rest, the subjects stood passively on the treadmill. When the subjects were unable to finish the 10-repetition cycle at the requested speed, speed was diminished by 0.5 $km \cdot h^{-1}$. Each subject thus completed the 10-repetition exercise but only 7.0 ± 2.5 repetitions were performed at 120% $MAV_{18\%}$, the others being performed at an intensity which was 0.5 $km \cdot h^{-1}$ slower. The subjects were equipped with a safety harness and verbal encouragement was used to motivate the subjects throughout the exercise.

Blood analysis

Fingertip blood samples were drawn immediately after exercise for blood lactate concentration and blood pH analysis. Blood samples were stored at 4 °C in heparinized glass capillaries until analysis (Rapidlab 860 system, Bayer corporation, Leverkusen, Germany).

Neuromuscular measurements

Subject position

The subjects sat in a Biodex isokinetic dynamometer (System 3: Biodex Shirley Corporation, NY, USA) during all strength measurements. The subjects were attached to the apparatus to prevent trunk movement. The knee and hip angles were 80° and 85° (0°= full extension), respectively. Muscle torque was recorded using a force transducer fixed to the distal part of the shank. The lever arm to the knee joint axis was kept constant.

Voluntary knee extension test

Subjects performed two isometric maximal voluntary contractions (IMVC). They were instructed to achieve their maximum torque after the first electrically evoked twitch and to maintain it for at least 2 s. A second electrically evoked twitch was superimposed 1100 ms after the first twitch, i.e. on the plateau reached during IMVC. The best trial was retained for analysis. Peak torque and average torque over a 200 ms period before the superimposed twitch were recorded. The subjects rested one minute between each contraction.

Electrical stimulation

The femoral nerve was stimulated using a monopolar cathode electrode (0.5 cm diameter) located in the femoral triangle. The anode (10 × 5 cm; Medicompex SA, Ecublens, Switzerland) was positioned in the gluteal fold. Electrical stimulations were delivered by a high-voltage stimulator (Model DS-7, Digitimer Stimulator, Hertfordshire, England). The amperage of a maximal 400 V rectangular pulse (500 µs) was raised progressively (10 mA increment) until the higher intensity no longer induced a higher twitch mechanical response and higher amplitude EMG signals (M-wave, see below). This intensity was considered maximal, i.e. the stimulus allowing recruitment of all motor units of the muscular group considered. This maximal intensity was maintained for the entire session. Maximal intensity was measured at the beginning of each session but no differences were observed between sessions (session 1: 77.1 ± 18.3 mA; session 2: 72.9 ± 12.8 mA; session 3: 71.4 ± 11.2 mA; p = 0.20). Three stimuli, each separated by a 4 s interval (see Fig. **1**), were delivered then averaged. This was considered as the control twitch.

The following parameters were obtained from the mechanical response of the evoked twitch: (i) peak twitch torque (Pt), i.e. the highest value of twitch torque production; (ii) twitch contraction time (CT), i.e. the time from the origin of the mechanical signal to twitch maximal torque; (iii) maximal rate of twitch force development (MRFD) i.e. maximal value of the first derivative of the torque signal; (iv) half relaxation time (HRT), i.e. the time to obtain half of the decline in twitch maximal torque and (v) maximal rate of twitch force relaxation (MRFR) i.e. lowest value of the first derivative of the torque signal.

Maximal voluntary muscle activation was estimated by the twitch interpolation technique using the two electrically evoked twitches during IMVC. The ratio of the amplitude of the superimposed twitch over the size of the control twitch was then used to calculate the level of voluntary activation (%VA) as follows:

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

Finally, a 500 ms high-frequency tetanus (80 Hz) and a 750 ms low-frequency tetanus (20 Hz) were electrically evoked on the relaxed muscle. The peak torque of both trains of stimuli were measured (P80 and P20, respectively) and the $P20 \cdot P80^{-1}$ ratio was calculated.

EMG recording

EMG signals from the vastus lateralis (VL), vastus medialis (VM) and biceps femoris (BF) were recorded using a bipolar arrangement of silver chloride surface electrodes during electrical stimulation and maximal voluntary contraction. The recording electrodes of 9 mm diameter (Controle Graphique Medical, Brie-Comte-Robert, France) were fixed lengthwise over the middle of the muscle belly with an interelectrode distance of 20 mm. The reference electrode was attached to the contralateral patella. Low impedance at the skin-electrode surface was obtained ($Z < 5\,k\Omega$) by abrading the skin with emery cloth and cleaning with alcohol. Myoelectrical signals were amplified with a bandwidth frequency ranging from 1.5 Hz and 2 kHz and simultaneously digitized online (sampling frequency 2000 Hz). For the evoked twitch, peak-to-peak amplitude (PPA), peak-to-peak duration (PPD), and surface (M_S) of electrically evoked compound action potentials (M-wave) were determined for VL and VM. During IMVC, the EMG of the VL, VM and BF over a 200 ms period before the superimposed twitch was analyzed to calculate the Root Mean Square (RMS). RMS values of both vastii were also normalized with respect to the surface of the respective M-wave recorded at the maximal intensity ($RMS \cdot M_S^{-1}$). The antagonist (BF) RMS was expressed as a fraction of its maximal agonist activity. The torque signal and EMG data were stored with commercially available software (Tida, Heka Elektronik, Lambrecht/Pfalz, Germany).

Finally, the ratio $Pt \cdot PPA^{-1}$ was calculated as follows:

$$Pt \cdot PPA^{-1} = Pt \cdot ([PPA\,VL + PPA\,VM]/2)^{-1}$$

Statistics

Because tetanic stimulations are painful for some subjects, only six results were taken into account to compare the non-fatigued and the fatigued state for P80, P20 and the $P20 \cdot P80^{-1}$ ratio. Thus, a Wilcoxon test was used for these parameters. A one-way analysis of variance was used to calculate the statistical significance of difference between sessions for the maximal intensity of stimulation. For other study variables, a two-way analysis of variance (session × pre-post) with repeated measure was used to calculate (i) the statistical significance of difference between initial measurement and after exercise, and (ii) the reproducibility of the measure. Post-hoc analyses of significant differences were investigated using the Newman Keuls test. Statistical significance was accepted at $p < 0.05$.

Results

No session effect for any parameter was revealed, indicating similar fatigue after each running session. Following exercise, blood lactate concentration and blood pH were found to be 18.4 ± 3.6 mmol·L^{-1} and 7.13 ± 0.08, respectively.

Evoked contractions

As shown in Table **2**, a decrease was found after exercise in Pt ($-28 \pm 11\%$, $p < 0.001$), MRFD ($-25 \pm 12\%$, $p < 0.001$) and MRFR ($-31 \pm 15\%$, $p < 0.001$). There was a reduction in CT ($-6 \pm 9\%$, $p < 0.05$) after exercise; however, HRT did not change significantly with fatigue. The surface of the M-wave increased with exercise ($p < 0.05$) for the vastus lateralis (VL) and tended to increase for the vastus medialis (VM) ($p = 0.056$; Table **3**). Post-exercise values of M-wave peak-to-peak duration (PPD) were not different for both vastii. There was a non-significant increase in the peak-to-peak amplitude (PPA) for VL ($p = 0.065$) and VM ($p = 0.10$) after exercise (Table **3**). The $Pt \cdot PPA^{-1}$ ratio decreased after exercise by $37 \pm 15\%$ (from 5.3 ± 2.8 Nm·mV^{-1} to 3.1 ± 1.3 Nm·mV^{-1}; $p < 0.01$).

As shown in Fig. **2**, P80 did not change significantly with exercise, whereas P20 decreased by $18 \pm 12\%$ ($p < 0.01$) so that the $P20 \cdot P80^{-1}$ ratio was $22 \pm 10\%$ ($p < 0.01$) lower in the fatigued state.

Maximal voluntary contraction and activation

Isometric MVC decreased after exercise by $7 \pm 8\%$ ($p < 0.05$; Fig. **3**). Following exercise, the maximal activation level did not change significantly (from $92 \pm 6\%$ to $88 \pm 6\%$; $p = 0.08$). Similarly, there was no significant difference between the sessions for $RMS \cdot M_S^{-1}$ for both VL and VM (Table **3**), and for the $IMVC \cdot P80^{-1}$ ratio (from 1.05 ± 0.19 to 1.02 ± 0.15). Finally, coactivation (biceps femoris) did not change significantly (Table **3**) after exercise.

Table **2** Twitch-mechanical parameters

	Pre-exercise	*Post-exercise*
Pt (Nm)	56.3 ± 8.8	$40.8 \pm 9.9^{***}$
CT (ms)	70.3 ± 7.8	$65.7 \pm 5.0^{*}$
HRT (ms)	95.4 ± 19.3	83.9 ± 18.2
MRFD (Nm·ms^{-1})	1.44 ± 0.27	$1.08 \pm 0.28^{***}$
MRFR (Nm·ms^{-1})	0.63 ± 0.13	$0.43 \pm 0.11^{***}$

Values are means ± SD. * $p < 0.05$. *** $p < 0.001$ compared with pre-exercise value. Pt: twitch peak torque, CT: contraction time, HRT: half-relaxation time, MRFD: maximal rate of force development, MRFR: maximal rate of force relaxation

Table **3** EMG activity parameters

	Pre-exercise	*Post-exercise*
PPA VL (mV)	10.7 ± 3.8	12.1 ± 4.8
PPA VM (mV)	14.0 ± 6.0	16.1 ± 4.1
PPD VL (ms)	7.5 ± 1.7	7.3 ± 1.5
PPD VM (ms)	9.1 ± 3.2	8.4 ± 3.1
M_s VL (mV·ms)	0.07 ± 0.03	$0.08 \pm 0.03^{*}$
M_s VM (mV·ms)	0.10 ± 0.04	0.12 ± 0.03
$RMS \cdot M_s^{-1}$ VL (a.u.)	8.8 ± 2.6	8.5 ± 2.4
$RMS \cdot M_s^{-1}$ VM (a.u.)	9.8 ± 4.4	8.2 ± 1.6
RMS BF (a.u.)	0.14 ± 0.06	0.15 ± 0.07

Values are means ± SD. * $p < 0.05$ compared with pre-exercise value. PPA: M-wave peak-to-peak amplitude, PPD: M-wave peak-to-peak duration, M_s: M-wave surface, RMS: root mean square, $RMS \cdot MS^{-1}$: RMS normalized to the surface of M-wave (see methods), VM: vastus medialis, VL: vastus lateralis, BF: biceps femoris, a.u.: arbitrary unit

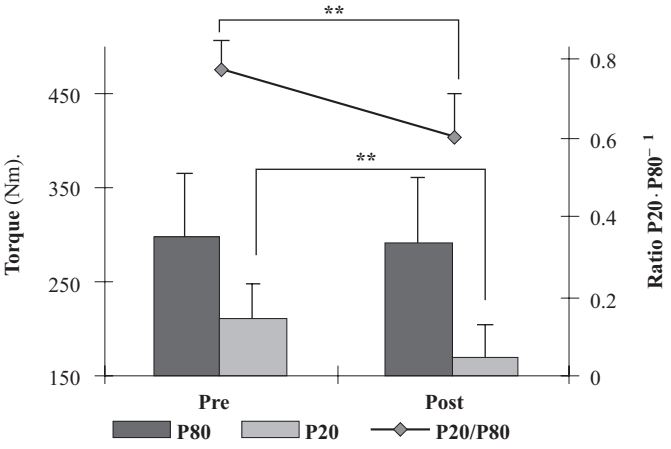

Fig. **2** Mean (± SD) values of the maximal mechanical response during 80 Hz tetanus (P80), 20 Hz tetanus (P20) and the ratio $P20 \cdot P80^{-1}$ before (Pre) and after (Post) high-intensity exercise. ** $p < 0.01$ compared with Pre value.

Discussion

The main findings of this study were that high-intensity uphill running exercise induced (i) low-frequency fatigue and large modifications in twitch contractile properties of knee extensors but (ii) only modest alterations in maximal voluntary strength and (iii) no change in torque evoked by high-frequency tetanus. The decrease in isometric strength can be mainly explained by the failure of excitation-contraction coupling and by the slight, though non-significant, alteration of the maximal activation level. This type of exercise was also found to increase the surface

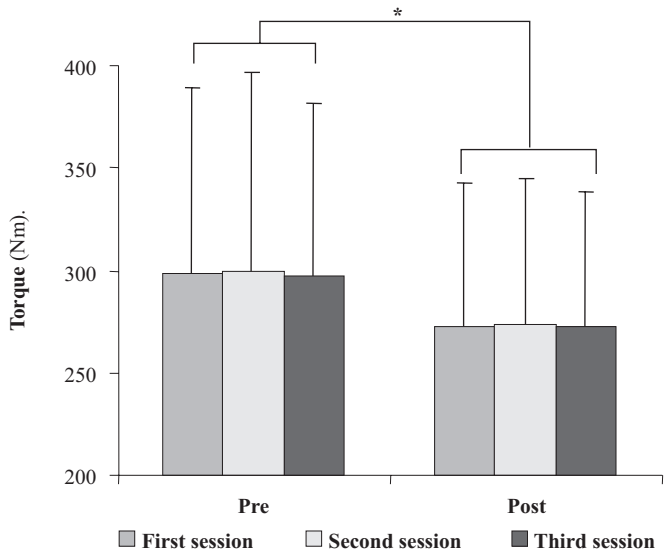

Fig. **3** Mean (± SD) values of the maximal voluntary contractions before (Pre) and after (Post) high-intensity exercise. * $p < 0.05$ compared with Pre value.

area of the M-wave for the vastus lateralis and vastus medialis muscles.

Evoked contractions

The present study investigated the neuromuscular effects of high-intensity exercise known to greatly perturb cellular homeostasis. As shown by the blood lactate levels and the pH values measured at the end of the 10 repetitions performed at 120% $MAV_{18\%}$, this type of exercise produces the expected metabolic effects. The study was designed to examine the causes of fatigue in humans after high-intensity exercise with low muscular damage. The results suggest that this type of exercise does not impair sarcolemmal excitability and does not change the force evoked by high-frequency tetanic stimulation, but alters excitation-contraction coupling (E-C). The first part of the discussion will focus on these three points.

Surprisingly, the surface of the M-wave for the two vastii increased after exercise and a similar tendency was found for the M-wave peak-to-peak amplitude. Muscle fatigue is frequently associated with a reduction in sarcolemmal excitability with a reduced amplitude and a prolonged duration [8]. It has also been suggested that Na^+-K^+ ATPase is inhibited at high concentrations of Pi and that this inhibition is reinforced in acidosis conditions [12]. However, in line with the present experiment, some studies have previously shown that M-wave potentiation can exist after short-duration fatigue [3,30]. West et al. [30] suggested that potentiation of the M-wave is due to the Na^+/K^+ pump-induced hyperpolarization of individual muscle fibers. From the present results, it can be hypothesized that similar mechanisms occur during high-intensity concentric contractions. Nevertheless, the interpretation of the M-wave is limited by at least two factors. First, there is a tendency for the integrated EMG to be higher in elevated than in cold temperatures [13]. Since Kenny et al. [15] have measured a rise in skin temperature following 15 min of treadmill running at 93% $\dot{V}O_{2max}$, it can be hypothesized that temperature may have played a role in the increase of M-wave surface area observed in our study. Secondly, the greater M-wave surface area may also have resulted from diminished temporal dispersion of muscle fiber action potentials without any increase in individual action potentials. However, since PPD did not change in this study, diminished temporal dispersion is doubtful. In addition, an increase in M-wave area did not allow to argue with complete certainty that a decrease of SR excitability did not occur. West et al. [30] have shown that even when M-wave amplitude is not affected by fatigue, the rise of extracellular $[K^+]$ may inhibit muscle action potential propagation at a site distal to sarcolemma, the most likely candidate being the T-tubules. Thus, even though the M-wave pattern is generally considered as an index of muscle fiber excitability in human studies [30], M-wave characteristics must be analyzed with caution, especially because they only reflect part of the action potential propagation mechanisms.

Results obtained from electrical stimulation at low- and high-frequency suggest that alterations mainly occur in the SR. Indeed, low-frequency fatigue has been related to E-C coupling failure [14]. This was supported by the fact that $Pt \cdot PPA^{-1}$ ratio decreased significantly after exercise. When defined as the sequence of events that starts with the release of acetylcholine at the neuromuscular junction and ends with the release of Ca^{2+} from the SR [29], the E-C coupling process can be divided into several distinct steps that include: (i) propagation of the sarcolemmal action potential, (ii) t-tubule charge movement, (iii) coupling between dihydropyridine receptor and ryanodine receptor and (iv) Ca^{2+} release from the SR. As discussed above, the first step was probably not implicated in the E-C coupling failure since the M-wave surface area increased. The non-invasive methods used here do not allow to further examine the origins of the E-C coupling failure but it is interesting to note that the mechanical link at step 3 has been shown to be sensitive to muscle stretch [5], which was not the case here since the lower limb extensor muscles were not exposed to eccentric contractions. On the contrary, it has been proposed that at high [Pi], there could be a net influx of inorganic phosphate into the SR, which could result in Ca^{2+}-Pi precipitation limiting Ca^{2+} available for release [9]. Dutka and Lamb [6] observed a 10% reduction in Ca^{2+} release in the presence of 30 mM lactate. Since at the end of the exercise blood lactate levels were higher than 18 mM in our subjects, such an elevated level of intracellular concentration of lactate is physiologically realistic.

Interestingly, E-C coupling was not altered enough to induce a decrease in torque after evoked tetanus at 80 Hz. In fact, P80 remained unchanged in our study, suggesting that the maximum Ca^{2+}-activated force was not altered. Thus, it can be speculated that in humans performing high-intensity exercise, acidosis and elevated concentrations of Pi and lactate do not have deleterious effects on the maximal tetanic isometric tension. These results differ from studies conducted on isolated fibers which have suggested that H^+, Pi and lactate can potentially decrease the force per crossbridge.

In line with the low-frequency fatigue observed after exercise, twitch mechanical properties were largely affected by the high-intensity exercise. With the exception of the half-relaxation time, all twitch mechanical parameters were altered despite the high-

er excitability found in the fatigued state. The lower Pt and the large decrease in maximal rates of twitch force development and relaxation found in the fatigued state are likely to depend on E-C coupling failure. The fact that the changes in twitch contraction and half-relaxation times were much lower than the modification of other parameters confirms this hypothesis. The results of our study regarding contractile properties were in accordance with the findings of Strojnik and Komi [28] who studied fatigue after intense stretch-shortening cycle exercise, but the underlying factors probably differ. Although we did not measure any index of muscular damage in the present study, the concentric nature of the exercise suggests that contractile tissue did not undergo any mechanical alteration [21]. In other words, the E-C coupling failure observed in the present experiment would be explained by metabolic rather than mechanical changes.

Maximal voluntary strength and activation

Despite the large changes in twitch mechanical properties and the existence of a low-frequency fatigue, there was only a modest loss in maximal voluntary strength. A small part of the IMVC loss could be explained by central fatigue even though there was only a tendency toward a decrease of maximal activation level ($p = 0.08$). This result is roughly the same as reported by Bentley et al. [4] who studied high intensity cycling exercise, i.e. mainly concentric contraction. In line with the non-significant changes in maximal activation level, there was no statistical difference between pre- and post-exercise $RMS \cdot M_S^{-1}$ for the vastus lateralis, and only a tendency ($p = 0.14$) for a decrease in the vastus medialis. Nevertheless, a study on fatigue induced by isometric contractions has shown a significantly greater relative decrease in EMG for the rectus femoris (RF) than for the VL and VM [7]. Consequently, the fact that $RMS \cdot M_S^{-1}$ of both vastii did not decrease significantly does not rule out a change in the RF.

Because alteration of central activation cannot explain the loss in voluntary isometric strength, one should expect a decrease in P80 after exercise, which was not the case. This paradox cannot be explained by antagonist coactivation since the biceps femoris RMS remained constant with fatigue, indicating this muscle was not involved in the isometric torque decrement. The most probable explanation of this apparent discrepancy is the fact that α-motoneurons discharge at a lower frequency during maximal voluntary activation than during evoked high-frequency stimulation [17]. In other words, it can be hypothesized that the deleterious effects of the E-C coupling failure in the fatigued condition were greater at low Ca^{2+} concentration, i.e. during voluntary contraction.

In conclusion, maximal voluntary isometric torque of the knee extensors decreased by only 8% following a highly strenuous uphill running exercise. Central fatigue may have played a role in strength loss, since a tendency was found for a higher activation deficit in the fatigued state. However, the main reason probably involves excitation-contraction coupling failure, as suggested by the large modifications of twitch contractile properties and the presence of low-frequency fatigue. Also, since this type of exercise did not alter torque evoked by a high-frequency train of stimulation, the present results suggest that in humans performing high-intensity exercise, acidosis and elevated concentrations of lactate do not have deleterious effects on maximal tetanic isometric tension.

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