Published in : Current Sports Medicine Reports (2019), vol. 18, n°12, pp. 477–489
DOI: 10.1249/JSR.0000000000000666
Status : Postprint (Author's version)

ECCENTRIC VERSUS CONCENTRIC — WHICH IS THE MOST STRESSFUL CARDIOVASCULARLY AND METABOLICALLY?

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Abstract

The purpose of this study was to compare the fatigability resistance profile and the physiological responses of strenuous concentric (CON) versus eccentric (ECC) isokinetic exercises. At two different sessions, 12 healthy sedentary male subjects (24.3 ± 2.5 years) performed strenuous CON and ECC isokinetic exercises. The protocol consisted of three sets of 12 maximal repetitions, separated by 30-s intervals, at a velocity of $60°\cdot s^{-1}$ for both flexor and extensor knee muscles of the dominant leg. Metabolic (ventilation, oxygen uptake, blood lactate concentration) and cardiovascular (HR, mean arterial blood pressure) parameters were registered before, throughout, and after the isokinetic session. The isokinetic data analysis revealed a more pronounced fatigue in the hamstrings than in the quadriceps in the ECC mode (fatigue index, ratio between the third and the first sets, of 94.8% ±11.8% vs 86.4% ± 10.8%; $P < 0.05$). All physiological responses studied increased gradually during the isokinetic evaluation, both in CON and ECC modes. For total work normalized by physiological responses, cardiovascular and metabolic variables were lower in the CON than in the ECC mode, a sign of a weaker efficiency in CON mode (ratio between performance and physiological cost). In conclusion, the study shows a specific fatigability resistance profile consisting of an early decrease of ECC hamstring performance compared with the quadriceps profile. In addition, we confirm that physiological consequences are important during strenuous isokinetic exercises but ECC exercise produces less stress on the cardiovascular and the metabolic systems than does CON exercise.

Introduction

The isokinetic dynamometer is becoming increasingly used due to its added value in evaluation, rehabilitation and preventive purposes. In the scope of musculoskeletal injuries, orthopedic surgery and after various periods of reduced activity, isokinetic measurements of strength are used frequently to assess muscle function.

Compared with concentric (CON) exercise, eccentric (ECC) exercise produces a greater peak torque (PT) (1). Eccentric protocols are increasingly prescribed in the rehabilitation of hamstring strains, tendinopathies, and so on (2,3). Under experimental conditions, researchers use strenuous isokinetic protocols to study muscle fatigue and delayed-onset muscle soreness induced by repeated ECC muscle actions. In such conditions, massive myocellular enzyme leakage may be observed (4). For instance, an isokinetic protocol consisting of three sets of 30 maximal ECC contractions of the knee extensor and flexor muscles caused a serum creatine kinase concentration of more than 35,000UI$\cdot$L^{-1} after 48-h recovery and a serum concentration of myoglobin greater than 7500 µg$\cdot$L^{-1} (5,6).

One may reasonably consider these protocols as highly demanding, yet knowledge of metabolic and cardiovascular responses to strenuous isokinetic exercise remains incomplete. Cardiovascular and/or metabolic responses to isokinetic exercises have previously been studied in men but these studies did not compare the physiological consequences of CON and ECC contractions (7–14), have examined other joints (15), were interested in elderly (7,9) or disabled subjects (16), collected only cardiovascular data (9,13,15–20), or studied submaximal isokinetic performance (18,21). Only Horstmann et al. (22) studied the differences between CON and ECC isokinetic contractions from a cardiovascular and metabolic point of view. However, in the protocol implemented by Horstmann et al. (22) subjects performed CON, isometric, and ECC evaluations in the same session (with 10-min rest between each condition), which potentially skewed the interpretation due to the cumulative and delayed effects of each evaluation on performance and on cardiovascular and metabolic data.

In addition, the respective fatigability resistance profiles of quadriceps and hamstring muscle groups are not yet completely elucidated in isokinetic. Providing additional findings on these topics would be useful to therapists and researchers to deliver adequate training and assessment programs.

Therefore, the purposes of this study were:

1. to examine the respective hamstring and quadriceps fatigability resistance profiles in both concentric and eccentric modes of strenuous contraction;
2. to analyze the differences in physiological (metabolic and cardiovascular) consequences following strenuous CON versus ECC isokinetic exercises.

Materials and Methods

EXPERIMENTAL APPROACH TO THE PROBLEM

SUBJECTS

Twelve healthy male subjects (age, 24.3 ± 2.5 years; weight, 69.7 ± 4.7kg; height, 180.3 ± 5.7cm; $\dot{V}O_{2max}$, 52 ± 7 mL$\cdot$min$^{-1}\cdot$kg^{-1}) volunteered to participate in the study. All the subjects were students who regularly performed physical activity but were not specifically trained.

The study conformed with ethical standards and (inter)national laws (23) and was approved by the ethics committee of the local university and faculty hospital. Each subject was informed of the nature and purpose of the investigation and gave written consent prior to participation. Neither intensive strength nor unusual exercise was performed within the last 72 h prior the first isokinetic exercise session and during the period between both exercise sessions. The subjects performed a cycling exercise or testing procedure at the same time of day on both occasions. All exercise bouts were performed between 9 a.m. and 11 a.m. All sessions were executed under the direction and encouragement of the same researcher.

A medical examination, resting electrocardiogram (ECG) and blood pressure measurement revealed no pathological findings. Each subject's maximal oxygen uptake ($\dot{V}O_{2max}$) and maximal HR (HR_{max}) was measured 1 to 2 wk before the isokinetic experiment during an incremental ride to exhaustion on an electrically braked cycle ergometer (Ergometrics 800, MEDA, Belgium). Respiratory gas exchange and HR were monitored throughout the ride using a breath-by breath analysis system and ECG monitor, respectively.

ISOKINETIC TESTING

At two different sessions separated by 2 wk, subjects performed either CON or ECC isokinetic contractions on a Cybex Norm dynamometer in a randomly assigned order. The protocol consisted of 3 sets of 12 reciprocal consecutive maximal contractions (separated by 30-s intervals (24)) of the hamstrings (H) and quadriceps (Q) of the dominant leg at $60°\cdot s^{-1}$ angular velocity (24–30). During the exercises, the subject was seated on the dynamometer (with 105° of coxofemoral flexion (31,32)) with the body stabilized by several straps around the thigh, waist, and chest to avoid compensation. The knee's range of motion (ROM) was fixed at 100° of flexion from the active maximum extension (without hyperextension) (31,33). The analysis of gravity compensation was performed by dynamometer software control. To motivate the subjects to develop the highest PT and maximal work (MW) at each repetition, the researcher intensely verbally encouraged the subjects throughout the testing session (34) but the subjects did not receive any visual feedback during the test.

PT (in $N\cdot m^{-1}$) and MW (in J) were computed for each repetition. The MW, although frequently neglected, has been included in our analyses due to the differences in information provided by these two parameters: the PT represents the highest torque produced during a given contraction while the MW is the sum total of area under the torque curve (35). As explained by Morrissey (36), a PT-based analysis in isolation may induce an overestimation of the muscular torque output. Considering these points, it seems essential to assess the isokinetic performance by PT, as well as MW. The cumulative data for MW are the sum of the values of the three sets of contractions. The Fatigue Index for PT (FI_{PT}) is the ratio, expressed as a percentage, of the best repetition between the third and the first sets, while the Fatigue Index for MW (FI_{MW}) is the ratio, also expressed as a percentage, of the sum of the MW of the 12 isokinetic repetitions between the third and the first sets (REF).

The relative isokinetic data correspond to the ratio between the performance (PT or MW) and the body mass of each subject.

Prior to the exercises and measurements, the subjects warmed-up for 8 min on a cycle ergometer at 75W. To ensure familiarization and complete the setup and warm-up, the subjects performed submaximal but progressively increasing to maximal intensity CON contractions.

PHYSIOLOGICAL ASSESSMENT

All measurements were recorded in the upright sitting position and preexercise measurements were recorded after 2 min of quiet rest.

During the isokinetic sessions of testing, expired gases were collected and analyzed continuously using the V_{max} 29c cardiopulmonary system (MEDA, Aartselaar, Belgium). The cardiorespiratory variables measured included oxygen uptake ($\dot{V}O_2$, L·min^{-1}), carbon dioxide production ($\dot{V}CO_2$, L·min^{-1}), and minute ventilation ($\dot{V}E$, L·min^{-1}). The metabolic system was calibrated before each test: the volume transducer was calibrated with a 3-L calibration syringe, and the gas analyzers with a gas mixture of known concentrations (20.93% O_2 and 0.03% CO_2; 15.5% O_2 and 5.8% CO_2). The HR was measured by telemetry (Polar Heart Rate Monitor RS300X, Finland) and automatically interfaced with the other physiological variables via the Metalyser software.

Systolic and diastolic blood pressure were measured continuously via an automated plethysmographic blood pressure device (Finapress System, Ohmeda 2300, Englewood, CO) (37,38) attached to the middle finger of the right hand maintained at heart level. Systolic, diastolic, and mean arterial pressures were averaged each minute and recorded onto a printer. In the Results section, we have only reported the value of the mean arterial pressure (MAP, mm Hg).

Five capillary blood samples were obtained by means of a finger prick and blood lactate concentration (La, mmol·L^{-1}) and was measured immediately post X using the Accusport Lactate Analyzer (Boehringer Mannheim, Germany). The reliability, sensibility, and accuracy of the Accusport Lactate Analyzer have been previously demonstrated (39–44). Quality control also was performed weekly in accordance with the manufacturer's instructions using specific test solutions.

All subjects completed the test protocols without any adverse incidents. Metabolic (ventilation, oxygen uptake, and blood lactate concentration) and cardiovascular (HR and mean arterial blood pressure) parameters were registered just before commencement (T0) and considered as baseline data, after each of the three exercise sets (T1, T2, T3) and 5 min after the (T4) isokinetic protocol, in accordance with recommendations (45) and observed time to peak blood concentration in other studies (46–50).

DATA NORMALIZATION

To compare CON and ECC isokinetic values according to cardiovascular and metabolic responses, we normalized the isokinetic values for each set by each type of physiologic value. We added MW isokinetic values of the extensors and of the flexors (in the same contraction mode) and divided this sum by the delta between a physiological data category (delta HR [ΔHR], delta mean arterial pressure [ΔMAP], delta $\dot{V}E$ [$\Delta\dot{V}E$], delta $\dot{V}O_2$ [$\Delta\dot{V}O_2$], or delta of blood lactate concentration [ΔLa]) at the end of the set considered and the rest values, at T0:

$$\text{Normalized data}_{\text{set n}} = \frac{\text{extensors values}_{\text{set n}} + \text{flexors values}_{\text{set n}}}{\text{physiological data}_{\text{Tn}-}\ \text{physiological data}_{\text{T0}}}$$

STATISTICAL ANALYSIS

All values are reported as means ± SD.

Systematic bias, which refers to a general trend for measurements to be different in a particular direction when compared between repeated tests (51), was assessed with a two- and a three-way mixed-model repeated-measures ANOVA for metabolic and isokinetic data, respectively. The compound symmetry or sphericity was checked by the Mauchly test. When the assumption of sphericity was not met, the significance of *F* ratios was adjusted according to the Greenhouse-Geisser or Huynh-Feldt procedure (when the epsilon correction factor was lower or higher than 0.75, respectively). Following a statistically significant *F* ratio, to clarify the interaction, multiple comparisons were made with the Newman-Keuls post hoc test.

Linear correlation, dependence between two variables, was measured by the Pearson's *r* product-moment correlation coefficient (PCC). Threshold values for PCC statistics were <0.10, 0.30, 0.50, 0.70, 0.90, and 1.00 for trivial, small, moderate, large, very large, almost perfect, and perfect correlation, respectively (52). The problem of multiple comparisons is dealt with using the Holm-Bonferroni method. Its sequential correction method was used to adjust *P* values for multiple comparisons to reduce the likelihood of type I error (53). This correction technique is known to be uniformly more powerful than the standard Bonferroni method. For all experiments, statistical was set at a $P < 0.05$ following Holm-Bonferroni correction. The PCC was calculated: 1) between the progress of the testing session and the (absolute and relative) variability (separately for PT and MW) to explore the relation between fatigue induction and variability of the performance; 2) between the PT and the MW of repetition (separately for the extensors and the flexors) to determine if fatigue had a similar influence on these two parameters over the three sessions; 3) between the extensors and the flexors (separately for the PT and the MW) to determine if fatigue had a similar influence on these antagonistic muscle groups.

The coefficient of variation (CV), reported as a percentage, was determined by dividing the standard deviation of the subject's results from each set by their average and multiplying by 100 (54).

Statistical significance was set at the level of a $P < 0.05$ for all analyses. All calculations were made with JMP 13 (SAS Institute JMP, Grégy-sur-Yerres, France) and MedCalc 13.3.3 (MedCalc Software, Ostend, Belgium).

Results

ISOKINETIC DATA

The isokinetic knee data from the three sets are presented in **Table 1** and **Figure 1**. The three-way repeated-measures ANOVA (mode [CON or ECC contraction] × muscle [Q or H] × time [set 1, set 2 or set 3]), *F* ratio and associated *P* value are presented in **Supplemental Table 1** (http://links.lww.com/CSMR/A34), demonstrated a highly significant effect for mode, muscle and time for PT and MW and also a significant mode-time interaction for MW.

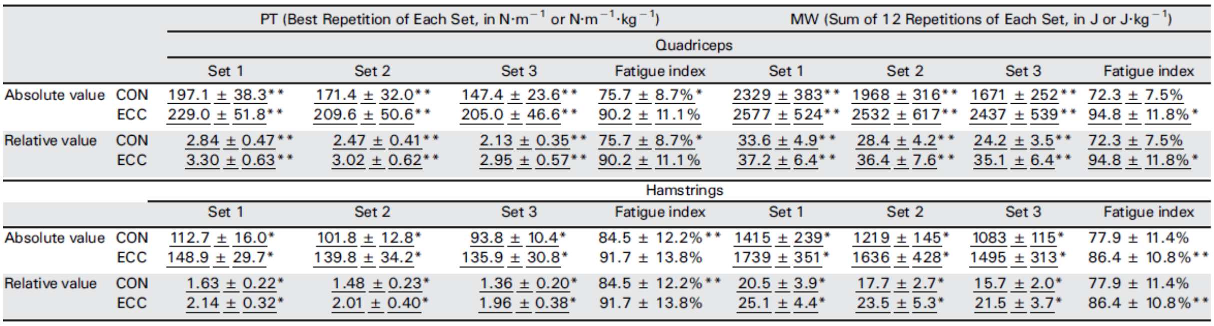
The multiple pairwise comparisons, P value presented in **Supplemental Table 2** (http://links.lww.com/CSMR/A35) and **Supplemental Table 3** (http://links.lww.com/CSMR/A36), showed that:

- the Q produced highly significant higher values than the H, whether for PT or MW, whether during sets 1, 2, or 3;
- the ECC values were significantly higher than the CON ones, whether for PT or MW, whether during sets 1, 2, or 3;
- there was a nonuniform difference between sets for Q and H (for PT or MW). There was a significant difference between all sets for the Q in CON (PT and MW); while in contrast, there was no significant difference between sets for PT for the H in ECC and for MW for the Q in ECC. (Very) significant differences appeared only between sets 1 and 3 for the H in CON (whether for PT and MW) and in ECC (only for the MW). The PT values for Q in ECC are significantly higher in the first set in comparison with the second and third, while there was no difference between sets 2 and 3.

The fatigue index in CON showed values of 72% ± 7% and 78% ± 11%, respectively, for the Q and H muscle groups (significant difference). The fatigue index in ECC remained higher than 85%, yet both muscle groups behaved differently: the ratio reached 95% ± 12% in the Q versus 86% ± 11% in the H which is a significant difference between Q and H. Moreover, the CV of H was double in ECC than in CON for the last set (22.6% vs 11.1% for PT and 21.0% vs 10.6% for MW). None of our isokinetic data (CON vs ECC or Q vs H) were found to be significantly correlated to each other (except the PT and MW for every mode and muscle crossing, see **Supplemental Table 4** (http://links.lww.com/CSMR/A37).

Table 1.

Isokinetic (CON and ECC) knee (quadriceps and hamstrings) mean value ± SD.



		PT (Best Repetition of Each Set, in N·m^{-1} or N·m^{-1}·kg^{-1})				MW (Sum of 12 Repetitions of Each Set, in J or J·kg^{-1})			
		Quadriceps							
		Set 1	Set 2	Set 3	Fatigue index	Set 1	Set 2	Set 3	Fatigue index
Absolute value	CON	197.1 ± 38.3**	171.4 ± 32.0**	147.4 ± 23.6**	75.7 ± 8.7%*	2329 ± 383**	1968 ± 316**	1671 ± 252**	72.3 ± 7.5%
	ECC	229.0 ± 51.8**	209.6 ± 50.6**	205.0 ± 46.6**	90.2 ± 11.1%	2577 ± 524**	2532 ± 617**	2437 ± 539**	94.8 ± 11.8%*
Relative value	CON	2.84 ± 0.47**	2.47 ± 0.41**	2.13 ± 0.35**	75.7 ± 8.7%*	33.6 ± 4.9**	28.4 ± 4.2**	24.2 ± 3.5**	72.3 ± 7.5%
	ECC	3.30 ± 0.63**	3.02 ± 0.62**	2.95 ± 0.57**	90.2 ± 11.1%	37.2 ± 6.4**	36.4 ± 7.6**	35.1 ± 6.4**	94.8 ± 11.8%*
		Hamstrings							
		Set 1	Set 2	Set 3	Fatigue index	Set 1	Set 2	Set 3	Fatigue index
Absolute value	CON	112.7 ± 16.0*	101.8 ± 12.8*	93.8 ± 10.4*	84.5 ± 12.2%**	1415 ± 239*	1219 ± 145*	1083 ± 115*	77.9 ± 11.4%
	ECC	148.9 ± 29.7*	139.8 ± 34.2*	135.9 ± 30.8*	91.7 ± 13.8%	1739 ± 351*	1636 ± 428*	1495 ± 313*	86.4 ± 10.8%**
Relative value	CON	1.63 ± 0.22*	1.48 ± 0.23*	1.36 ± 0.20*	84.5 ± 12.2%**	20.5 ± 3.9*	17.7 ± 2.7*	15.7 ± 2.0*	77.9 ± 11.4%
	ECC	2.14 ± 0.32*	2.01 ± 0.40*	1.96 ± 0.38*	91.7 ± 13.8%	25.1 ± 4.4*	23.5 ± 5.3*	21.5 ± 3.7*	86.4 ± 10.8%**

The dotted and solid underlined values represent significant (*P* <0.05) and very significant (*P* <0.01) differences between CON and ECC values for the same muscle group, respectively; *Very significant (*P* <0.01) and **significant (*P* <0.05) differences between quadriceps and hamstrings values for the same contraction mode, respectively.

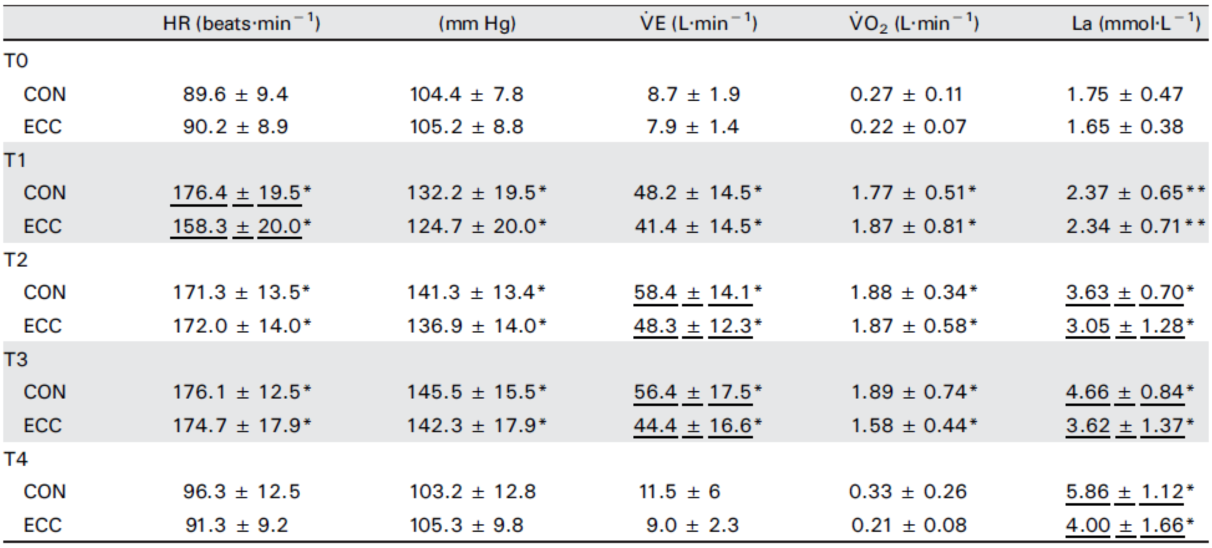
Figure 1. Isokinetic performance in CON mode compared to ECC for quadriceps and hamstrings.

PHYSIOLOGICAL DATA

Table 2 shows physiological responses to strenuous CON versus ECC isokinetic exercises of the lower extremity. The two-way repeated-measures ANOVA (mode [concentric or eccentric contraction]-time [set 1, set 2 or set 3]), *F* ratio and associated *P* value are presented in **Supplemental Table 5** (http://links.lww.com/CSMR/A38) and demonstrate a highly significant effect of time for all variables and a highly significant effect of mode for $\dot{\mathrm{V}}\mathrm{E}$ and La. There also was highly significant mode-time interaction for La.

Table 2.

Metabolic and cardiovascular data during CON and ECC isokinetic testing session mean value ± SD.



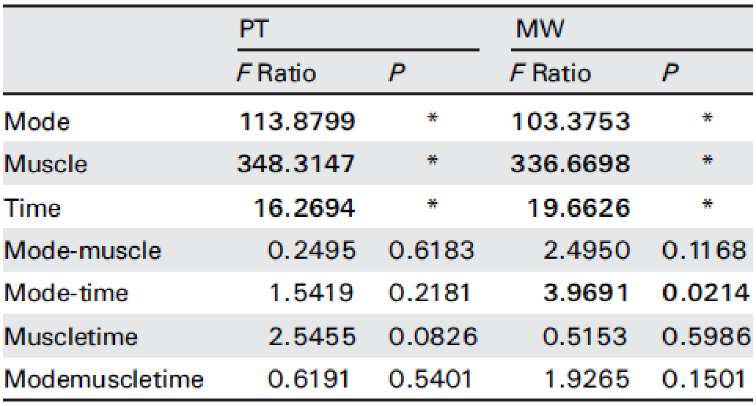
	HR (beats·min^{-1})	(mm Hg)	$\dot{V}E$ (L·min^{-1})	$\dot{V}O_2$ (L·min^{-1})	La (mmol·L^{-1})
T0					
CON	89.6 ± 9.4	104.4 ± 7.8	8.7 ± 1.9	0.27 ± 0.11	1.75 ± 0.47
ECC	90.2 ± 8.9	105.2 ± 8.8	7.9 ± 1.4	0.22 ± 0.07	1.65 ± 0.38
T1					
CON	176.4 ± 19.5*	132.2 ± 19.5*	48.2 ± 14.5*	1.77 ± 0.51*	2.37 ± 0.65**
ECC	158.3 ± 20.0*	124.7 ± 20.0*	41.4 ± 14.5*	1.87 ± 0.81*	2.34 ± 0.71**
T2					
CON	171.3 ± 13.5*	141.3 ± 13.4*	58.4 ± 14.1*	1.88 ± 0.34*	3.63 ± 0.70*
ECC	172.0 ± 14.0*	136.9 ± 14.0*	48.3 ± 12.3*	1.87 ± 0.58*	3.05 ± 1.28*
T3					
CON	176.1 ± 12.5*	145.5 ± 15.5*	56.4 ± 17.5*	1.89 ± 0.74*	4.66 ± 0.84*
ECC	174.7 ± 17.9*	142.3 ± 17.9*	44.4 ± 16.6*	1.58 ± 0.44*	3.62 ± 1.37*
T4					
CON	96.3 ± 12.5	103.2 ± 12.8	11.5 ± 6	0.33 ± 0.26	5.86 ± 1.12*
ECC	91.3 ± 9.2	105.3 ± 9.8	9.0 ± 2.3	0.21 ± 0.08	4.00 ± 1.66*

The dotted and solid underlined values represent significant (*P* <0.05) and very significant (*P* <0.01) differences between CON and ECC values for the same evaluating timing, respectively; *significant (*P* <0.05) and **differences from baseline value (T0), respectively.

Baseline measures for all variables (HR, MAP, $\dot{V}E$, $\dot{V}O_2$, and La) were within normal ranges for healthy adults (55) and did not differ significantly between both CON and ECC. Except for the La, there was neither a significant difference between baseline and 5 min postexercise (T4) values nor between CON and ECC at T4 (**Table 3**).

Table 3.

Three-way repeated -measures ANOVA (mode [CON or ECC contraction]-muscle [Q or H]-time [set 1, set 2 or set 3]) *F* ratio and *P* value for isokinetic data.

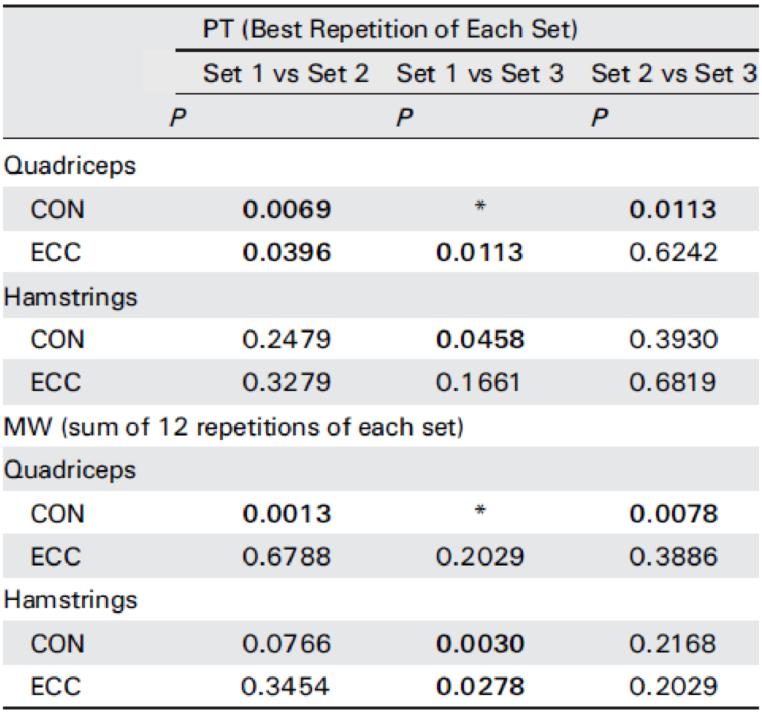


	PT		MW	
	F Ratio	*P*	*F* Ratio	*P*
Mode	**113.8799**	*	**103.3753**	*
Muscle	**348.3147**	*	**336.6698**	*
Time	**16.2694**	*	**19.6626**	*
Mode-muscle	0.2495	0.6183	2.4950	0.1168
Mode-time	1.5419	0.2181	**3.9691**	**0.0214**
Muscletime	2.5455	0.0826	0.5153	0.5986
Modemuscletime	0.6191	0.5401	1.9265	0.1501

The significant *P* values are in boldface type (**P* < 0.0001).

All variables increased (very) significantly throughout the CON and ECC isokinetic protocol (see **Supplemental Table 6**, http://links.lww.com/CSMR/A39). The $\dot{V}O_2$ (both for CON and ECC), the $\dot{V}E$ (for ECC), and the HR (for CON) increased significantly between T0 and T1, but there was no significant difference between T1, T2 and T3. This means that the values immediately reached a plateau and remained stable during the whole testing session. The $\dot{V}E$ (for CON), the HR (for ECC) and the MAP (for both CON and ECC) increased significantly between T0 and T1 but also between T1 and T2, while there was no significant difference between T2 and T3. This means that the values progressively reached a plateau, remained stable during the second part of the testing session, and returned to their baseline values after it. The La increased significantly during CON and ECC testing sessions continuously between T0, T1, T2, T3, and T4 (except between T3 and T4 in ECC, where the augmentation in lactatemia is not significant). Modifications in lactate concentrations appeared more progressive during exercise than other variables, even if the difference with resting values appeared highly significant from the first set of exercises. At the end of the experimental protocol, plasma concentrations of lactate were higher in 9 of the 12 subjects after exercise in the CON condition compared with the ECC condition. At 5 min postexercise, the plasma concentration of lactate was very highly significantly greater in the post-CON condition (**Table 4**).

Table 4.
Three-way repeated-measures ANOVA multiple pairwise comparisons *P* value for isokinetic data.



	PT (Best Repetition of Each Set)		
	Set 1 vs Set 2	Set 1 vs Set 3	Set 2 vs Set 3
	P	*P*	*P*
Quadriceps			
CON	**0.0069**	*	**0.0113**
ECC	**0.0396**	**0.0113**	0.6242
Hamstrings			
CON	0.2479	**0.0458**	0.3930
ECC	0.3279	0.1661	0.6819
MW (sum of 12 repetitions of each set)			
Quadriceps			
CON	**0.0013**	*	**0.0078**
ECC	0.6788	0.2029	0.3886
Hamstrings			
CON	0.0766	**0.0030**	0.2168
ECC	0.3454	**0.0278**	0.2029

The significant *P* values (<0.05) are in boldface type (**P* value <0.0001).

Between CON and ECC (see **Supplemental Table 7**, http:// links.lww.com/CSMR/A40), we found:

- a (highly) significant difference for the HR at T1 (176.4 ± 19.5 beats·min^{-1} for CON vs 158.3 ± 20.0 beats·min^{-1} for ECC) (but not at T2 or T3);
- a (highly) significant difference for the $\dot{\mathrm{V}}\mathrm{E}$ at T2 (58.4 ± 14.1 L·min^{-1} for CON vs 48.3 ± 12.3 L·min^{-1} for ECC) and T3 (56.4 ± 17.5 L·min^{-1} for CON vs 44.4 ± 16.6 L·min^{-1} for ECC) (but not at T1);
- a (very highly) significant difference for the La at T2 (3.63 ± 0.70 mmol·L^{-1} for CON vs 3.05 ± 1.28 mmol·L^{-1} for ECC), T3 (4.66 ± 0.84 mmol·L^{-1} for CON vs 3.62 ± 1.37 mmol·L^{-1} for ECC), and T4 (5.86 ± 1.12 mmol·L^{-1} for CON vs 4.00 ± 1.66 mmol·L^{-1} for ECC) (but not at T1);

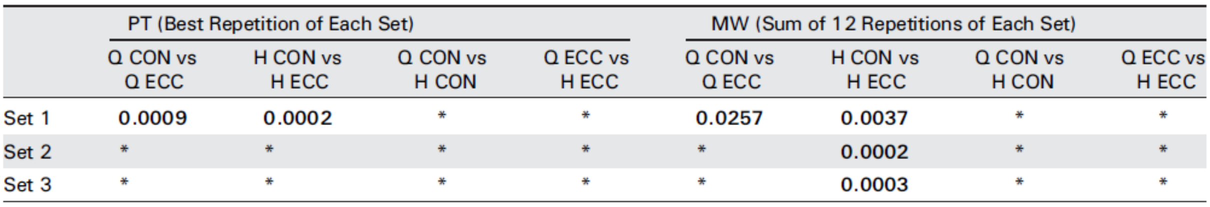
- no significant difference regardless of the considered timing for $\dot{V}O_2$ and for MAP.

$\dot{V}O_2$ and $\dot{V}E$ correlated almost perfectly with each other (r_{CON} = 0.93 and r_{ECC} = 0.92, with both P < 0.0001), were both very largely correlated with HR (r ranging between 0.80 and 0.89, with all P < 0.0001), and largely with MAP (r ranging between 0.49 and 0.68, with all P < 0.0001) (see **Supplemental Table 8**, http://links.lww.com/CSMR/A41). HR and MAP were (very) largely correlated with each other (r_{CON} = 0.76 and r_{ECC} = 0.69, with both P < 0.0001). Lactatemia was not significantly correlated with any other physiological variable (−0.30 < r <0.30 for all pairwise comparisons). The physiological data are very largely (MAP, $\dot{V}E$, $\dot{V}O_2$, and La) or almost perfectly (HR) correlated between CON and ECC mode (see **Supplemental Table 9**, http:// links.lww.com/CSMR/A42).

HR peak value, observed at T3, was 87.1% ± 6% and 85.2% ± 8% of HR_{max}, respectively, for the CON and ECC exercises. Oxygen uptake peak value was equal, respectively, for the CON and ECC exercises, at 68.1% ± 10% (observed atT3) and 64.2% ± 6% (observed at T1) of $\dot{V}O_{2max}$ (**Table 5**).

Table 5.

Three-way repeated-measures ANOVA multiple pairwise comparisons *P* value for isokinetic data



	PT (Best Repetition of Each Set)				MW (Sum of 12 Repetitions of Each Set)			
	Q CON vs Q ECC	H CON vs H ECC	Q CON vs H CON	Q ECC vs H ECC	Q CON vs Q ECC	H CON vs H ECC	Q CON vs H CON	Q ECC vs H ECC
Set 1	**0.0009**	**0.0002**	*	*	**0.0257**	**0.0037**	*	*
Set 2	*	*	*	*	*	**0.0002**	*	*
Set 3	*	*	*	*	*	**0.0003**	*	*

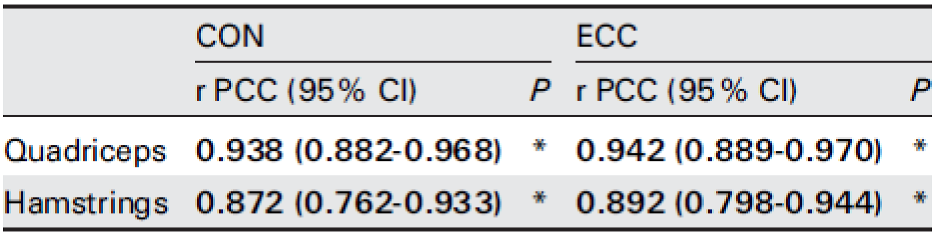
The significant *P* values (<0.05) are in boldface type (**P* < 0,0001).
Q, quadriceps; H, hamstrings.

NORMALIZED DATA

Supplemental Table 10 (http://links.lww.com/CSMR/A43) shows isokinetic MW normalized parameters by cardiovascular and metabolic variables. The two-way repeated-measures ANOVA (mode [concentric or eccentric contraction]-time [set 1,set 2 or set 3]), *F* ratio and associated *P* value, presented in **Supplemental Table 11** (http://links.lww.com/CSMR/A44), found a highly significant effect of time for all variables and a highly significant effect of mode for all variables except La (see **Supplemental Table 12**, http://links.lww.com/CSMR/A45, for the two-way repeated-measures ANOVA multiple pairwise comparisons). There also was a very highly significant mode-time interaction for MAP (**Table 6**).

Table 6.

Pearson's *r* product-moment correlation coefficient with 95% CI and associated *P* value for isokinetic CON and ECC testing session between PT and MW data.



	CON		ECC	
	r PCC (95% CI)	*P*	r PCC (95% CI)	*P*
Quadriceps	**0.938 (0.882-0.968)**	*	**0.942 (0.889-0.970)**	*
Hamstrings	**0.872 (0.762-0.933)**	*	**0.892 (0.798-0.944)**	*

The significant *P* values (<0.05) are in boldface type (**P* value <0.0001).

Published in : Current Sports Medicine Reports (2019), vol. 18, n°12, pp. 477–489
DOI: 10.1249/JSR.0000000000000666
Status : Postprint (Author's version)

For isokinetic MW, normalized parameters by cardiovascular (see **Fig. 2**) and metabolic (see **Fig. 3**) variables showed higher values in ECC than in CON mode. However, these differences between CON and ECC were very significant for the three sets only for the $\dot{V}E$ and the MAP. For the $\dot{V}O_2$, the difference between CON and ECC was not significant for the first set (but, rather for the second and third sets), while the disparity between CON and ECC was significant only for the first set for the La (see **Supplemental Table 13**, http://links.lww.com/CSMR/A46).

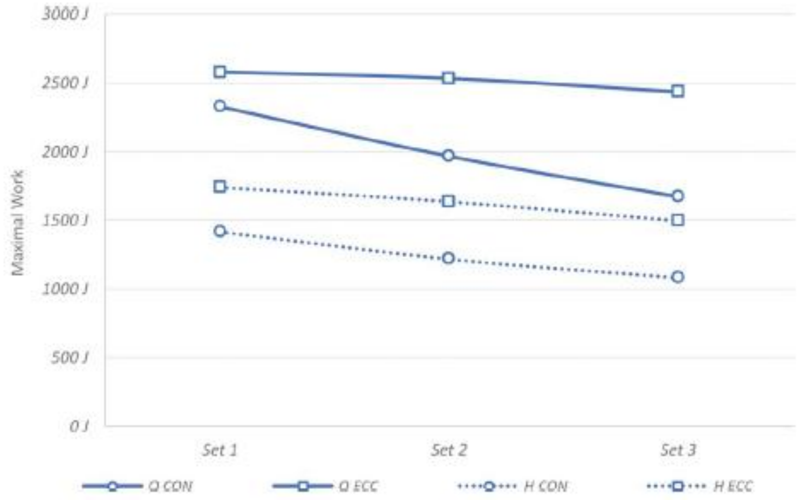


Figure 2: Isokinetic performance in CON and ECC mode normalized by cardiovascular data; * (very) significant differences between CON and ECC values.

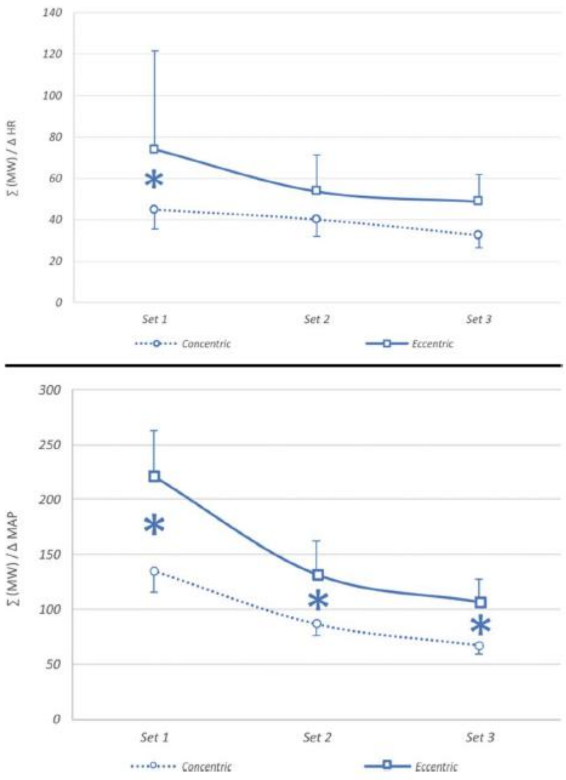


Figure 3: Isokinetic performance in CON and ECC mode normalized by metabolic data; *(very) significant differences between CON and ECC values.

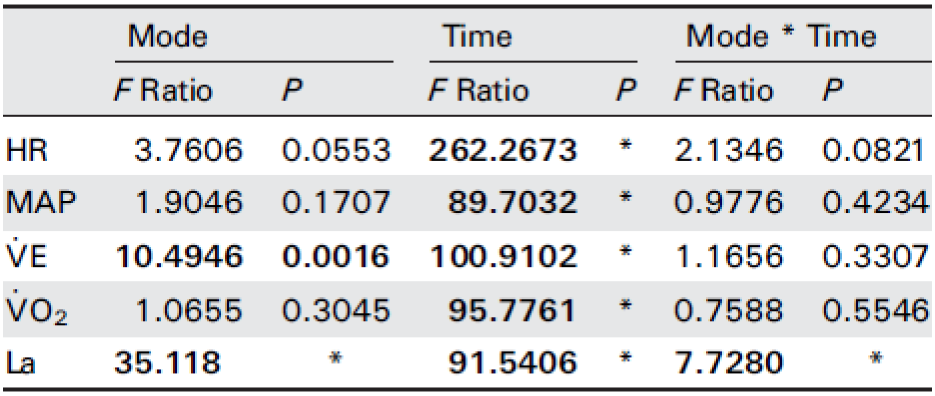
The number of joules produced by the subject per physiological unit was not significantly different between the three sets for the HR in CON, the La in CON and the $\dot{V}O_2$ in ECC but decreased:

- highly significantly and continuously (all pairwise comparisons) for MAP, both in CON and ECC mode;
- significantly from the first to the second (and from the first to the third) sets but not between the second and the third sets for $\dot{V}E$ in CON and ECC, $\dot{V}O_2$ in CON, HR in ECC, and La in ECC.

The correlation of isokinetic normalized data by physiological variable in CON and in ECC was at best moderate, except for the MAP which had a very large correlation (r = 0.90 with a $P < 0.0001$, see **Supplemental Table 9**, http://links.lww.com/ CSMR/A42). Except between isokinetic normalized by the La and the MAP in CON (r = 0.81[0.65/0.90] with a $P < 0.0001$) and between isokinetic normalized by the $\dot{V}O_2$ and the $\dot{V}E$ in ECC (0.80 [0.64/0.90] with a $P < 0.0001$), the correlation between isokinetic data normalized by two physiological variables was, at best, moderate to large (**Table 7**).

Table 7.

Two-way repeated-measures ANOVA (mode [CON or ECC contraction]-time [set 1, set 2 or set 3]) *F* ratio and *P* values for metabolic and cardiovascular data.



	Mode		Time		Mode * Time	
	F Ratio	*P*	*F* Ratio	*P*	*F* Ratio	*P*
HR	3.7606	0.0553	**262.2673**	*	2.1346	0.0821
MAP	1.9046	0.1707	**89.7032**	*	0.9776	0.4234
$\dot{V}E$	**10.4946**	**0.0016**	**100.9102**	*	1.1656	0.3307
$\dot{V}O_2$	1.0655	0.3045	**95.7761**	*	0.7588	0.5546
La	**35.118**	*	**91.5406**	*	**7.7280**	*

The significant *P* values are in boldface type (*P <0.0001).

Discussion

Eccentric actions are important in daily as well as in sports activities, in particular those situations in which the agonist and antagonist muscle groups are working together to prevent joint injury (31). However, little effort has been devoted to assessing the physiological responses and the fatigability resistance profiles elicited by this type of exercise, particularly when addressing strenuous protocols (**Table 8**). The isokinetic dynamometer appears, to our knowledge, to be the only safe tool for exploring maximal CON and ECC contraction for antagonist muscles (Q and H). Our results indicate that during strenuous isokinetic exercises:

1. ECC muscle activity is associated with total work and torque values higher than during CON muscle activity;

2. The fatigability resistance profile appears specific to the muscle group with a more pronounced fatigue in the hamstrings than in the quadriceps in the ECC mode while in the CON mode, the fatigability resistance profile is similar in Q and H;
3. All the physiological responses increase throughout the CON and ECC isokinetic strenuous protocol;
4. The isokinetic MW normalized parameters by cardiovascular and metabolic variables are higher during ECC than during CON muscle activity.

Table 8.

Two-way repeated-measures ANOVA multiple pairwise comparisons *P* value for metabolic and cardiovascular data.

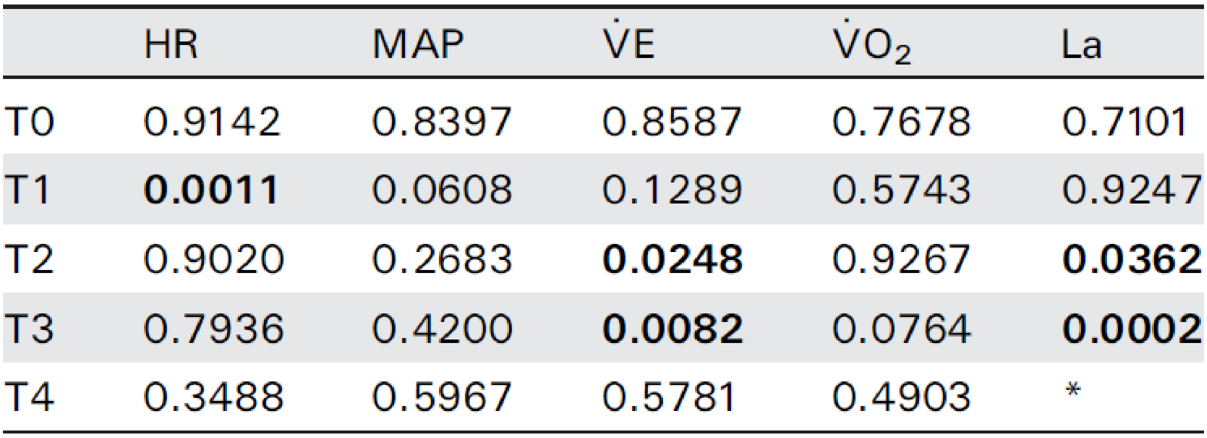
	HR	MAP	$\dot{V}E$	$\dot{V}O_2$	La
CON					
T0 vs T1	*	*	*	*	**0.0263**
T0 vs T2	*	*	*	*	*
T0 vs T3	*	*	*	*	*
T0 vs T4	0.2143	0.7626	0.5294	0.7389	*
T1 vs T2	0.3488	**0.0234**	**0.0237**	0.5237	*
T1 vs T3	0.9509	**0.0011**	0.0689	0.4932	*
T1 vs T4	*	*	*	*	*
T2 vs T3	0.3812	0.2906	0.6477	0.9620	**0.0002**
T2 vs T4	*	*	*	*	*
T3 vs T4	*	*	*	*	*
ECC					
T0 vs T1	*	*	*	*	**0.0129**
T0 vs T2	*	*	*	*	*
T0 vs T3	*	*	*	*	*
T0 vs T4	0.8414	0.9799	0.8018	0.9506	*
T1 vs T2	**0.0124**	**0.0026**	0.1244	0.9875	**0.0113**
T1 vs T3	**0.0030**	*	0.5028	0.0987	*
T1 vs T4	*	*	*	*	*
T2 vs T3	0.6225	0.1751	0.3824	0.1019	**0.0375**
T2 vs T4	*	*	*	*	**0.0007**
T3 vs T4	*	*	*	*	0.1731

The significant *P* values (<0.05) are in boldface type (**P* value <0.0001).

The higher ECC torque values relative to CON torque are in agreement with previous studies (2,56,57). The usual explanation for the greater force produced during ECC muscle activity is that, when stretched, the cross bridges operate higher in their stress-strain curves and thus, develop greater tension up to the point of mechanical rupture than when shortened, although neural control strategies also can be raised up to explain the discrepancies between CON and ECC (58). As expected, we also observed that the total work, accumulated throughout the three series of our protocol, was significantly higher for the ECC than for the CON mode (**Table 9**). Moreover, our results showed clearly that CON contractions induced greater fatigue and different force decay time courses compared with ECC contractions for the quadriceps, while there was a nonsignificant difference between CON and ECC for the hamstrings. These different characteristics of ECC muscle activity, greater strength and lower fatigue, represent one reason why ECC forms of exercise are interesting in the field of training, sports medicine and rehabilitation, keeping in mind that the ECC mode induces greater mechanical stress on muscle, myotendinous junctions, and tendons (59).

Table 9.

Two-way repeated-measures ANOVA multiple pairwise comparisons CON vs ECC *P* value for metabolic and cardiovascular data.



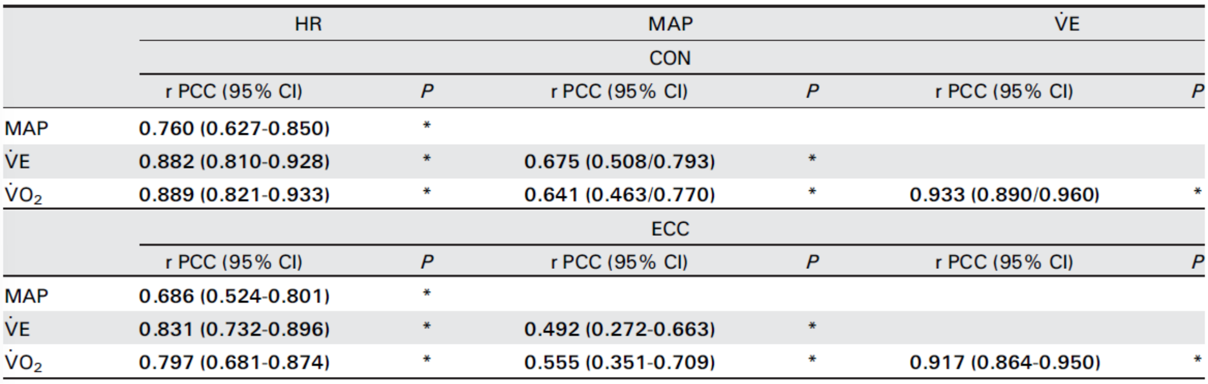
	HR	MAP	$\dot{V}E$	$\dot{V}O_2$	La
T0	0.9142	0.8397	0.8587	0.7678	0.7101
T1	**0.0011**	0.0608	0.1289	0.5743	0.9247
T2	0.9020	0.2683	**0.0248**	0.9267	**0.0362**
T3	0.7936	0.4200	**0.0082**	0.0764	**0.0002**
T4	0.3488	0.5967	0.5781	0.4903	*

The significant *P* values (<0.05) are in boldface type (**P* value <0.0001).

Original findings have been reported with respect to fatigability resistance profile depending on muscle group (**Table 10**).

Table 10.

Pearson's *r* product-moment correlation coefficient with 95% CI and associated *P* value for CON and ECC testing session between metabolic and/or cardiovascular data.

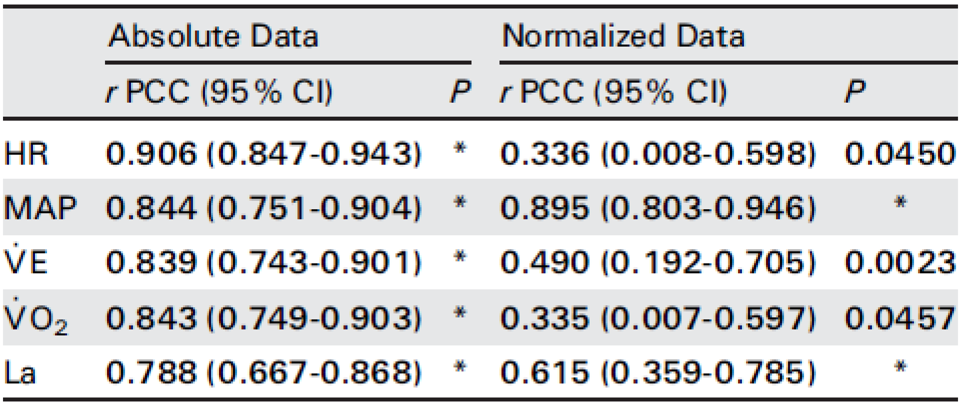


	HR		MAP		$\dot{V}E$	
	CON					
	r PCC (95% CI)	*P*	r PCC (95% CI)	*P*	r PCC (95% CI)	*P*
MAP	**0.760 (0.627-0.850)**	*				
$\dot{V}E$	**0.882 (0.810-0.928)**	*	**0.675 (0.508/0.793)**	*		
$\dot{V}O_2$	**0.889 (0.821-0.933)**	*	**0.641 (0.463/0.770)**	*	**0.933 (0.890/0.960)**	*
	ECC					
	r PCC (95% CI)	*P*	r PCC (95% CI)	*P*	r PCC (95% CI)	*P*
MAP	**0.686 (0.524-0.801)**	*				
$\dot{V}E$	**0.831 (0.732-0.896)**	*	**0.492 (0.272-0.663)**	*		
$\dot{V}O_2$	**0.797 (0.681-0.874)**	*	**0.555 (0.351-0.709)**	*	**0.917 (0.864-0.950)**	*

The significant *P* values (<0.05) are in boldface type (**P* value <0.0001).

To our knowledge, this is the first time that a more pronounced fatigue is highlighted in the hamstring muscle group through exhaustive ECC exercises. This finding is of interest when focusing on factors presumably associated with hamstring injuries. Currently, most authors emphasize the role of strength imbalance between agonist and antagonist muscle groups, particularly in the form of H/Q strength ratio (1,3,11,60). The role of fatigue in muscle strain occurrence also is frequently suggested. Through animal experimentation, Mair et al. (61) indicated that fatigued muscles had a decreased ability to absorb energy before reaching the amount of stretch that causes injury (**Table 11**). Furthermore, these muscles were injured at the same length, regardless of the effects of fatigue. Considering that hamstring injury circumstances frequently correspond to exceeding the ECC mechanical limit tolerated by the muscle unit, we draw attention to the particular fatigability resistance profile of the hamstrings in the ECC mode. The higher CV for H in ECC than in CON mode seems to indicate that some subjects are more susceptible to fatigue and so, may be more susceptible to hamstring injury (61). The possible relationship between fatigue in ECC exercise and hamstring injury occurrence will deserve further investigation: a prospective study would seem, to us, very relevant (**Table 12**).

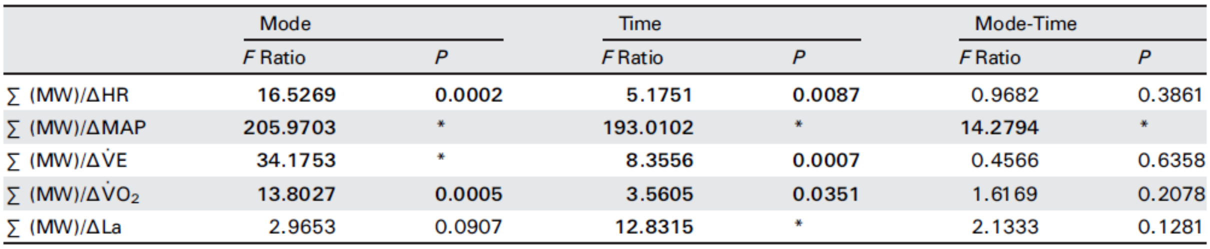
Table 11.
Pearson's *r* product-moment correlation coefficient with 95% CI and associated *P* value for physiological data between CON and ECC testing session ("absolute data") and for the isokinetic data normalized by the physiological data ("normalized data").



	Absolute Data		Normalized Data	
	r PCC (95% CI)	*P*	*r* PCC (95% CI)	*P*
HR	0.906 (0.847-0.943)	*	0.336 (0.008-0.598)	0.0450
MAP	0.844 (0.751-0.904)	*	0.895 (0.803-0.946)	*
$\dot{V}E$	0.839 (0.743-0.901)	*	0.490 (0.192-0.705)	0.0023
$\dot{V}O_2$	0.843 (0.749-0.903)	*	0.335 (0.007-0.597)	0.0457
La	0.788 (0.667-0.868)	*	0.615 (0.359-0.785)	*

The significant *P* values (<0.05) are in boldface type (**P* <0.0001).

Table 12.
Two-way repeated-measures ANOVA (mode [CON or ECC contraction]-time [set 1, set 2 or set 3]) *F* ratio and *P* value for isokinetic normalized data.



	Mode		Time		Mode-Time	
	F Ratio	*P*	*F* Ratio	*P*	*F* Ratio	*P*
∑ (MW)/ΔHR	16.5269	0.0002	5.1751	0.0087	0.9682	0.3861
∑ (MW)/ΔMAP	205.9703	*	193.0102	*	14.2794	*
∑ (MW)/Δ$\dot{V}E$	34.1753	*	8.3556	0.0007	0.4566	0.6358
∑ (MW)/Δ$\dot{V}O_2$	13.8027	0.0005	3.5605	0.0351	1.6169	0.2078
∑ (MW)/ΔLa	2.9653	0.0907	12.8315	*	2.1333	0.1281

The significant *P* values are in boldface type (* *P* <0.0001).

In the second part of our study, we investigated systemic physiological consequences of strenuous isokinetic exercises. Indeed, the literature remains sparse about the acute effects of strenuous isokinetic exercises and the majority of previous studies dealt only with cardiovascular effects of isokinetic exercises. Currently, few data on metabolic responses are available (11,12,62). In view of comparing CON and ECC muscle performances a similar angular velocity of 60°·s^{-1} was selected. We note the reduced validity of high isokinetic ECC velocities, because in such conditions, the period of constant velocity expressed as a percentage of the whole ROM appears drastically reduced (2). Through data analysis, we have distinguished between absolute values that are of interest in clinical applications, and work normalized values, useful in the study of physiological consequences (**Table 13**).

Table 13.

Two-way repeated-measures ANOVA multiple pairwise comparisons *P* value for isokinetic normalized data.

	$\sum$ (MW)/Δ HR	$\sum$ (MW)/Δ MAP	$\sum$ (MW)/Δ $\dot{V}E$	$\sum$ (MW)/Δ $\dot{V}O_2$	$\sum$ (MW)/Δ La
CON					
T1 vs T2	0.5747	*	**0.0119**	**0.0251**	0.0869
T1 vs T3	0.1454	*	**0.0051**	**0.0074**	0.0505
T2 vs T3	0.3656	**0.0067**	0.7531	0.6331	0.7990
ECC					
T1 vs T2	**0.0194**	*	**0.0100**	0.2498	**0.0015**
T1 vs T3	**0.0041**	*	0.0805	0.8083	*
T2 vs T3	0.5625	**0.0005**	0.3796	0.3619	0.1194

The significant *P* values (<0.05) are in boldface type (**P <0.0001).*

Our study revealed significant increases in all studied physiological parameters from baseline values during both our CON and ECC exercise protocols (**Table 14**). As already discussed in the literature, there are several plausible reasons to explain the difference in energy demands and cardiovascular consequences between CON and ECC exercise. Concentric exercise has been shown to recruit a larger number of motor units compared with ECC (21). It also has been previously reported that the increase in stroke volume and decrease in peripheral resistance and blood pressure during ECC exercise compared with CON, reduces the workload imposed on the heart (21). From a physiological viewpoint, it is known that both the HR and blood pressure response increase with increased active muscle mass, even if the response is not linear (63). In ECC contractions requiring less muscle activation, the intramuscular forces are reduced and consequently result in a decrease in MAP (64). CON and ECC exercises utilize a combination of aerobic and anaerobic metabolism to produce sufficient quantities of ATP (adenosine triphosphate). A sustained increase in blood lactate was observed in our study, resulting in a measurable increase in carbon dioxide output derived from bicarbonate buffering. Blood lactate accumulated to 4.7 ± 0.84 mmol·L^{-1} at the end of CON exercises and to 3.6 ± 1.4 mmol·L^{-1} at the end of ECC exercises. These concentrations at the end of both tasks were significantly increased above resting levels. A higher intramuscular lactate concentration resulting from an increased relative contribution of an aerobic metabolism to ATP production in the CON condition may be advocated. However, an increased blood lactate accumulation is not necessarily the consequence of tissue hypoxia. Other factors, such as an increase of intracellular pH, of intracellular calcium concentration or of activation of glycogen phosphorylase by catecholamine also could induce an increase in intramuscular lactate production (65,66). Our lactate values are similar to the values (4.14 ± 1.19 mmol·L^{-1}) presented by Baltzopoulos et al. (56) during a 30-s isokinetic protocol. The lower concentration of La after the ECC set might be due to a non-ATP-dependent "mechanical" rupture of the actin-myosin crossbridges and/or to the greater distance covered by each individual actin-myosin crossbridge (58). In our study, minute ventilation during CON exercise was higher compared with ECC exercise. The most likely explanation for this is a respiratory compensation for the greater blood lactate accumulation during the CON exercise. Our results also showed that the oxygen uptake ranged between 0.88 and 3.61 L·min^{-1} during isokinetic testing and appeared related to the relatively small muscle mass involved in the exercise (67). These values demonstrate that, from a metabolic viewpoint, our strenuous isokinetic protocol requires only about 50% of the subjects' maximum capacities (evaluated using a cycle ergometer). This highlights that during our isokinetic protocol the relative overload on the cardiovascular system is much more significant than the total body metabolic cost of performance (**Table 15**). We can, nevertheless, conclude that the metabolic and physiological considerations should not restrain the use of ECC mode in reinforcement or evaluation programs.

Table 14.

Two-way repeated-measures ANOVA multiple pairwise comparisons CON vs ECC *P* value for isokinetic normalized data.

	∑ (MW)/Δ HR	∑ (MW)/Δ MAP	∑ (MW)/Δ $\dot{V}E$	∑ (MW)/Δ $\dot{V}O_2$	∑ (MW)/Δ La
T1	**0.0010**	*	**0.0038**	0.3621	**0.0155**
T2	0.1105	*	**0.0046**	**0.0443**	0.3690
T3	0.0561	*	**0.0001**	**0.0011**	0.6760

The significant *P* values (<0.05) are in boldface type (**P* <0.0001).

Table 15.

Isokinetic normalized data during CON and ECC isokinetic testing session mean value ± SD.

	∑ (MW)/Δ HR ($J \cdot beats^{-1} \cdot min^{-1}$)	∑ (MW)/ΔMAP ($J \cdot mm\ Hg^{-1}$)	∑ (MW)/Δ$\dot{V}E$ ($J \cdot L^{-1} \cdot min^{-1}$)	∑ (MW)/Δ$\dot{V}O_2$ ($J \cdot L^{-1} \cdot min^{-1}$)	∑ (MW)/ΔLa ($J \cdot mmol^{-1} \cdot L^{-1}$)
Set 1					
CON	44.7 ± 9.4	134.7 ± 19.2	107.1 ± 39.5	2861.9 ± 1258.4	7631.1 ± 3409.2
ECC	73.8 ± 47.8	221.4 ± 41.2	153.1 ± 72.4	3177.7 ± 1507.8	15 923.3 ± 16 451.4
Set 2					
CON	40.0 ± 8.2	86.4 ± 10.8	67.6 ± 15.3	2070.5 ± 526.5	1841.7 ± 533.7
ECC	53.6 ± 17.6	131.5 ± 31.0	112.5 ± 46.9	2777.9 ± 1102.1	4849.6 ± 2962.9
Set 3					
CON	32.4 ± 5.8	67.0 ± 8.1	62.8 ± 17.7	1905.5 ± 620.4	991.8 ± 205.1
ECC	48.7 ± 13.2	106.0 ± 21.6	126.0 ± 55.1	3093.9 ± 934.5	2665.4 ± 1607.2

The dotted and solid underlined values represent significant (P <0.05) and very significant (P <0.01) differences between CON and ECC values for the same evaluation timing, respectively.

While already significant through absolute values for lactatemia and $\dot{V}E$ after the third isokinetic set, the difference between both contraction modes increases when the isokinetic MW values are normalized by cardiovascular and metabolic data. This normalization represents the amount of work produced by the subject for each cardiovascular or metabolic unit value: the higher this normalized value, the better the muscle efficiency. This normalization is essential to be able to compare cardiovascular and metabolic responses to CON and ECC maximal performance. Previous research studied the cardiovascular response to submaximal CON and ECC contractions at the same (absolute or relative) output to be able to compare one mode to another (15,21). Our aim was to compare the cardiovascular and metabolic responses to maximal CON and ECC contraction so the efficiency, measured via normalization, appears to be the unique way to correctly compare both modes. The efficiency of ECC contraction was significantly higher for the MAP and $\dot{V}E$ during the three isokinetic sets, for the HR and La only after the first set and for the $\dot{V}O_2$ during the second and third sets in comparison to CON. Nevertheless, the difference between ECC and CON efficiency decreases between sets for the HR, MAP and La, while it remains constant for the $\dot{V}E$ and increases for $\dot{V}O_2$. It is important to keep in mind that the appearance of lactate in the venous blood is delayed comparatively with its production (68), and therefore, the isokinetic normalization for La must be carefully interpreted. The higher standard deviation for ECC efficiency in regards to CON is the reflection of a greater variability which can explain the nonsignificance of the large difference between CON and ECC efficiency (for the HR and the La after the second and third sets, for example).

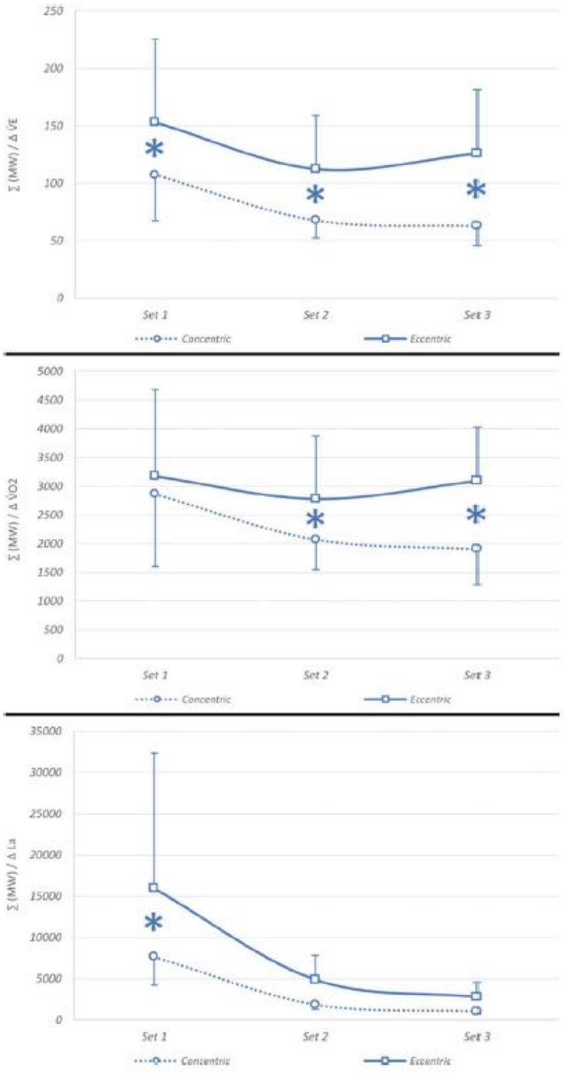


Figure 4: Isokinetic performance in concentric and eccentric mode normalized by metabolic data; * represents (very) significant differences between concentric and eccentric values. $\Delta\,\dot{V}E$: delta of minute ventilation

Conclusions

This study shows a specific fatigability resistance profiles consisting of an early decrease of ECC hamstring performance compared with the quadriceps profile. That specific feature could be hypothesized as representing a risk factor for hamstring muscle injury. Such a possible role calls for further investigations in the field of sports medicine. Our observations also confirmed noteworthy physiological consequences resulting from strenuous isokinetic exercises, which suggest that the effects of these exercises are not limited to skeletal muscle. Because ECC exercise exerts a lower stress on the cardiovascular and metabolic systems, this mode of contraction could be a safer form of exercise in some fields of revalidation, rehabilitation or training, keeping in mind that the ECC mode induces greater mechanical stress on muscle, myotendinous junctions, and tendons.

The authors declare no conflict of interest and do not have any financial disclosures.

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