

MUSCLE CONDUCTION VELOCITY, SURFACE ELECTROMYOGRAPHY VARIABLES, AND ECHO INTENSITY DURING CONCENTRIC AND ECCENTRIC FATIGUE

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ABSTRACT: *Introduction:* Concentric (CON) and eccentric (ECC) contractions may involve different mechanisms related to changes in sarcolemma status and the consequent alteration of action potential transmission along muscle fibers. *Methods:* Muscle conduction velocity (CV), surface electromyography signal (sEMG), muscle quality, and blood lactate concentrations were analyzed during CON and ECC actions. *Results:* Compared with ECC, the CON protocol resulted in greater muscle force losses, blood lactate concentrations, and changes in sEMG parameters. Similar reductions in CV were detected in both protocols. Higher echo intensity values were observed 2 days after ECC due to greater muscle damage. *Conclusion:* The effects of the muscle damage produced by ECC exercise on the transmission of action potentials along muscle fibers (measured as the CV) may be comparable with the effects of hydrogen accumulation produced by CON exercise (related to greater lactate concentrations), which causes greater force loss and change in other sEMG variables during CON than during ECC actions.

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Concentric muscle fatigue is involved in daily human performance, and its relationship to surface electromyography (sEMG) parameters has been widely studied.^{1–3} Acute decreases in muscle torque and mean sEMG frequency, and increases in the Dimitrov fatigue index, sEMG amplitude, and lactate concentration have been observed during concentric fatiguing contractions.^{4,5} In the past several years, however, eccentric exercise has started to gain importance in areas such as rehabilitation.⁶ Eccentric contractions are characterized by greater muscle force, lower metabolic cost, and greater muscle damage, which cause muscle stiffness and soreness in untrained subjects in the days after the exercise.⁷ Nevertheless, the resultant changes in muscle stiffness are still controversial and may increase or decrease after eccentric bouts.^{8,9}

The effects of muscle actions on maximal force and sEMG parameters measured during maximal fatiguing contractions have been compared recently. Depending on the muscle group involved

and the fatiguing protocol, muscle force can decrease further after eccentric^{10–12} or concentric protocols,^{13,14} or it can decrease at a similar rate during both types of induced fatigue protocols.^{15,16} Regarding sEMG parameters, the mean frequency has been shown to have greater decreases during either concentric¹³ or eccentric exercise.¹² These different behaviors of sEMG parameters may be related to differences in the nature of concentric and eccentric actions and/or to the limitations of these techniques in addressing the non-stationarity of the sEMG signal during dynamic contractions.¹⁷ During eccentric contractions, a cross-bridge cycling interaction occurs, with less adenosine triphosphate hydrolysis taking place than during concentric contractions.¹⁸ Therefore, concentric actions induce increased muscle acidosis (related to greater lactate values),¹⁹ which could have a stronger impact on neuromuscular function, thereby inducing greater changes in sEMG parameters than eccentric exercise.²⁰

Muscle conduction velocity, which depends on the polarization state of the sarcolemma, has also been examined. The transmission of action potentials along the sarcolemma is influenced by numerous factors, including the membrane potential, extracellular and intracellular Na⁺ and K⁺ concentrations, internal and external resistances, and membrane resistance and capacitance.²¹ Many of these factors can vary due to concentric fatigue to produce changes in action potential transmission along muscle fibers.²¹ On the other hand, the muscles that perform eccentric contractions are prone to incur muscle fiber membrane damage (among other types of damage or injury), causing changes in action potential propagation along the fibers.⁷ Therefore, it appears that, during concentric and eccentric actions, different mechanisms may be responsible for the alterations that occur in sarcolemma status and the consequent changes in action potential transmission along muscle fibers. However, few studies have analyzed the evolution of the muscle conduction velocity during fatiguing concentric and/or eccentric actions, most likely because of difficulties in measuring this parameter.²²

As mentioned above, it is well known that eccentric exercise produces greater muscle damage

Abbreviations: ANOVA, analysis of variance; CON, concentric contraction; CV, conduction velocity; ECC, eccentric contraction; Fl_{nsm5}, Dimitrov fatigue index; RFD, rate of force development; RMS, root mean square; sEMG, surface electromyography

Key words: concentric; eccentric; echo intensity; muscle conduction velocity; muscle fatigue

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than concentric exercise due to greater disorganization of sarcomeres, mainly at the Z lines, and damage to the T-tubules and sarcolemma.²³ Some studies have assessed the echo intensity using ultrasound gray-scale values as an indirect method for determining muscle damage.^{24–27} Several of these studies have revealed greater echo intensity values in the days after eccentric exercise.^{24,26,27} Moreover, traditional resistance exercise, consisting of concentric and eccentric actions, also results in increased echo intensity.²⁵ Nevertheless, no study has compared the echo intensity responses that occur after eccentric and concentric exercises, and it is unclear whether this method is sufficiently sensitive to detect the different magnitudes of muscle damage that are generally observed between these 2 types of exercise.

The main objective of the current investigation was to compare the evolution of muscle force and the different sEMG parameters that are used traditionally to assess muscle fatigue (Dimitrov fatigue index, mean frequency, root mean square) and muscle conduction velocity during a fatiguing exercise consisting of a series of eccentric or concentric actions. In addition, lactate and echo intensity levels were determined before and after the fatiguing exercises to quantify acidosis resulting from the exercise and muscle damage. In addition, based on the effects of eccentric exercise on muscle damage assessed by the echo intensity responses recorded in the days after exercise,^{24,26,27} we compared the observed echo intensity values as a model for determining muscle damage induced after 48 hours. We hypothesized that muscle damage produced by eccentric fatiguing exercise could be measured in terms of echo intensity values, and its effects on the transmission of action potentials along muscle fibers (measured as the muscle conduction velocity) may be comparable to the effects of hydrogen accumulation resulting from concentric exercise.

METHODS

Subjects. Sixteen healthy and physically active volunteers (6 men and 10 women; age: 21.5 ± 6.9 years; weight: 60.5 ± 10.1 kg; height: 160.5 ± 7.7 cm; percent fat mass: $19.6 \pm 5.7\%$) participated in the study. The subjects were asked to avoid strenuous exercise for 2 days before the experimental sessions. The experiment was conducted in accordance with the Declaration of Helsinki and was approved by the local ethics committee. All participants were informed about the possible risks of the experiment, and they provided written informed consent before participation.

Experimental Protocol. The study consisted of 2 sessions separated by at least 1 week to ensure

recovery from the previous strenuous fatiguing session. In 1 session, the subjects performed concentric maximal contractions (CON), whereas, in the other session, they performed eccentric maximal contractions (ECC). The order of the sessions was randomized.

In each session, the subjects were seated on isokinetic chair, and the right leg was attached to the isokinetic arm (Humac Norm; CSMi Solutions, Stoughton, Massachusetts) such that the rotation axis of the knee was aligned with the rotation axis of the isokinetic arm. Each subject's trunk was fixed to the isokinetic chair using a belt.

Each session consisted of 2 maximal voluntary contractions (MVCs) performed at the beginning of the protocol at a knee angle of 60° (full extension = 0°), followed by 4 sets of 20 maximal contractions (CON or ECC, depending the session) of the flexors and extensors of the knee (from knee angles of 0 – 90°) at $60^\circ/s$ separated by 2 min of rest. An MVC contraction was performed both immediately after the fatiguing protocol (Post0) and 5 min later (Post5) to evaluate the loss of force and force recovery after the strenuous exercise (Fig. 1).

Measurement of Maximal Muscle Strength and Rate of Force Development.

The isokinetic torque exerted by the knee flexors and extensors was measured continuously, and the data were exported to the EMG amplifier and analyzed offline using MATLAB software (R2012; The MathWorks, Inc., Natick, Massachusetts). The maximum torque output values associated with the dynamic contractions were obtained from the concentric and eccentric actions of the knee extensors. The maximum isometric values of the MVCs were also determined.

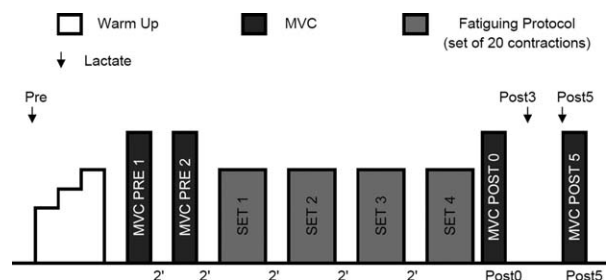


FIGURE 1. Experimental protocol: 4 sets of 20 maximal eccentric or concentric contractions separated by 2 minutes of rest were performed. Before and after each, several isometric contractions were performed (2 before, immediately after, and 5 minutes after). Lactate concentration values were obtained at the beginning of the protocol and 3 and 5 minutes afterward. Surface electromyography (amplitude, mean frequency, the Dimitrov fatigue index, and muscle conduction velocity) was recorded from the vastus lateralis muscle.

The rate of force development (RFD) determines the force that can be generated in the early phase of muscle contraction, that is, explosive muscle force. This parameter is obtained from the slope of the force–time curve ($\Delta\text{force}/\Delta\text{time}$) of the isometric contractions over time intervals. In this study, the RFD50 and RFD100 values, obtained in time intervals of 0–50 and 0–100 ms relative to the onset of contraction, respectively, were calculated.

Electromyography. Surface electromyography (sEMG) data were recorded throughout the experimental protocol from the vastus lateralis using a semi-disposable linear array of 8 electrodes, with a 5-mm interelectrode distance in a single differential configuration. Prior to electrode placement, the skin was shaved and cleaned with alcohol, and the innervation zone was located using a linear array of 16 electrodes with a 5-mm interelectrode distance. The array of 8 electrodes was then placed between the innervation zone and the distal tendon of the vastus lateralis, parallel to the muscle fibers.

To assure the same placement of electrodes on the muscle between sessions, the position of the electrodes was marked on the skin using a permanent marker. In addition, in both sessions, the innervation zone of the vastus lateralis was located to confirm and ensure a similar position of the electrodes between sessions.

sEMG signals were recorded using a 128-channel surface EMG amplifier (EMG-USB2; OT Bioelettronica, Torino, Italy) (3-dB bandwidth, 10–500 Hz) and sampled at a rate of 2048 samples per second per channel.

sEMG signals were analyzed using MATLAB software. The following parameters were obtained from the sEMG signals for evaluation of muscle fatigue, which included the root-mean-square (RMS) value, mean frequency, and the Dimitrov spectral parameter (Fl_{ms5}).²⁸ The mean of each parameter across the sEMG channels of the array was obtained.

The RMS and mean frequency were calculated in this study because these parameters are traditionally used to evaluate muscle fatigue. In addition, the Dimitrov fatigue index was determined, because it appeared to be more sensitive to changes in the sEMG power spectrum than the mean or median frequencies. This parameter represents the ratio between different moment orders (–1 and 5) and emphasizes the increases in the low and ultralow frequencies of the sEMG spectrum due to increased negative afterpotentials as well as the decreases in high frequencies due to increments in duration of intracellular action potentials and decrements in action potential propagation velocity. In addition, it was more accurate to track the changes in muscle

power loss during the fatiguing leg-press exercise than the other traditional sEMG parameters (median frequency or RMS).³

The last sEMG parameter studied was the velocity obtained via the multidip approach²⁹ using channels 3–6 of the electrode array. The parameters/factors employed to calculate the conduction velocity were the same as those described previously.²⁹

Blood Lactate. Capillary blood samples were obtained from the fingertip before the exercise and 3 min (Post3) and 5 min (Post5) post-exercise for the determination of lactate concentrations (Fig. 1).

After cleaning and puncturing the fingertip, the first blood sample was cleaned, and the second sample was immediately analyzed with a lactate meter (Lactate Pro; Arkay, Inc., Kyoto, Japan).

Echo Intensity. For the purpose of assessing muscle damage induced by the CON and ECC protocols, muscle echo intensity was measured before and 48 hours after the fatigue protocols. Images were obtained using B-mode ultrasonography (MyLab50Xvision; Esaote, Genoa, Italy), and the procedures for echo intensity assessment were adopted from previous studies.^{24,25,30} During image acquisition, the subjects remained supine with the tested leg relaxed (neutral position). The vastus lateralis measurement was performed midway between the lateral condyle of the femur and the greater trochanter,³¹ and the linear 10.0-MHz probe was positioned perpendicular to the evaluated muscle. A water-based gel was used to promote acoustic contact without causing excessive probe pressure on the skin during image acquisition. The ultrasound probe was placed on a marked site on a muscle belly at a consistent angle (90°), and pressure was applied to obtain a B-mode ultrasound image. To assure similar measurement characteristics (in terms of angle and pressure) to obtain comparable ultrasound images between sessions, an experienced investigator conducted all measurements. The echo intensity in the region of interest was assessed using ImageJ software, version 1.37 (National Institutes of Health, Bethesda, Maryland). Echo intensity of the vastus lateralis in each thigh was determined over a 2-cm² region, based on a gray-scale histogram (0 = black, 256 = white). The same investigator performed all echo intensity measurements. The coefficient of variation was 2.4%, and baseline test–retest reliability (intraclass correlation coefficient) was 0.92.

Statistical Analysis. SPSS statistical software (SPSS, Inc., Chicago, Illinois) was used to analyze the data. The results are reported as the mean \pm standard error (mean \pm SE) of the sEMG variables and

torque, and as the mean \pm standard deviation (mean \pm SD) for the other variables. Normal distribution parameters were checked using the Shapiro–Wilk test. Statistical comparisons between the parameters recorded in the 2 sessions (CON and ECC) were performed using paired Student *t*-test. Fatigue-related effects were assessed via 2-way analysis of variance (ANOVA) with repeated measures (type of protocol \times repetition). When a significant *F*-value was achieved, the least significant difference *post-hoc* procedure was employed to locate the differences. The selected relative changes between groups were compared by 1-way ANOVA. In addition, the reliability of measurements was calculated based on intraclass correlation coefficient (ICC) using single values. $P < 0.05$ was considered statistically significant.

RESULTS

Concentric and Eccentric Fatiguing Protocols.

Isokinetic Torque. A significant repetition effect ($P < 0.001$), protocol effect ($P < 0.001$), and repetition-vs.-protocol interaction ($P < 0.001$) were observed. The CON and ECC exercise protocols both resulted in significant decreases in mean torque, but the reduction of torque was significantly greater after the CON protocol than the ECC protocol (Fig. 2). Compared with the mean torque observed during the first 10 repetitions of the first set, the CON protocol reduced the mean torque in all of the torque intervals (i.e., in the second half of the first set, the first and second halves of the second set, the first and second halves of the third set, and the first and second halves of the fourth set; all $P < 0.001$). Compared with the mean torque observed during the first 10 repetitions of the first set, the ECC protocol resulted in decreases of mean torque only in the second half of the repetitions in all the sets

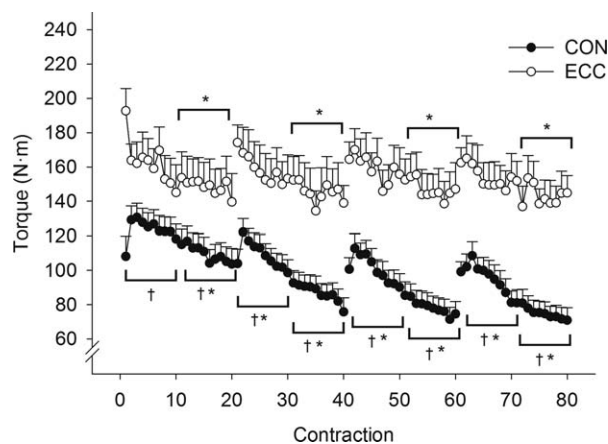


FIGURE 2. Isokinetic torque in the concentric (CON) and eccentric (ECC) exercises. *Significant difference with respect to the 10 repetitions of the first set ($P < 0.05$). †Significant difference between protocols ($P < 0.05$).

(first, second, third, and fourth; $P < 0.05$), and recovery of mean torque was observed during the first 10 repetitions of the second, third, and fourth sets. As expected, the ECC torque was always greater than the CON torque ($P < 0.001$).

Muscle Conduction Velocity during Dynamic Contractions. There was a significant repetition effect on conduction velocity (CV; $P < 0.05$). Both the CON and ECC exercise protocols resulted in decreased CV, and no differences were detected between the protocols. Compared with the values observed during the last 10 repetitions of the first set and the first 10 repetitions of the second set, both the CON and ECC protocols resulted in decreased CV in the second half of the last set ($P < 0.05$) (Fig. 3a).

Root-Mean-Square Values during Dynamic Contractions. No changes in root-mean-square (RMS) values were observed after the CON or ECC exercise protocols in any of the repetitions considered. As expected, the RMS values observed during the CON protocol were greater in all sets of the protocol (in the first and second halves of the sets) (from $P < 0.001$ to 0.05) than during the ECC protocol (Fig. 3b).

Dimitrov Fatigue Index during Dynamic Contractions. There were significant effects of repetition ($P < 0.001$), protocol ($P < 0.01$), and repetition-vs.-protocol interaction ($P < 0.001$) detected in the Dimitrov fatigue index values. Only the CON exercise protocol resulted in an increase in the Dimitrov fatigue index, with no difference being detected during the ECC protocol. Compared with the first 10 repetitions (first half) of the first set, the CON protocol resulted in an increased Dimitrov fatigue index in the second half of the first set ($P < 0.01$), the second half of the second set ($P < 0.001$), the first and second halves of the third set ($P < 0.01$), and the first ($P < 0.05$) and second ($P < 0.05$) halves of the fourth set. Excluding the first 10 repetitions of the first set, the Dimitrov fatigue index values during the CON protocol were greater than those observed during the ECC protocol ($P < 0.01$ –0.05) (Fig. 3c).

Mean Frequency Values during Dynamic Contractions. There were significant effects of repetition ($P < 0.001$), protocol ($P < 0.05$), and the repetition-vs.-protocol interaction ($P < 0.001$) observed in the mean frequency values. Only the CON exercise protocol resulted in decreased mean frequency values, with no difference being detected during the ECC protocol. Compared with the first 10 repetitions (first half) of the first set, the CON protocol resulted in reduced mean frequency values in the second half of the first set ($P < 0.001$), the first ($P < 0.05$) and second ($P < 0.001$) halves of the second set, the first ($P < 0.05$) and second ($P < 0.001$)

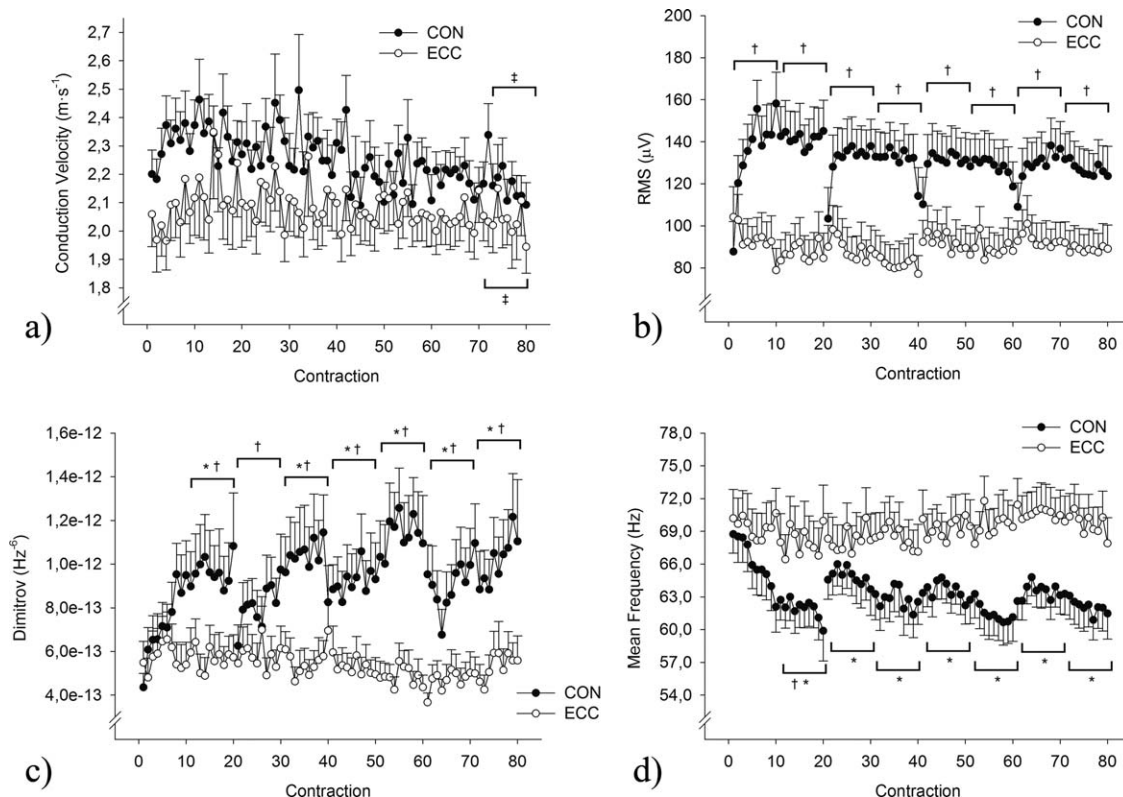


FIGURE 3. sEMG parameters in the concentric (CON) and eccentric (ECC) exercises. **(a)** Conduction velocity; **(b)** RMS values; **(c)** Dimitrov fatigue index (Flnsm5); and **(d)** mean frequency (MNF). *Significant difference with respect to the first 10 repetitions of the first set ($P < 0.05$); †Significant difference with respect to the last 10 repetitions of the first set ($P < 0.05$); ‡Significant difference between protocols ($P < 0.05$).

halves of the third set, and the first and second halves of the fourth set ($P < 0.01$) (Fig. 3d).

Pre- and Post-Isometric Contractions. *Isometric Torque.* Both the CON and ECC exercise protocols resulted in a decreased isometric peak torque immediately and 5 min after exercise ($P < 0.01$). The torque reduction was significantly greater after the CON than the ECC protocol immediately post-exercise ($P < 0.01$), but no difference was observed after 5 min. The isometric torque immediately after the exercise protocol was significantly lower after the CON than the ECC protocol ($P = 0.011$) (Table 1).

Rate of Force Development. There were significant effects of repetition ($P < 0.05$) and the repetition-vs.-protocol interaction ($P < 0.05$) on the slope of the rate recorded in the first 50 ms of the isometric contractions. The rate of force development (RFD) in the first 50 ms decreased significantly ($P < 0.05$) during both protocols immediately post-exercise, but returned to previous values after 5 min. However, the RFD in the first 50 ms was significantly lower after 5 min of the exercise protocol in the ECC compared with the CON protocol ($P < 0.05$) (Table 1).

There were significant effects of repetition ($P < 0.05$) and contraction ($P < 0.05$) on the slope of the rate obtained in the first 100 ms of the isometric contractions. As above, the RFD recorded in the first 100 ms decreased significantly ($P < 0.05$) in both protocols immediately post-exercise but returned to the previous values after 5 min. However, the RFD in the first 50 ms was significantly lower both immediately and 5 min after the exercise protocol in the ECC compared with the CON protocol ($P < 0.05$) (Table 1).

Muscle CV, RMS, and Dimitrov Fatigue Index during Isometric Contractions. There were no changes in the CV, RMS, or Dimitrov fatigue index values measured during the isometric contractions after either the CON or ECC exercise protocols in any of the repetitions evaluated (Table 1).

Mean Frequency Values during Isometric Contractions. There were significant effects of repetition ($P < 0.001$) and the repetition-vs.-protocol interaction ($P < 0.001$) on the mean frequency values obtained during the isometric contractions. Both the CON and ECC exercise protocols resulted in decreased mean frequency values immediately post-exercise ($P < 0.01$), but the reduction was

Table 1. Torque and sEMG parameters [conduction velocity (CV), root mean squared amplitude (RMS), mean frequency (MNF) and Dimitrov fatigue index (Fl_{nsm5}), pre-exercise, immediately post-exercise (Post0), and 5 minutes post-exercise (Post5) values obtained from the isometric contractions.

Parameter	Concentric			Eccentric		
	Pre-exercise	Post0	Post5	Pre-exercise	Post0	Post5
Torque (Nm)	198.8 ± 12.8	131.3 ± 10.3 [†]	160.1 ± 11.4 [*]	186.7 ± 12.0	148.5 ± 12.2 [*]	165.0 ± 11.5 [*]
RFD50 (Nm/s)	485.9 ± 100.9	201.8 ± 41.2 [*]	530.5 ± 71.9 [†]	526.9 ± 129.9	145.5 ± 17.9 [*]	272.4 ± 48.1
RFD100 (Nm/s)	445.7 ± 84.2	272.2 ± 46.8 [*]	421.3 ± 54.5 [†]	447.6 ± 87.4	157.7 ± 14.8 [*]	241.6 ± 41.8
CV (m/s)	2.3 ± 0.1	2.1 ± 0.1	2.2 ± 0.1	2.1 ± 0.1	2.2 ± 0.1	2.1 ± 0.1
RMS (μV)	144.2 ± 15.5	134.6 ± 14.3	127.9 ± 12.5	128.0 ± 15.1	116.2 ± 13.4	110.0 ± 12.5
MNF (Hz)	65.4 ± 1.9	60.8 ± 1.6 [†]	65.4 ± 1.8	67.3 ± 2.6	66.5 ± 2.1 [*]	70.6 ± 2.4
Fl _{nsm5} (Hz ⁻⁶) (10 ⁻¹³)	6.4 ± 1.1	9.3 ± 1.9	7.2 ± 1.5	5.4 ± 1.1	5.4 ± 0.9	3.8 ± 0.9

^{*}Significant difference ($P < 0.05$) with respect to the pre-exercise values.

[†]Significant difference between protocols ($P < 0.05$).

significantly greater after the CON than the ECC protocol. After 5 min, the mean frequency values returned to basal levels in both the CON and ECC protocols (Table 1).

Echo Intensity. Under basal conditions, no significant differences in echo intensity were observed between the exercised leg (99.2 ± 31.2) and the control leg (93.7 ± 27.5). In the exercised leg, there was a significant increase ($P < 0.01$) in the echo intensity values recorded 48 hours after the ECC protocol (113.9 ± 22.1), which were greater than those obtained 48 hours after the CON protocol (104.1 ± 26.0). No significant change in the echo intensity values was observed 48 hours after the CON protocol. However, after the CON ($P < 0.01$) and ECC ($P < 0.001$) protocols, the exercised leg displayed significantly greater echo intensity values than the control leg (CON: 88.7 ± 22.1 ; ECC: 84.2 ± 22.4).

Blood Lactate Concentrations. There were significant effects of repetition ($P < 0.001$) and the repetition-vs.-protocol interaction ($P < 0.001$) on the blood lactate concentration. Significant increases in blood lactate concentrations were detected 3 and 5 min after both the CON (1.4 ± 0.6 vs. 6.8 ± 2.2 vs. 6.4 ± 2.7 for pre-exercise vs. Post3 vs. Post5, respectively) and the ECC protocols (1.3 ± 0.5 vs. 4.4 ± 2.3 vs. 3.4 ± 1.7 for pre-exercise vs. Post3 vs. Post5, respectively) ($P < 0.001$). However, the increases were significantly greater after the CON protocol than after the ECC protocol ($430 \pm 226\%$ vs. $283 \pm 238\%$, respectively) ($P < 0.001$) (Fig. 4).

DISCUSSION

A unique finding of this study was that the CON and ECC fatigue protocols resulted in similar marked changes in muscle CV recorded during dynamic contractions and the RFD obtained at 50 ms and 100 ms. In contrast, the changes in the

other parameters (torque, lactate concentration, and sEMG parameters, including amplitude, Dimitrov fatigue index, and mean frequency associated with isometric or dynamic actions) were greater immediately after the CON fatigue protocol. As expected, the ECC protocol resulted in greater muscle damage 48 h after exercise, but this effect did not result in greater impairment of the examined neuromuscular parameters immediately after exercise. These results suggest that the sarcolemma damage produced by eccentric exercise and the metabolic impact produced by the concentric fatiguing exercise may cause comparable impairment of action potential transmission along muscle fibers, as measured based on the muscle CV. In addition, the lower RFD values recorded 5 min after the ECC fatigue protocol compared with the CON protocol may also be related to an impairment of explosive force production due to muscle damage. However, the other parameters studied (mean frequency, Dimitrov fatigue index, sEMG amplitude, and torque) may have been more influenced by accumulation of hydrogen ions and

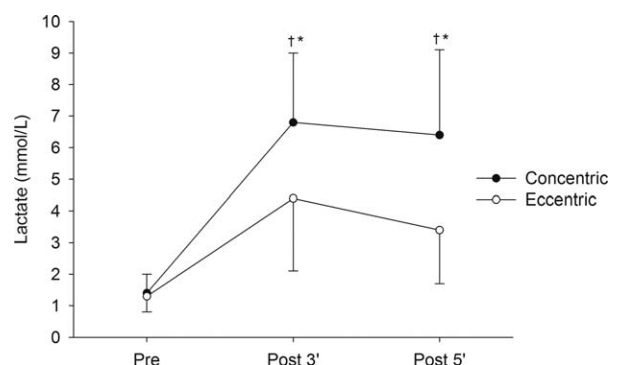


FIGURE 4. Lactate concentrations (mmol/L) (mean ± SD) before and after 3 and 5 minutes of concentric (filled circles) and eccentric (open circles) protocols (4×20 repetitions). ^{*}Significant difference from pre-exercise values ($P < 0.001$). [†]Significant difference from eccentric protocol ($P < 0.001$).

therefore showed greater changes after the CON protocol.

Although both the CON and ECC protocols led to increased echo intensity values in the exercised leg compared with the control leg, significant increases in echo intensity were only observed at 48 h after ECC exercise. Other studies have also shown higher echo intensity values in the days after eccentric exercise.^{24,26,27} In addition, traditional resistance exercise, consisting of both concentric and eccentric actions, also results in increased echo intensity.²⁵ A unique finding of our study is that the observed echo intensity response was greater after the ECC protocol than after the CON protocol, which suggests that evaluation of the echo intensity was an appropriate technique for detecting differences in muscle damage induced by the ECC and CON protocols. Furthermore, resulting in even greater muscle damage, the ECC protocol induced smaller decreases in peak dynamic torque and mean frequency, smaller increases in the Dimitrov fatigue index, and decreased CV, similar to the CON protocol immediately after exercise.

The CV decreased acutely during both the CON and ECC protocols and was lower during the last 10 repetitions of the last set (fourth) than in the last 10 repetitions of the first set. Our results are in contrast to findings by Piitulainen *et al.*,³² who observed decreased CV during isometric contractions only 2 hours after the applied eccentric protocol, whereas no changes were observed immediately after either their concentric or eccentric protocols. The discrepancies between these results may be explained by the different conditions that were used to assess CV. In the study by Piitulainen *et al.*,³² this parameter was measured only during isometric contraction, whereas in our study it was assessed during both the dynamic and isometric contractions. In agreement with the results of Piitulainen *et al.*,³² no changes were observed in CV during the isometric contractions performed immediately after the concentric or eccentric actions. However, the decreases observed by Piitulainen *et al.*³² at 2 hours after eccentric exercise may be related to a delayed influence of the resultant muscle damage on neural function that may arise after a longer recovery period. Based on our results, it can be suggested that, independent of the contraction type (i.e., concentric or eccentric), there is a decrease in CV induced by fatigue during dynamic actions, which may not be observed during isometric actions, and this result could be related to the specificity of the muscle contraction. From this perspective, it is possible that the changes in CV due to fatigue or muscle damage induced in the dynamic protocols are observed

more readily during dynamic than during isometric contractions.

On the other hand, significant changes were detected in the other sEMG parameters analyzed (RMS, mean frequency, and Dimitrov fatigue index) compared with the initial values (first 10 repetitions of the first set) associated with the concentric exercise, whereas no changes were detected when the eccentric exercise was analyzed. The results obtained from the CON fatigue protocol (torque, sEMG amplitude, Dimitrov fatigue index, mean frequency, and lactate levels) were similar to those obtained in other studies performed by our research group involving the concentric fatiguing leg-press exercise.^{4,33} Under the CON protocol, the amplitude of the sEMG signal increased due to the additional recruitment of motor units and/or changes in the shape of the intracellular action potential as well as increases in negative afterpotentials due to muscle fatigue.³⁴ We detected decreases in mean frequency during the last contractions of each set. This result may be explained as a result of the changes in shape of the motor unit action potentials produced by changes in CV.³⁵ However, Bigland-Ritchie *et al.*³⁶ and Broman *et al.*³⁷ suggested that there must be additional factors other than changes in CV that could affect the power spectrum of the sEMG, as they did not detect equal changes in CV and the sEMG power spectrum. Our results are in agreement with this assumption, because different behaviors of mean frequency and CV were observed during the progression of concentric muscle fatigue. However, as the action potentials detected on the skin surface along muscle fibers are, in practice, not equal in shape, estimation of the delay in propagation and therefore CV is a difficult task.²² Thus, the different behaviors of the mean frequency and the CV recorded during fatiguing contractions may also be related to inaccuracies in estimation of CV.

The final sEMG parameter studied, the Dimitrov fatigue index, was found to increase during the concentric fatiguing exercise, which is in agreement with other results obtained by our research group.⁴ This parameter was observed to increase during muscle fatigue, as it emphasizes the increases in the low and ultralow frequencies of the sEMG spectrum due to increased negative afterpotentials, decreases in the high frequencies due to increments in the duration of intracellular action potentials, and decrements in the action potential propagation velocity.²⁸

However, fatigue-related evolution of the sEMG parameters due to eccentric fatigue was different from the evolution observed during concentric fatigue. In contrast to the results obtained during the concentric exercise, we did not detect significant changes in the spectral parameters (mean frequency

or Dimitrov fatigue index) during the eccentric fatiguing exercise. This result is not novel, as other investigators found that the power spectrum of the sEMG signal does not change during eccentric contractions.¹³ These opposing results (for concentric vs. eccentric exercises) may be related to the greater muscle metabolic impact induced by the CON protocol, as suggested by the higher lactate values obtained, which could have a stronger impact on neuromuscular function and therefore induce greater changes in sEMG parameters.²⁰ A number of other investigators have also found higher lactate values after a CON protocol than after an ECC protocol.^{19,38,39} It has been suggested that the accumulation of hydrogen ions as well as the inorganic phosphate concentration may interfere with calcium ion-binding sites at the troponin level.⁴⁰ These findings may explain the reduced mechanical force output and greater changes in EMG parameters detected during the CON fatigue protocol compared with the ECC protocol.

In summary, both the concentric and the eccentric fatigue protocols applied in this study resulted in marked changes in neuromuscular parameters (isometric and isokinetic torque, mean frequency, and isokinetic Dimitrov fatigue index), but the magnitude of the changes was greater immediately after the concentric protocol. On the other hand, the muscle conduction velocity decreased to the same extent during the concentric and eccentric protocols. These neuromuscular changes occurred despite the greater muscle damage induced by the eccentric protocol, as observed in the echo intensity values obtained 48 h after exercise. Our results suggest that, immediately after exercise, the stronger metabolic impact induced by the concentric protocol, as assessed by lactate values, has a greater negative influence on neuromuscular function than the local muscle damage induced by the eccentric protocol.

REFERENCES

- Al-Mulla MR, Sepulveda F, Colley M. A review of non-invasive techniques to detect and predict localised muscle fatigue. *Sensors* 2011;11:3545–3594.
- Cifrek M, Medved V, Tonkovic S, Ostojic S. Surface EMG based muscle fatigue evaluation in biomechanics. *Clin Biomech (Bristol, Avon)* 2009;24:327–340.
- Gonzalez-Izal M, Malanda A, Gorostiaga E, Izquierdo M. Electromyographic models to assess muscle fatigue. *J Electromyogr Kinesiol* 2012;22:501–512.
- Gonzalez-Izal M, Malanda A, Navarro-Amezqueta I, Gorostiaga EM, Mallor F, Ibanez J, et al. EMG spectral indices and muscle power fatigue during dynamic contractions. *J Electromyogr Kinesiol* 2010;20:233–240.
- Izquierdo M, Gonzalez-Izal M, Navarro-Amezqueta I, Calbet J, Ibanez J, Malanda A, et al. Effects of strength training on muscle fatigue mapping from sEMG and blood metabolites. *Med Sci Sports Exerc* 2011;43:303–311.
- Alfredson H. The chronic painful Achilles and patellar tendon: research on basic biology and treatment. *Scand J Med Sci Sports* 2005;15:252–259.
- Proske U, Morgan DL. Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications. *J Physiol* 2001;537:333–345.
- Chleboun GS, Howell JN, Conatser RR, Giesey JJ. Relationship between muscle swelling and stiffness after eccentric exercise. *Med Sci Sports Exerc* 1998;30:529–535.
- Kay AD, Blazevich AJ. Isometric contractions reduce plantar flexor moment, Achilles tendon stiffness, and neuromuscular activity but remove the subsequent effects of stretch. *J Appl Physiol* 2009;107:1181–1189.
- Hamlin MJ, Quigley BM. Quadriceps concentric and eccentric exercise 1: changes in contractile and electrical activity following eccentric and concentric exercise. *J Sci Med Sport* 2001;4:88–103.
- Newham DJ, Mills KR, Quigley BM, Edwards RH. Pain and fatigue after concentric and eccentric muscle contractions. *Clin Sci (Lond)* 1983;64:55–62.
- Linnamo V, Bottas R, Komi PV. Force and EMG power spectrum during and after eccentric and concentric fatigue. *J Electromyogr Kinesiol* 2000;10:293–300.
- Tesch PA, Dudley GA, Duvoisin MR, Hather BM, Harris RT. Force and EMG signal patterns during repeated bouts of concentric or eccentric muscle actions. *Acta Physiol Scand* 1990;138:263–271.
- Pasquet B, Carpentier A, Duchateau J, Hainaut K. Muscle fatigue during concentric and eccentric contractions. *Muscle Nerve* 2000; 23:1727–1735.
- Mullaney MJ, McHugh MP. Concentric and eccentric muscle fatigue of the shoulder rotators. *Int J Sports Med* 2006;27:725–729.
- Kawakami Y, Kanehisa H, Ikegawa S, Fukunaga T. Concentric and eccentric muscle strength before, during and after fatigue in 13 year-old boys. *Eur J Appl Physiol Occup Physiol* 1993;67:121–124.
- Bonato P, Roy SH, Knafitz M, De Luca CJ. Time-frequency parameters of the surface myoelectric signal for assessing muscle fatigue during cyclic dynamic contractions. *IEEE Trans Biomed Eng* 2001;48:745–753.
- Ryschon TW, Fowler MD, Wysong RE, Anthony A, Balaban RS. Efficiency of human skeletal muscle in vivo: comparison of isometric, concentric, and eccentric muscle action. *J Appl Physiol* 1997;83:867–874.
- Durand RJ, Castracane VD, Hollander DB, Tryniecki JL, Bammam MM, O'Neal S, et al. Hormonal responses from concentric and eccentric muscle contractions. *Med Sci Sports Exerc* 2003;35:937–943.
- Tesch PA, Komi PV, Jacobs I, Karlsson J, Viitasalo JT. Influence of lactate accumulation of EMG frequency spectrum during repeated concentric contractions. *Acta Physiol Scand* 1983;119:61–67.
- Allen DG, Lamb GD, Westerblad H. Skeletal muscle fatigue: cellular mechanisms. *Physiol Rev* 2008;88:287–332.
- Farina D, Merletti R. Methods for estimating muscle fibre conduction velocity from surface electromyographic signals. *Med Biol Eng Comput* 2004;42:432–445.
- Allen DG. Eccentric muscle damage: mechanisms of early reduction of force. *Acta Physiol Scand* 2001;171:311–319.
- Chen TC, Lin KY, Chen HL, Lin MJ, Nosaka K. Comparison in eccentric exercise-induced muscle damage among four limb muscles. *Eur J Appl Physiol* 2011;111:211–223.
- Radaelli R, Bottaro M, Wilhelm EN, Wagner DR, Pinto RS. Time course of strength and echo intensity recovery after resistance exercise in women. *J Strength Cond Res* 2012;26:2577–2584.
- Chen TC, Chen HL, Lin MJ, Chen CH, Pearce AJ, Nosaka K. Effect of two maximal isometric contractions on eccentric exercise-induced muscle damage of the elbow flexors. *Eur J Appl Physiol* 2013;113:1545–1554.
- Nosaka K, Newton M, Sacco P, Chapman D, Lavender A. Partial protection against muscle damage by eccentric actions at short muscle lengths. *Med Sci Sports Exerc* 2005;37:746–753.
- Dimitrov GV, Arabadzhiev TI, Mileva KN, Bowtell JL, Crichton N, Dimitrova NA. Muscle fatigue during dynamic contractions assessed by new spectral indices. *Med Sci Sports Exerc* 2006;38:1971–1979.
- Farina D, Negro F. Estimation of muscle fiber conduction velocity with a spectral multidip approach. *IEEE Trans Biomed Eng* 2007;54:1583–1589.
- Chapman DW, Newton M, McGuigan M, Nosaka K. Effect of lengthening contraction velocity on muscle damage of the elbow flexors. *Med Sci Sports Exerc* 2008;40:926–933.
- Kumagai K, Abe T, Brechue WF, Ryushi T, Takano S, Mizuno M. Sprint performance is related to muscle fascicle length in male 100-m sprinters. *J Appl Physiol* 2000;88:811–816.
- Piitulainen H, Botter A, Merletti R, Avela J. Muscle fiber conduction velocity is more affected after eccentric than concentric exercise. *Eur J Appl Physiol* 2011;111:261–273.
- Izquierdo M, Ibanez J, Calbet JA, Gonzalez-Izal M, Navarro-Amezqueta I, Granados C, et al. Neuromuscular fatigue after resistance training. *Int J Sports Med* 2009; 30:614–623.
- Dimitrova NA, Dimitrov GV. Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies. *J Electromyogr Kinesiol* 2003;13:13–36.

35. Lindstrom L, Magnusson R, Petersen I. Muscular fatigue and action potential conduction velocity changes studied with frequency analysis of EMG signals. *Electromyography* 1970;10:341–356.
36. Bigland-Ritchie B, Donovan EF, Rousso CS. Conduction velocity and EMG power spectrum changes in fatigue of sustained maximal efforts. *J Appl Physiol* 1981;51:1300–1305.
37. Broman H, Bilotto G, De Luca CJ. Myoelectric signal conduction velocity and spectral parameters: influence of force and time. *J Appl Physiol* 1985;58:1428–1437.
38. Dufour SP, Lampert E, Doutreleau S, Lonsdorfer-Wolf E, Billat VL, Piquard F, et al. Eccentric cycle exercise: training application of specific circulatory adjustments. *Med Sci Sports Exerc* 2004;36:1900–1906.
39. Perrey S, Betik A, Candau R, Rouillon JD, Hughson RL. Comparison of oxygen uptake kinetics during concentric and eccentric cycle exercise. *J Appl Physiol* 2001;91:2135–2142.
40. Nakamura Y, Schwartz S. The influence of hydrogen ion concentration on calcium binding and release by skeletal muscle sarcoplasmic reticulum. *J Gen Physiol* 1972;59:22–32.