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Mechanical and EMG responses of the vastus lateralis and changes in biochemical variables to isokinetic exercise in endurance and power athletes

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Abstract

Twelve endurance athletes and six power athletes performed fatiguing isokinetic knee flexions/extensions. Isokinetic torque was recorded during the exercise. Isometric torque, cortisol and lactate responses, electromyographic (EMG) mean power frequency, average rectified value, and conduction velocity were analysed before and after the isokinetic exercise to determine correlations between electrophysiological variables and mechanical performances and/or blood concentrations of biomarkers in the two groups of athletes. The EMG variables were estimated from signals recorded from the vastus lateralis in both voluntary and electrically elicited isometric contractions. Power athletes recorded higher values than endurance athletes for the following variables: pre-exercise isometric maximal voluntary contraction (MVC), isokinetic MVC, rate of mechanical fatigue during isokinetic contractions, pre–post exercise variations and recovery times of conduction velocity and mean power frequency, and lactate concentrations. Moreover, conduction velocity overshooting was observed in endurance athletes during the recovery phase after exercise. The correlation analyses showed that the higher the rate of mechanical fatigue, the higher the lactate production and the reduction in conduction velocity due to the exercise.

Keywords: *Isokinetic exercise, cortisol, lactate, myoelectric manifestations of fatigue, electrically elicited contractions*

Introduction

Muscle contraction results in the production of force, electromyographic (EMG) signals, and changes in the blood concentration of specific biomarkers. It has been demonstrated that these quantities are related and affected by fatigue and fibre type distribution in the investigated muscle(s). Many authors (Bosco & Komi, 1979; Colliander, Dudley, & Tesch, 1988; Froese & Houston, 1985; Inbar, Kaiser, & Tesch, 1981; Suter, Herzog, Sokolosky, Wiley, & Macintosh, 1993; Thorstensson & Karlsson, 1976) have reported that mechanical performance (peak force, endurance, jumping time) of the vastus lateralis is related to the proportion of fast-twitch fibres within the muscle. Others (Bouissou, Estrade, Goubel, Guezennec, & Serrurier, 1989; Brody, Pollock, Roy, De Luca, & Celli, 1991; Gerdle, Henriksson-Larsen, Lorentzon, & Wretling, 1991; Komi & Tesch, 1979; Lindstrom, Magnusson, & Petersen, 1970; Mannion, Dumas, Stevenson, & Cooper, 1998; Tesch, Sjodin, & Karlsson, 1978; Vestergaard-Poulsen, Thomsen, Sinkjaer, & Henriksen, 1995) have reported correlations between fibre type distribution and muscle fibre conduction velocity and/or spectral features such as median and/or mean frequency. Some have observed that the reduction in these variables during sustained isometric contractions was associated with a decrease in blood pH and was a function of fibre type distribution (Bouissou *et al.*, 1989; Brody *et al.*, 1991; Komi & Tesch, 1979; Kupa, Roy, Kandarian, & De Luca, 1995; Lindstrom *et al.*, 1970).

Biochemical assays of blood samples, drawn serially from individuals performing an intense aerobic exercise that exceeds 60% of maximal aerobic power (Luger *et al.*, 1987) or anaerobic exercise above maximal oxygen uptake (Buono, Yeager, & Hodgdon, 1986), show the activation of the hypothalamic–pituitary–adrenal axis. The amount of activation depends on the type (Hackney, Premo, & McMurray, 1995; Hakkinen & Pakarinen,

1993) and timing of exercise (Kanaley, Weltman, Pieper, Weltman, & Hartman, 2001).

An integrated approach to the assessment of muscle fatigue, based on correlations among biochemical markers, mechanical and EMG variables, is still lacking. The aim of this study was to test the hypothesis that non-invasive (such as force and EMG measurements) or minimally invasive (such as blood sampling) techniques provide insight into such correlations. Endurance athletes and power athletes were studied. Electromyographic signals were recorded from the vastus lateralis because: (1) many studies have reported a correlation between fibre type distribution resulting from muscle biopsies and EMG or force modifications due to chronic stress (Mador & Bozkanat, 2001), physical exercise (e.g. Tesch, Thorsson, & Kaiser, 1984), or pathological conditions (Falla, Rainoldi, Merletti, & Jull, 2003); and (2) the suitability of the vastus lateralis for surface EMG investigations (Rainoldi, Melchiorri, & Caruso, 2004).

The main hypothesis was broken down into the following series of questions:

1. Is the selected exercise suited to generate a significant increase in serum lactate and cortisol?
2. Is the production of lactate and cortisol different in power and in endurance athletes?
3. Are mechanical and myoelectric manifestations of muscle fatigue different in power and endurance athletes?
4. Are the recovery times of mechanical and myoelectric manifestations of muscle fatigue different in power and endurance athletes?
5. Are the time patterns of serum lactate and cortisol serum concentrations reflected in the mechanical and EMG variables?

Materials and methods

Participants

Thirteen endurance male athletes (three marathon runners, one long-distance cyclist, one triathlete, seven rowers, one cross-country skier) and seven power male athletes (three alpine skiers, three bodybuilders, one volleyball player) participated in the study (see Table I for their physical characteristics). All athletes had competed at national or international standard and were tested during the training-out-of competition period of their season. None of the participants smoked or was receiving medication. They were instructed to abstain from caffeine and alcohol consumption and to refrain from any strenuous physical activity in the 24 h before the study. Tests were always performed in the afternoon (16.00 h) 3 h after a standardized meal. A complete medical examination was performed for all participants and they were thoroughly informed about the purposes and procedures of the study before providing written informed consent. The study conformed with the guidelines in the Declaration of Helsinki and was approved by the regional ethics committee.

Table I. Age, body mass index (BMI), training history, and subcutaneous tissue thickness of the endurance and power athletes (mean $\pm$ *s*).

	Endurance ($n = 13$)	Power ($n = 7$)	*P*-value
Age (years)	25.2 $\pm$ 7.8	32.0 $\pm$ 5.9	N.S. (0.07)
BMI ($kg \cdot m^{-2}$)	22.8 $\pm$ 1.8	24.9 $\pm$ 3.2	N.S.
Training history (years)	6.8 $\pm$ 5.2	11.4 $\pm$ 3.9	N.S.
Subcutaneous tissue thickness (mm)	2.8 $\pm$ 0.7	3.1 $\pm$ 0.9	N.S.

Experimental procedure

Consistent with previous studies (Aagaard & Andersen, 1998; Bosco & Komi, 1979; Suter *et al.*, 1993; Thorstensson & Karlsson, 1976) we used maximal isokinetic knee extension torque and its rate of decrease during the isokinetic exercise as indexes of mechanical performance. Before, immediately after, and at different times during the subsequent 120 min of recovery after the isokinetic exercise, blood was sampled to determine cortisol and lactate concentrations in serum, and isometric maximal contractions were performed by both voluntary contraction (MVC) of the knee extensors of the dominant leg and transcutaneous electrical stimulation of the vastus lateralis to assess the time course of mechanical and myoelectric manifestations of fatigue.

As previously described, one of the aims of this study was to assess the time course of biochemical variables during and after exercise. To achieve this goal, an exercise intensity was required that could elicit significant variation of such biomarkers. For this reason, the participants were asked to perform the exercise with both legs, to increase the chance of a systemic response. For practical reasons, the order of testing was non-dominant leg followed by dominant leg so that the dominant leg would be ready for the isometric test (and the evaluation of myoelectric fatigue) immediately after completion of the isokinetic exercise. Due to exercise intensity, however, the contractions performed with the dominant leg were impaired by the fatigue elicited by the previous isokinetic contractions (performed with the non-dominant leg). For this reason and because no significant differences are usually found in MVC between the two legs

(Rainoldi, Bullock-Saxton, Cavarretta, & Hogan, 2001), we decided to increase the significance of the correlation analyses using the isokinetic performance of the non-dominant leg.

For each individual experimental session, the following protocol was adopted:

1. *Basal reference trial (PRE)*. An antecubital venous catheter was inserted 30 min before starting the warm-up. Two blood samples, collected 15 and 5 min before the warm-up, were taken. Cortisol and lactate concentrations were averaged to establish pre-exercise baseline values. After the warm-up exercise on a cycle ergometer (15 min cycling at 75 – 100 W and stretching of the muscles), the participant was positioned on the dynamometer and three isometric MVCs were performed with the dominant leg (5 s duration with 3 min of recovery between MVCs). Visual feedback on torque was provided to the participant during the MVC contractions. The participant was encouraged to exceed the torque value obtained in the previous contraction. The EMG signals were recorded during the three MVC attempts and the highest of the three MVC values and the corresponding EMG signal were used as the reference. An electrically elicited contraction was then generated at a frequency of 25 Hz (rectangular current pulses with width of 0.3 ms) for 5 s in supramaximal mode (that is, with the stimulation amplitude above the value generating the maximal M-wave) and the EMG signal (recorded from the dominant leg with electrodes placed in the same positions as in the voluntary trial) was stored.
2. *Fatiguing exercise (EXE)*. After 3 min of recovery and 2 – 3 short tests, used to accustom the athletes to the isokinetic exercise, the athlete undertook, for each leg, four sets of 20 maximal contractions of the knee extensor muscles at an angular velocity of 3.14 $\mathrm{rad \cdot s^{-1}}$, starting with the non-dominant leg. A 30-s rest was allowed between sets and a 3-min rest period (INT) between testing of the two legs. The complete exercise routine (a total of 80 maximal knee extensions for each leg) was completed in about 15 min.
3. *End of the fatiguing exercise (POST) and recovery*. Immediately after the exercise, the dominant leg was evaluated as follows: a second electrically elicited contraction identical to the first was generated and the induced EMG signal recorded; then the participant was requested to perform a single MVC and the corresponding EMG signal was recorded. The same procedure was repeated after 15, 30, 45, 60, 90, and 120 min. Blood for cortisol determination was sampled immediately after the exercise and 7, 15, 30, 45, 60, 90, and 120 min thereafter. Blood for lactate determination was sampled during the recovery time between the two legs (INT), immediately after exercise, and 30, 60, and 120 minutes thereafter. Each blood sample was 10 ml.

Instrumentation and measurements

A Cybex 6000 device (Cybex, Division of Lumex Inc., Ronkonkoma, USA) was used for isokinetic exercise and isometric MVC contractions. The participant was seated on the Cybex with the axis of rotation of the dynamometer aligned with the knee joint line. The backrest and seat angles were adjusted so that the hip was at approximately 80° of flexion. A strap was placed across the participant's pelvis to minimize hip movement during the tests. The cuff (load cell) of the Cybex was placed at a distance of 50% of the lower leg length (measured from the top of the fibular head to the mid-point of the lateral malleolus). The knee joint was placed at 90° of flexion for all MVC testing. Isokinetic contractions of the knee extensor muscles were performed at an angular velocity of 3.14 $\mathrm{rad \cdot s^{-1}}$ throughout a constant range of motion of 100° (between 75° and 175°, with 180° being full extension).

Surface EMG signals were detected from the vastus lateralis using a linear array (Merletti, Farina, & Gazzoni, 2003) of eight electrodes (silver bars 10 mm apart, 5 mm long, 1 mm diameter; OT Bioelettronica, Rivarolo, Italy) in a single differential configuration; double differential signals were computed off-line for estimation of conduction velocity. The skin was lightly abraded with abrasive paste and cleaned with water before electrode placement. The ground electrode was placed on the wrist. The most sensitive (maximal mechanical response with the minimum current injected) motor point over the vastus lateralis was identified and an adhesive stimulation electrode (Spes Medica, Milano, Italy) was placed over it. Thereafter, the optimal position and orientation of the array was searched and selected as described by Rainoldi *et al.* (2004). Reference points of the selected locations were marked on the skin for correct electrode replacement for both the voluntary and electrically elicited contraction during each trial.

The EMG signals, amplified at a bandwidth of 10 – 500 Hz (EMG16-16 channel amplifier, LISiN Centro di Bioingegneria, Politecnico di Torino, Torino, Italy), were sampled at 2048 samples per second, digitized by a 12-bit analog-to-digital converter, and stored on a disk of a personal computer. Since the subcutaneous tissue thickness under the

electrode array strongly affects EMG variable estimates (Farina & Rainoldi, 1999), this thickness was measured over the linear array location adopted during EMG signal acquisition using an ultrasound device at the end of each session (FFSonic UF-4000L, 9 MHz linear array transducer, Fukuda Denshi, Tokyo, Japan).

Serum lactate concentrations were measured spectrophotometrically with an Aeroset analyser (Abbott Laboratories, Abbott Park, IL, USA), while serum cortisol was measured by radioimmunoassay (Sorin Biomedica, Saluggia, Italy). Sera were immediately separated and stored at -20°C until ready for assay. All samples for each participant were processed in duplicate in the same assay session. Calculated sensitivities of the assays were for $0.5\ \mu g \cdot dl^{-1}$ for serum cortisol and $0.9\ mmol \cdot l^{-1}$ for serum lactate. Intra- and inter-assay coefficients of variation for the above-mentioned assays were below 6% and 8% respectively.

Data management and statistical analysis

Biochemical variables. Serum concentrations of cortisol and lactate were evaluated using different sampling schedules, since their responses to exercise are characterized by two different dynamics. The area under the response curve of these biochemical variables was calculated.

Mechanical variables. The studied mechanical variables were: (1) the peak torque recorded by the dominant leg during the isometric MVC in each trial; (2) the peak extension torque recorded by the non-dominant leg (i.e. the first leg tested) during the isokinetic exercise (MVC_{ISK}); and (3) the rate of change of the maximal voluntary extension torque produced by the non-dominant leg during the isokinetic exercise ($SLOPE_{ISK}$) (Figure 1).

EMG variables. The surface EMG variables of interest were: (1) mean frequency (MNF, Hz) of the power spectral density, (2) average rectified value (ARV, μV), and average muscle fibre conduction velocity (CV, $m \cdot s^{-1}$). Values for these variables were calculated for each available triplet, as previously described (Merletti, Knaflitz, & De Luca, 1990). A triplet was defined as a group of three consecutive single differential signals (five triplets in total provided by the eight electrode array). The EMG estimates used for further analysis were obtained from the best of the five triplets. The repeatability of such estimates was assessed in a previous study of the vastus lateralis, in which the same equipment was used (Rainoldi *et al.*, 2001). In the case of voluntary isometric contractions, the best triplet was the one showing the highest correlation coefficient between the two double differential signals (>0.70) and physiological estimates of conduction velocity (range $3-6\ m \cdot s^{-1}$). Conduction velocity and mean frequency were estimated in epochs of 0.5 s centred in the time corresponding to the peak average rectified value. Average rectified values were also estimated in epochs of 0.5 s. In the case of electrically elicited contractions, a negligible truncation of the M-wave due to the subsequent stimulus was a requisite in addition to the criteria described for voluntary contractions. The EMG variables were computed from the M-wave resulting from the average of 12 responses (30 ms averaging time).

Statistical analysis

Mechanical, EMG, and biochemical modifications *within* each group throughout recovery were assessed with the non-parametric Wilcoxon paired test. The differences *between* the two groups (endurance vs. power) were analysed for each trial using analysis of

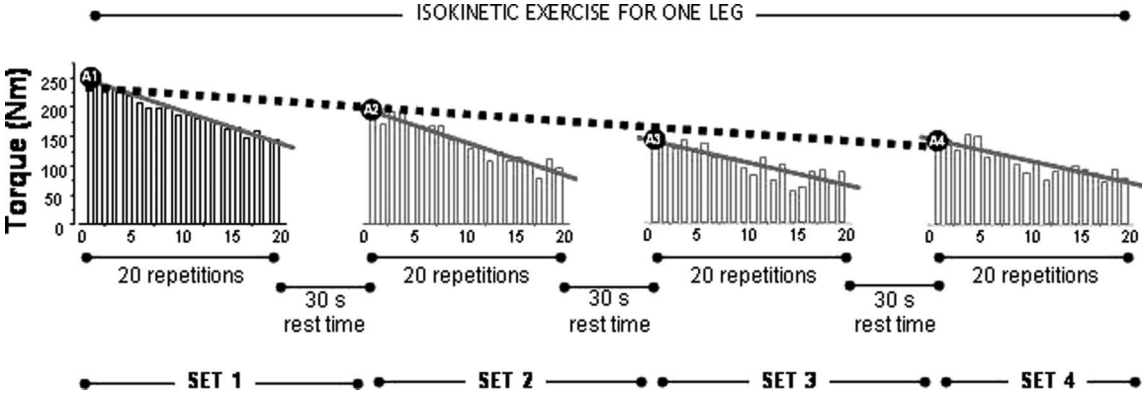

Figure 1. Schematic representation of the isokinetic exercise test. Four sets of 20 maximal contractions of the knee extensor muscle groups were performed for each leg. $SLOPE_{ISK}$ ($N \cdot m$/set) was obtained as the rate of change of the regression line (dotted line) fitting the A1, A2, A3, and A4 points (i.e. the intercepts of the regression lines – grey lines – within each of the four sets performed with the non-dominant leg). MVC_{ISK} is defined as point A1 of the non-dominant leg and the corresponding unit is $N \cdot m$.

covariance (ANCOVA) (covariates: age, body mass index, training duration, and subcutaneous tissue thickness) of all studied variables. The Spearman rank-order coefficient was also used to check for correlations among all pairs of measured variables. Statistical analysis was performed with the Statistica 6 for Windows (Statsoft Inc., Tulsa, OK) software package. All values are reported as means and standard deviation (s). Statistical significance was set at $P < 0.05$.

Results

Because of problems with the Cybex data recording procedure, mechanical information (MVC and $SLOPE_{ISK}$) was lost for one endurance athlete and one power athlete studied on the same day. In addition, the quality of the EMG signals for the same two participants and another two endurance athletes did not meet the specified criteria. Thus data used for mechanical comparisons were from 12 endurance athletes and 6 power athletes, whereas data used for EMG comparisons were from 10 endurance athletes and 6 power athletes.

Biochemical variables

The isokinetic exercise test elicited significant serum cortisol and lactate responses in the two groups of athletes, as shown in Table II (Wilcoxon paired test). Table II also shows, for each variable, the mean pre-exercise, post-exercise and recovery values, and the absolute levels of the area under the response curve. No differences were found between the cortisol responses in the two groups, whereas the power athletes showed a higher lactate response than the endurance athletes (Figure 2). No significant interaction was evident between biochemical variables and the following factors: age, body mass index, training history, and subcutaneous tissue thickness.

Mechanical variables

Significant differences were observed between the two groups for pre-exercise isometric MVC (power athletes: 353 $N \cdot m$, $s = 63$; endurance athletes: 268 $N \cdot m$, $s = 62$; $P = 0.03$) and pre- to post-exercise decreases (power athletes: 34.5%, $s = 11.8$; endurance athletes: 17.3%, $s = 10.4$; $P = 0.03$). No significant difference was observed immediately after exercise and in the following 2 h of recovery. When scaling by body mass raised to an allometric exponent of 0.67 (Jaric, 2002) was introduced, pre-exercise isometric MVC was higher ($P < 0.05$, Mann-Whitney U-test) in the power (18.08 $N \cdot m \cdot kg^{-1}$, $s = 2.85$) than in the endurance athletes (14.59 $N \cdot m \cdot kg^{-1}$, $s = 2.92$), as anticipated.

Peak extension torque during the isokinetic exercise (MVC_{ISK}) was significantly dependent on

Table II. Biomechanical responses of endurance and power athletes to the isokinetic exercise test.

	Endurance ($n = 12$)		Power ($n = 6$)		Within-group P-value	
	Mean	s	Mean	s	Endurance	Power
Cortisol ($\mu g \cdot dl^{-1}$)						
PRE	20.8	8.2	15.8	8.0	–	–
POST	25.9	12.5	21.7	9.2	N.S.	<0.05
+7 min	31.1	16.9	27.1	8.6	<0.05	<0.05
+15 min	28.1	12.0	31.4	7.0	<0.05	<0.05
+30 min	29.3	13.6	38.2	7.7	N.S.	<0.05
+45 min	29.0	16.0	34.8	9.7	N.S.	<0.05
+60 min	24.8	11.8	30.6	11.4	N.S.	<0.05
+90 min	25.5	16.8	26.7	11.4	N.S.	<0.05
+120 min	18.7	8.6	24.0	8.6	N.S.	N.S.
AUC ($\mu g \cdot dl^{-1} \cdot 150$ min)	1303.1	992.0	1906.5	721.2		
Lactate ($mmol \cdot l^{-1}$)						
PRE	1.2	0.5	1.1	0.2	–	–
INT	10.4	2.8	14.3	3.0	<0.05	<0.05
POST	11.1	2.6	15.0	1.5	<0.05	<0.05
+30 min	5.6	2.4	9.1	1.7	<0.05	<0.05
+60 min	3.2	1.2	4.5	1.2	<0.05	<0.05
+120 min	1.7	0.5	2.5	0.6	N.S.	<0.05
AUC ($mmol \cdot l^{-1} \cdot 150$ min)	528.5	202.8	843.4	152.4		

Note: The last column reports the significances obtained in the comparison of each trial value with respect to pre-exercise values (Wilcoxon paired test, $P < 0.05$). PRE = pre-exercise (baseline), INT = recovery time between testing of the two legs, POST = immediately post-exercise.

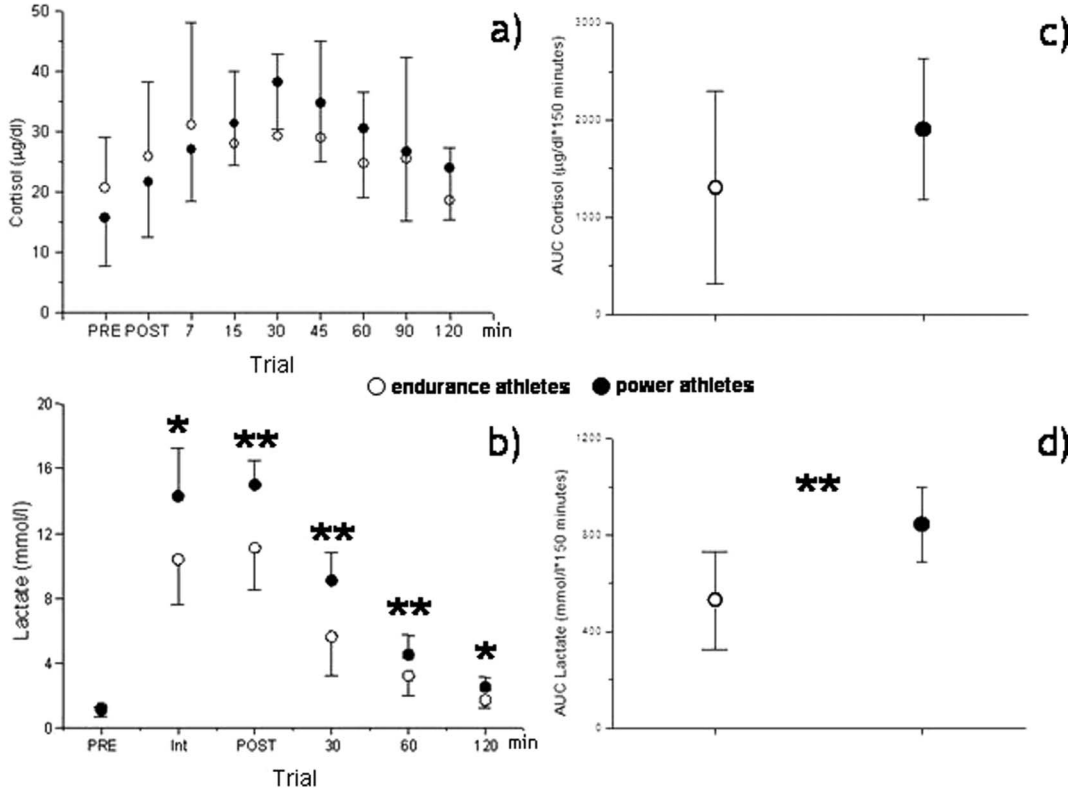

Figure 2. Cortisol (a) and lactate (b) concentrations for each trial throughout the 150-min sessions are depicted for the two groups (●, power athletes, $n = 6$; ○, endurance athletes, $n = 12$). Statistically significant differences between the two groups within each trial are highlighted (*$P < 0.05$; **$P < 0.01$). Global behaviours are described by the cortisol (c) and lactate (d) areas under the curve (AUC). Values are reported as means and standard deviations.

the "group" and "age" factors ($P < 0.05$); that is, power athletes (who were also older than the endurance athletes) were able to generate greater strength than endurance athletes during the isokinetic exercise. When scaling by body mass raised to the power of 0.67 (Jaric, 2002) was introduced, MVC_{ISK} was still significantly higher ($P < 0.05$, Mann-Whitney *U*-test) in the power athletes ($9.96\ N \cdot m \cdot kg^{-1}$, $s = 1.62$) than in the endurance athletes ($8.97\ N \cdot m \cdot kg^{-1}$, $s = 1.59$). Figure 3 plots the values of $SLOPE_{ISK}$ in ascending order showing the performances of the 18 participants during the isokinetic fatiguing exercise. In 6 of 18 participants, the decline in mechanical output was remarkably high ($SLOPE_{ISK} < -20\ N \cdot m/set$, corresponding to a calculated reduction of 35–55% of the initial values). In another 6 participants this decline was in the range -15 to $-5\ N \cdot m/set$ (corresponding to a calculated reduction of 20–25% of the initial values), and in the others it was in the range -5 to $0\ N \cdot m/set$ (corresponding to a calculated reduction of 0–10% of the initial values). As shown in Figure 3, a clean-cut distinction ($P < 0.01$, Mann-Whitney *U*-test) can be observed between power athletes ($-28.91\ N \cdot m/set$, $s = 4.06$; $n = 6$) and endurance athlete ($-6.31\ N \cdot m/set$, $s = 4.06$; $n = 12$).

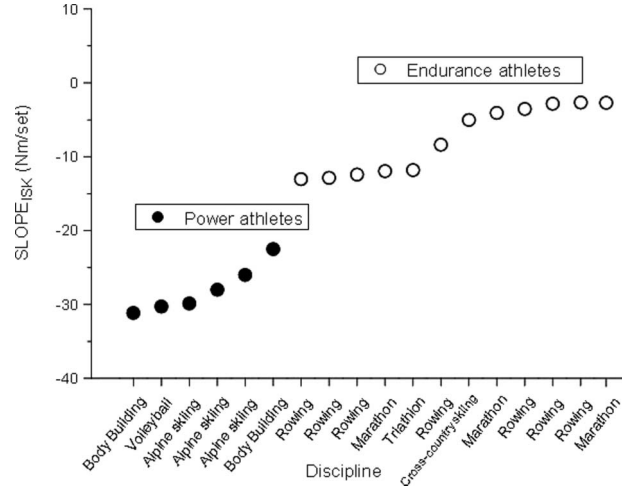

Figure 3. The values of $SLOPE_{ISK}$ ($N \cdot m/set$) obtained for the isokinetic exercise are plotted in ascending order and labelled according to the discipline types. A clear-cut distinction was observed between power athletes ($SLOPE_{ISK} < -20\ N \cdot m/set$; $n = 6$) and endurance athletes ($SLOPE_{ISK}$ -15 to $0\ N \cdot m/set$; $n = 12$). Athletes in the endurance/power disciplines are in the group showing smaller/greater rates of change of torque.

EMG variables

Figure 4a shows the estimates of EMG variables (ARV, CV, and MNF) obtained during isometric MVCs in the two groups throughout the

eight trials. All values were normalized with respect to values recorded at baseline. No difference in average rectified value was observed between the two groups, whereas conduction velocity was higher in endurance than power athletes immediately after, 15 min, and 30 min after exercise, and mean frequency was higher in endurance than power athletes immediately after exercise.

The same variables were plotted in Figure 4b for the electrically elicited contractions. Mean frequency in the endurance athletes was higher pre-exercise and lower immediately post-exercise than in the power athletes – that is, the pre- to post-exercise decrease in mean frequency was higher in the endurance than power athletes.

As for the biochemical variables, the ANCOVA applied to all EMG variables showed no significant

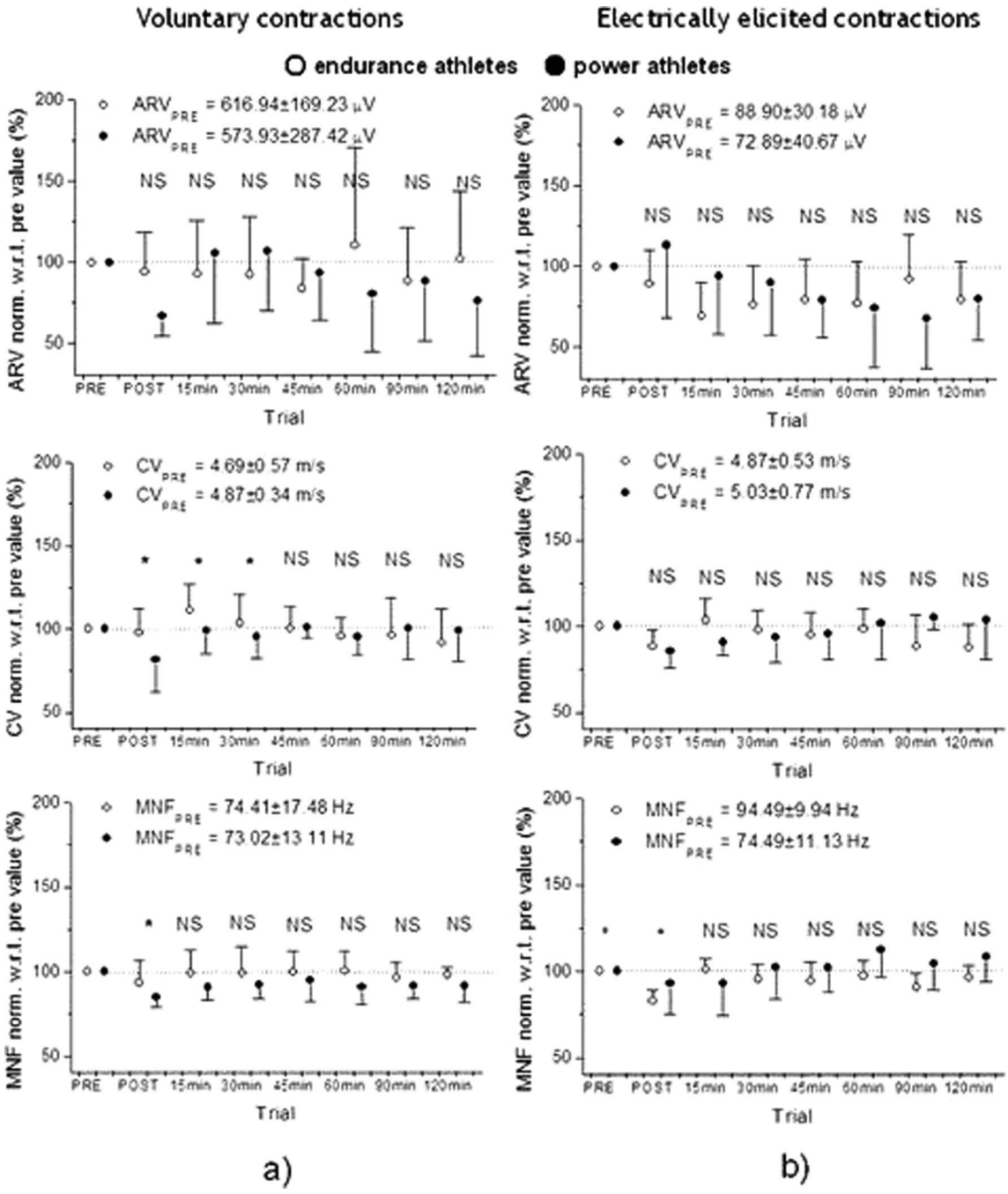

Figure 4. Values of EMG variables (ARV, CV, and MNF), normalized with respect to the values obtained for each participant at baseline (PRE), are reported for both voluntary (a) and electrically elicited contractions (b) in the two groups of athletes (●, power athletes, $n = 6$; ○, endurance athletes, $n = 10$; $^{*}P < 0.05$ differences between the two groups). The means and standard deviations of the absolute values at baseline are reported.

interaction between any of them and the following factors: age, body mass index, training history, and subcutaneous tissue thickness.

Mechanical and EMG recovery times

The recovery time for each mechanical and EMG variable was assessed (Wilcoxon paired test) as the time in which the estimate was no longer statistically different with respect to the pre-exercise mean value. These recovery values are reported in Table III for both groups and the two contraction modalities (voluntary and electrically elicited). Power athletes required a longer recovery time than endurance athletes in all the variables under study for the voluntary contractions, while no consistent difference was evident for the electrically elicited contractions. Moreover, recovery of the mechanical variables to pre-exercise values was slower than that of the myoelectric variables, especially for the power athletes.

Table III. Recovery times (min) after exercise (Wilcoxon paired test, $P < 0.05$).

	Athletes	Voluntary contractions	Electrically elicited contractions
MVC	Power	+45 min	Not applicable
MVC	Endurance	+15 min	Not applicable
ARV	Power	+15 min	POST
ARV	Endurance	POST	POST
CV	Power	+15 min	+30 min
CV	Endurance	POST	+15 min
MNF	Power	+45 min	POST
MNF	Endurance	POST	+15 min

Note: MVC = maximum voluntary contraction, ARV = average rectified value, CV = conduction velocity, MNF = mean frequency, POST = immediately post-exercise.

Correlation analysis

Correlation analysis showed a significant relationship between isometric MVC recorded before the isokinetic exercise and MVC_{ISK} both with ($r = 0.57$, $P = 0.05$) and without ($r = 0.72$, $P = 0.013$) adjustment for body mass (Figure 5a). Moreover, correlations were observed between $SLOPE_{ISK}$ and both lactate area under the response curve ($r = -0.59$, $P = 0.015$) and conduction velocity immediately after exercise during voluntary contractions ($r = 0.64$, $P = 0.04$) (Figure 5b), and between lactate area under the response curve and conduction velocity immediately after exercise during electrically elicited contractions ($r = -0.50$, $P = 0.04$) (Figure 5c); that is, the higher the rate of mechanical fatigue, the higher the lactate production and the greater the reduction in conduction velocity due to exercise.

Discussion

Biochemical and mechanical responses to exercise

The isokinetic exercise test used elicited significant biochemical responses, as shown by the time course of lactate and cortisol.

Measurement of lactate in venous blood could imply an underestimation of peak lactate concentrations (Oyono-Enguelle *et al.*, 1989); this, however, would have affected both groups. Power athletes showed greater increases in lactate as a result of the exercise than the endurance athletes, in line with data reported in the literature (Stallknecht, Vissing, & Galbo, 1998; Tesch *et al.*, 1978).

It is well-known that adaptation of the pituitary–adrenal axis during continuous or repeated exposure to stressful stimuli is stressor-specific

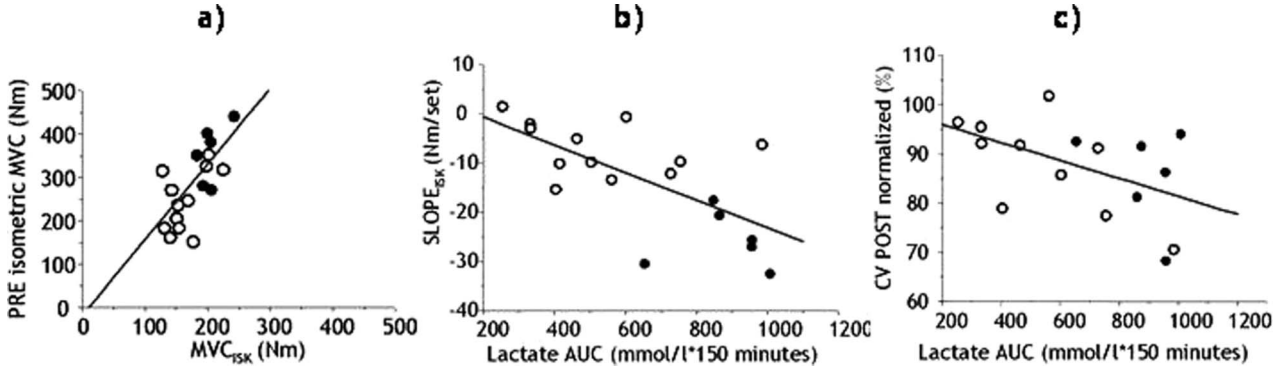

Figure 5. (a) Correlation between isometric MVC at baseline (PRE) and MVC_{ISK} without adjustments for body mass ($r = 0.72$, $P = 0.013$, $n = 18$). Note that isometric MVC is always higher than MVC_{ISK}. (b) Correlation between $SLOPE_{ISK}$ and lactate AUC ($r = -0.59$, $P = 0.015$, $n = 18$). (c) Correlation between lactate AUC and conduction velocity immediately after exercise (POST) ($r = -0.50$, $P = 0.04$, $n = 16$) in electrically elicited contractions. Conduction velocity POST values were normalized with respect to the values obtained for each participant at baseline. ●, power athletes (PA); ○, endurance athletes (EA).

(Kant *et al.*, 1985), and the hormonal response to an acute bout of exercise is related to different training programmes (Kraemer *et al.*, 1993, Tremblay, Copeland, Van Helder, 2004). However, no significant difference in the cortisol responses to this protocol was evident between the two groups of athletes, possibly in relation to the small sample size and to the heterogeneity of group composition. To evaluate this discepancy, two subgroups of participants were selected: the six power athletes whose $SLOPE_{ISK}$ was below -20 N·m/set, and the six endurance athletes whose $SLOPE_{ISK}$ was above -5 N·m/set (i.e. the two extreme clusters depicted in Figure 3). Under this re-grouping, the absolute values (at +30 and +45 min) and areas under the response curve for cortisol become statistically higher in power than in endurance athletes.

Similarly, the differences in the mechanical variables (pre-exercise and recovery times) between the two groups of athletes, as well as the correlation between isometric and isokinetic torque assessment, confirmed and added to already published observations (Bosco & Komi, 1979; Colliander *et al.*, 1988; Froese & Houston, 1985; Inbar *et al.*, 1981; Thorstensson & Karlsson, 1976).

Myoelectric responses to exercise

The EMG variables were estimated both for electrically elicited and voluntary contractions with the aim of distinguishing the different contributions of membrane properties (peripheral fatigue) and of both peripheral and control properties (central fatigue) of the motor units in the two groups of athletes. The results for the electrically elicited contractions appear to be slightly contradictory: post-exercise conduction velocity and lactate production were negatively correlated, and conduction velocity recovery time was longer in power athletes than in endurance athletes (in line with expectations), whereas the mean frequency and average rectified value recovery times were not consistently different between the two groups, and pre-exercise mean frequency was greater in endurance than in power athletes (opposite to expectations).

This might be explained by the fact that the athletes in the present study were not drawn from widely different disciplines, as was the case in previous studies, in which long-distance runners and sprinters were assessed (Komi & Tesch, 1979; Sadoyama, Masuda, Miyata, & Katsuta, 1988). Thus only conduction velocity and mean frequency during voluntary contractions were able to distinguish between the two groups, both in terms of pre- to post-exercise variation, and in terms of recovery velocity towards pre-exercise values. In the electrically elicited contractions, only the conduction velocity results are consistent with "peripheral manifestations" of fatigue. This method of investigation appears less promising than voluntary contractions in distinguishing between athletes with minor differences in muscular properties.

Conduction velocity overshooting. Post-exercise conduction velocities in the endurance athletes were higher than pre-exercise values. The increase in conduction velocity is a well-known phenomenon called "conduction velocity overshooting" (or long-lasting supernormal conduction velocity), which has been observed after fatiguing exercise (Hara, Findley, Sugimoto, & Hanayama, 1998; Van der Hoeven and Lange, 1994). This phenomenon might be a consequence of (1) the increased muscle fibre diameter due to muscle swelling, and/or (2) long-lasting changes in membrane properties.

As depicted in Figure 4a, conduction velocity overshooting (11%, $s = 15$; $P < 0.05$) was observed in the endurance athletes only after 15 min of rest. Since contraction-related ischaemia can be considered comparable between our two groups of athletes, and since slow motor units have a greater sensitivity to ischaemia than fast motor units (Gossen, Ivanova, & Garland, 2004), our findings also suggest that the estimation of conduction velocity overshooting may be used to distinguish participants with different muscular properties.

Confounding factor management

In the present study, serum cortisol and lactate concentrations were not adjusted for changes in plasma volume. It is well known that exercise in humans is accompanied by a loss of plasma fluid (Convertino, Keil, Bernauer, & Greenleaf, 1981) and by a redistribution of regional and organ blood volume with increased blood flow to the exercising muscles (Flamm *et al.*, 1990). The former mechanism prevails in the case of submaximal prolonged exercise, the latter during maximal short-duration efforts. For this reason, no estimation of changes in plasma volume was made. Moreover, since the standardized timing of testing during the afternoon hours avoided any appreciable effect of the circadian rhythm, a resting control session checking for spontaneous variations of serum cortisol concentrations was not considered necessary.

The inter-individual differences in the biochemical, mechanical, and myoelectric responses we observed are likely to be related not only to muscle characteristics, but also to the individual's confidence in the adopted protocol. To counteract this

biasing factor, we included participants not engaged in routine isokinetic exercise training before the study.

Finally, the power athletes were older than the endurance athletes, although not significantly ($P = 0.07$), as reported in Table I. However, they were all aged below 40, allowing us to consider both groups to be "young". Moreover, since age-related differences in MVC and in EMG variables become detectable only in a comparison of young and elderly participants, as shown by Merletti and colleagues (Merletti, Farina, Gazzoni, & Schieroni, 2002) in young (23–34 years) and elderly (67–86 years) sedentary participants, we believe that age did not result in a strong bias. In addition, age-related differences in myoelectric fatigue can be counteracted by continuous physical exercise (Casale, Rainoldi, Nilsson, & Bellotti, 2003), as in the present study.

Conclusions

Although no bioptic evaluation was performed in the present study, it is reasonable to assume that the studied athletes presented a wide spectrum of muscle functional properties due to inter-individual differences in muscle composition. The differences in mechanical, EMG, and biochemical variables observed support the use of the proposed tool for the non-invasive (or minimally invasive) assessment of muscle function, which would be relevant in sports medicine and exercise physiology especially when bioptic evaluations are not admissible and/or feasible.

Referring to the questions listed in the Introduction, our conclusions can be summarized as follows:

1. Significant increases in the biochemical variables were observed in response to the selected isokinetic exercise.
2. Lactate concentrations in each trial (except for pre-exercise values) were greater in power than in endurance athletes, whereas no differences were observed for cortisol production.
3. The following mechanical and myoelectric variables were found to be significantly different between endurance and power athletes: pre-exercise isometric MVC, MVC_{ISK}, $SLOPE_{ISK}$, pre- to post-exercise variation in conduction velocity and mean frequency (in voluntary contractions), recovery times of conduction velocity and mean frequency (in voluntary contractions), and conduction velocity overshooting (in voluntary contractions).
4. Voluntary contractions provided the greatest amount of information to distinguish between the two groups. The information provided by electrically elicited contractions requires further investigation.
5. Lactate concentrations and their time course during the recovery correlated with mechanical fatigue ($SLOPE_{ISK}$) and with the reduction in conduction velocity after electrically elicited contractions. This was not the case for cortisol concentrations.

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