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ORIGINAL ARTICLE

Acute effects of aerobic exercise performed with different volumes on strength performance and neuromuscular parameters

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Abstract
The aim of the present study was to investigate the acute effect of the aerobic exercise volume on maximum strength and strength-endurance performance; and possible causes of strength decrements (i.e. central and peripheral fatigue). Twenty-one moderately trained men were submitted to a maximal incremental test to determine anaerobic threshold (AnT) and maximum dynamic strength (1RM) and strength-endurance (i.e. total volume load [TV]) tests to determine their baseline strength performance. Following, subjects performed six experimental sessions: aerobic exercise sessions (continuous running at 90% AnT) with different volumes (3 km, 5 km or 7 km) followed by 1RM or strength-endurance test in the 45° leg press exercise. Maximum voluntary isometric contraction (MVIC), voluntary activation (VA) level, contractile properties, and electromyographic activity (root mean square [RMS]) of the knee extensor muscles were assessed before and after aerobic exercises and after strength tests. TV was lower after 5 km and 7 km runs than in the control condition (12% and 22%, respectively). Additionally, TV was lower after 7 km than 3 km (14%) and 5 km (12%) runs. MVIC, VA, RMS, and contractile properties were reduced after all aerobic exercise volumes (~8%, ~5%, ~11% and ~6–14%, respectively). Additionally, MVIC, VA, and contractile properties were lower after strength tests (~15%, ~6%, ~9–26%, respectively). In conclusion, strength-endurance performance is impaired when performed after aerobic exercise and the magnitude of this interference is dependent on the aerobic exercise volume; and peripheral and central fatigue indices could not explain the different TV observed.

Keywords: *Fatigue, performance, resistance, strength, training*

Abbreviations: 1RM: Maximum dynamic strength; AnT: Anaerobic threshold; Ca^{2+}: Calcium; CO_2: Carbon dioxide; CT: Concurrent training; K^+: potassium; [La]: Lactate concentration; MVIC: Maximum voluntary isometric contraction; O_2: Oxygen; P_i: inorganic phosphate; PT: Peak twitch torque; TPT: Time to peak twitch torque; 1/2 RT: Half relaxation time; RMS: Root mean square; RTD: Average rate of twitch torque development; SE: Strength-endurance; TV: Total volume load; VA: Voluntary activation; VO_2: Oxygen uptake; VO_2peak: Peak oxygen uptake

Highlights

- Strength-endurance performance is impaired by previous aerobic exercise in a volume-dependent manner, with decrements after 5 Km and 7 Km, but not after 3 Km trials.
- Maximum dynamic strength performance is not affected by previous aerobic exercise.
- All aerobic exercise volumes induce similar central and peripheral fatigue, but peripheral fatigue is greater after the strength-endurance tests than the maximum dynamic strength ones.

Introduction

Physically active individuals and athletes usually perform aerobic and strength exercises on the same training session or period (i.e. concurrent training – CT) to develop strength and aerobic fitness (Balabanis, Psarakis, Moukas, Vassiliou, & Behrakis, 2003; Garber et al., 2011). Nevertheless, CT may impair strength gains and skeletal muscle hypertrophy over time (Bell, Syrotuik, Martin, Burnham, & Quinney, 2000; De Souza et al., 2014; Kraemer

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et al., 1995). Among the few hypotheses put forward to explain this interference effect (Leveritt, Abernethy, Barry, & Logan, 1999), the acute hypothesis has received some empirical support. According to this hypothesis, the previous execution of an aerobic exercise may impair the subsequent performance on the strength exercise (Craig, Lucas, & Pohlman, 1991; Leveritt et al., 1999). Thus, the reduction in strength performance in each CT session may hamper strength and hypertrophy gains chronically when compared with resistance training alone (Cadore et al., 2012; Sale, MacDougall, Jacobs, & Garner, 1990).

The magnitude of the acute interference seems to be dependent on several training variables such as aerobic exercise intensity (De Salles Painelli et al., 2014; De Souza et al., 2007), rest interval length between aerobic and resistance exercises (Panissa et al., 2012; Sporer & Wenger, 2003), muscle groups involved in both exercises (De Souza et al., 2007; Reed, Schilling, & Murlasits, 2013), type of resistance exercise (i.e. isoinertial or isokinetic) (Leveritt & Abernethy, 1999; Leveritt, MacLaughlin, & Abernethy, 2000), and aerobic exercise mode (i.e. running or cycling) (Panissa et al., 2015).

Another important variable to be considered is the aerobic exercise volume, as high volumes may reduce voluntary drive to the active muscles (i.e. central fatigue) and muscle force production capacity (i.e. peripheral fatigue) (Millet & Lepers, 2004; Millet, Martin, Lattier, & Ballay, 2003), while low volume of aerobic exercise seems to have a small effect on both (Place, Lepers, Deley, & Millet, 2004; Ross, Goodall, Stevens, & Harris, 2010; Thomas et al., 2015). Considering that strength performance can be impaired by decreases in voluntary drive to active muscles and muscle force production capacity, it is reasonable to suggest that the magnitude of the acute CT interference may be dependent on the aerobic exercise volume.

Although Wilson et al. (2012) suggested that long duration aerobic exercise may hinder strength training-related outcomes (i.e. strength performance and hypertrophy), to the best of our knowledge, no study has compared the effects of different aerobic exercise volumes on maximum strength and strength-endurance performance and associated causes of strength performance impairments (i.e. central and peripheral fatigue). Therefore, the primary purpose of the present study was to investigate the acute effects of different aerobic exercise volumes (i.e. 3 km, 5 km, and 7 km) on maximum strength and strength-endurance performance. We also investigated the impact of central and peripheral fatigue (i.e. contractile properties) on maximum strength and strength-endurance performance impairments. We hypothesized that a high volume aerobic exercise will result in greater acute interference on maximum strength and strength-endurance performance as well as impairment in central drive.

Methods

Experimental design

We used a cross-over design in which participants performed all of the experimental conditions. To investigate the effects of aerobic exercise volume on maximum strength and strength-endurance performance, participants were submitted to 11 sessions divided into two phases. In the first phase, five sessions were conducted: (1) anthropometric measurements and anaerobic threshold (AnT) assessment during a maximal incremental test; (2 and 3) familiarizations with the neuromuscular and strength tests: maximum voluntary isometric contraction (MVIC), voluntary activation (VA) and contractile properties of the knee extensor muscles, and maximum dynamic strength (1RM) in the 45° leg press exercise; (4) assessment of the knee extensors MVIC and 45° leg press exercise 1RM load; and (5) assessment of strength-endurance performance (4 sets of maximum repetitions at 80% 1RM) in the 45° leg press exercise. Sessions 4 and 5 were used as control conditions, in which only the 1RM test or the strength-endurance test was performed. In the second phase, six sessions were performed following a William's square distribution with 72 h interval between them: six aerobic exercise sessions with distinct volumes (i.e. 3 km, 5 km, or 7 km, two sessions for each volume) were followed by either a 1RM test or a strength-endurance test. Neuromuscular assessments (i.e. MVIC, VA level, and contractile properties) were performed before and after the aerobic exercises and after the strength tests, on each experimental session, as follows: (A) pre-aerobic exercise neuromuscular assessment, (B) aerobic exercise, (C) post-aerobic exercise neuromuscular assessment, (D) strength test, and (E) post-strength test neuromuscular assessment (Figure 1). Aerobic exercise consisted of running on a treadmill at 90% of AnT

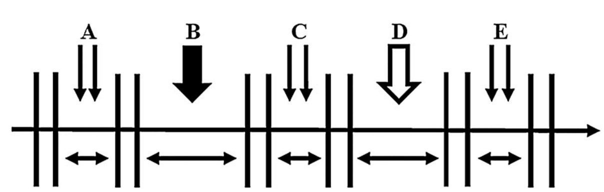

Figure 1. Pictorial view of the experimental sessions. A Pre-aerobic exercise neuromuscular assessment. B Aerobic exercise (either 3 km or 5 km or 7 km). C Post-aerobic exercise neuromuscular assessment. D Strength test (either 1 RM or Strength-endurance test). E Post-strength test neuromuscular assessment.

(~10.2 km h^{-1}) until the completion of the defined training volume (i.e. 3 km, 5 km, or 7 km). A 10 min rest interval was granted between the aerobic exercise and the strength test.

Participants

Twenty-four moderately trained men (age: 26.3 ± 4.6 years; height: 176.8 ± 9.2 cm; body mass: 79.0 ± 10.2 kg, $\dot{V}O_2$peak: 47.4 ± 5.6 ml kg^{-1} min^{-1}, AnT velocity: 11.4 ± 1.7 km h^{-1}, 2–3 years of experience with aerobic and resistance training) participated in this study. Participants were requested to maintain their usual level of physical activity and dietary intake throughout the study. They were free from health problems and/or neuromuscular disorders that could affect their ability to complete the experimental protocol. Three participants withdrew from the study due to personal reasons; thus, 21 participants completed all study procedures. The study was conducted according to the Declaration of Helsinki and the University's Research Ethics Committee approved the experimental protocol. All of the participants were informed of the possible risks, discomforts, and benefits of the study before signing an informed consent form.

Maximal incremental test

Participants performed an incremental test to volitional exhaustion in a motorized treadmill (Movement Technology, Brudden, São Paulo, Brazil). Oxygen uptake ($\dot{V}O_2$) was measured during the test using a gas analyzer (Quark CPET, Cosmed, Rome, Italy). Before each test, the gas analyzer was calibrated using ambient air and a gas of a known composition (20.9% O_2 and 5% CO_2). The turbine flowmeter was calibrated using a 3-L syringe (Quinton Instruments, Seattle, WA, USA). Throughout the test, participants wore a mask (Hans Rudolph®, Kansas City, MO) connected to the gas analyzer to measure breath-by-breath gas exchange. Heart rate was monitored with a frequency counter (model RS800CX, Polar®, Kempele, Finland). The test started at 7 km h^{-1} with increments of 1 km h^{-1} per 3 min stage until exhaustion. At the end of each stage, 25 µl of arterial blood was taken from the ear lobe to measure blood lactate concentrations [La] (Yellow Springs 1500 Sport, Yellow Springs®, USA). The velocity associated with the AnT was the velocity corresponding to a fixed concentration of 3.5 mmol L^{-1} of lactate (Heck et al., 1985). $\dot{V}O_2$peak was defined as the highest average value obtained in a 15 sec window, which always occurred in the last stage of the test, or in the stage before the last. To ensure that participants performed maximum effort, two or more of the following criteria had to be met: an increase in $\dot{V}O_2$ of less than 2.1 ml kg^{-1} min^{-1} between two consecutive stages (featuring a plateau), respiratory exchange ratio exceeding 1.1, [La] greater than 8.0 mmol L^{-1}, and participants' heart rate at or above 90% of maximum predicted by age (i.e. 220-age) (Howley, Bassett, & Welch, 1995). Participants informed their rates of perceived exertion at the end of each stage and verbal encouragement was provided throughout the test to ensure maximal effort.

Maximum dynamic strength test

The maximum dynamic strength (1RM) test was performed in the 45° leg press equipment (Nakagym®, Diadema, Brazil). Participants executed a 5-min general warm-up on a treadmill at 9 km.h^{-1} followed by a specific warm-up composed of two sets of eight and three repetitions with 50% and 70% of their estimated 1RM, respectively, with 2 min rest interval between sets. Three minutes after the specific warm-up, participants were submitted to the test. Subjects had up to five attempts to achieve the 1RM load (i.e. maximum weight that could be lifted once with proper technique) with a 3 min rest between them. The 45° leg press exercise started with full knee extension going up to 90° of knee flexion and returning to the starting position. To better control the 1RM test procedures, each participant had his body position and feet placement on the 45° leg press equipment recorded and reproduced throughout the study. Strong verbal encouragement was provided during all trials.

Strength-endurance test

Participants executed a 5-min general warm-up on a treadmill at 9 km h^{-1} followed by a specific warm-up composed of two sets of five repetitions at 50% 1RM separated by 1 min rest interval. After the specific warm-up, they rested for 2 min before being submitted to the test. The strength-endurance test consisted of four sets of maximum repetitions at 80% 1RM in the 45° leg press exercise. Each set was separated by a 2-min rest interval. Total volume load (TV) performed was calculated (sets × repetitions × weight lifted) and recorded for future analysis.

Maximal voluntary isometric contraction test

Participants performed a 5-min general warm-up on a treadmill at 9 km h^{-1}; then, they were positioned on an isokinetic dynamometer (Biodex System 4, Biomedical Systems®, Newark, CA, USA) and fixed by straps across their chest, waist, and thigh of their dominant leg (defined as the leg used to kick a ball). The hip joint was fixed at 85° of flexion and the participant's arms were folded across their chest. The predicted anatomical axis of rotation of the knee joint was aligned with the dynamometer's lever arm centre of rotation. The ankle was fixed with a Velcro strap on the lower edge of the contact pad of the lever arm and 60° of knee flexion (full extension being 0°). Then, they performed a specific warm-up composed of three submaximal isometric contractions separated by 30 s of rest. After the specific warm-up, participants rested for 3 min before being submitted to the test. The MVIC test was composed of two maximal knee extension voluntary isometric contractions (5 s in duration) separated by 1 min rest. All subjects were instructed to produce maximal torque as rapidly as possible and to maintain it for approximately four seconds. The MVIC with the highest value was selected for analysis. Strong verbal encouragement and visual feedback were provided during the test. Participants' adjustments on the dynamometer were recorded to guarantee the same positioning throughout the study.

Neuromuscular assessments

Voluntary activation level and contractile properties. Voluntary activation (VA) level was assessed during the MVIC test. Doublets were applied to the belly of the quadriceps muscle using an electrical stimulator (Nicolet®, VikingQuest, Middleton, USA) connected to self-adhesive electrodes (Axelgaard, Valutrode 7.5 × 13 cm). Electrodes were attached to the distal (anode) and proximal (cathode) regions of the knee extensor muscles. The intensity of electrical stimuli was determined by delivering doublets of progressively higher intensities to the quadriceps muscle, starting with an intensity of 180 V and gradually increasing by 40 V steps until no further increment in twitch torque was observed. Supra-maximal stimulation of the quadriceps muscle was attained by adding 20% to stimulation intensity that produced peak twitch torque (i.e. supramaximal stimulus, ~340 V) (Neyroud, Vallotton, Millet, Kayser, & Place, 2014). The electrical stimuli consisted of doublets with 1 ms duration fired at 100 Hz (Place, Maffiuletti, Martin, & Lepers, 2007). Supramaximal doublets were manually delivered both during the plateau phase of the MVIC (superimposed) and 2 sec after the completion of the MVIC (i.e. potentiated twitches). Potentiated twitches were used to estimate VA and muscle contractile properties. The MVIC with the highest peak value was selected for further analysis. VA level was estimated using the following equation: % VA = [1 − (superimposed/potentiated)] × 100] (Allen, Gandevia, & Mckenzie, 1995). The following contractile parameters were assessed from potentiated twitch: peak twitch torque (PT) (i.e. highest value of twitch torque production), time to peak twitch torque (TPT) (i.e. time from torque initiation to PT), average rate of twitch torque development (RTD) (i.e. change in torque from torque onset to peak torque), and half relaxation time (1/2 RT) (i.e. time to obtain half of the decline in PT). A customized script (Visual Basic, Microsoft) was used to calculate neuromuscular parameters (i.e. VA level and contractile properties).

Electromyographic activity (EMG). Vastus lateralis (VL) electrical activity was recorded (Delsys Myomonitor® IV, Boston, USA) using a bipolar bar surface electrode with an inter-electrode distance of 2 cm. The skin area was shaved, abraded, and cleaned with an isopropyl alcohol pad to reduce skin impedance before electrode placement. The electrode was placed over the belly of the VL muscle, aligned in parallel with the expected muscle fibre orientation of participants' dominant leg. In addition, a reference ground electrode was positioned on the patella of the contralateral leg. To ensure the same electrode placement between experimental sessions, the position of the electrode was marked on the skin with semi-permanent ink. The root mean square (RMS) of the EMG signal was calculated over a 300 ms window around MVIC peak torque. EMG signal was acquired at 1000 Hz frequency, amplified to 1000 and hardware bandpass filtered at 20–500 Hz. The EMG amplifiers had an input-to-noise ratio of less than 1.2 µV RMS and an effective common rejection mode > 80 dB. EMG signal was synchronized with torque data obtained from the isokinetic dynamometer through a 16-bit A/D convertor. EMG data was analyzed offline using a customized script (Visual Basic, Microsoft).

Statistical analyses

After normality assurance, two mixed models were performed, one having condition (i.e. control, 3 km, 5 km, and 7 km) as fixed factor and subjects as random factor to compare 1RM and TV values; and other having condition (i.e. 3 km, 5 km, and 7 km), time of neuromuscular assessment (i.e. pre- and post-aerobic exercise assessment, and post-strength test assessment) and strength test (i.e. 1RM or strength-endurance) as fixed factors and subjects as random factor to compare neuromuscular variables (i.e. MVIC, VA, PT, TPT, RTD, 1/2 RT, and RMS). A post-hoc test with Tukey adjustment was used whenever a significant F value was detected.

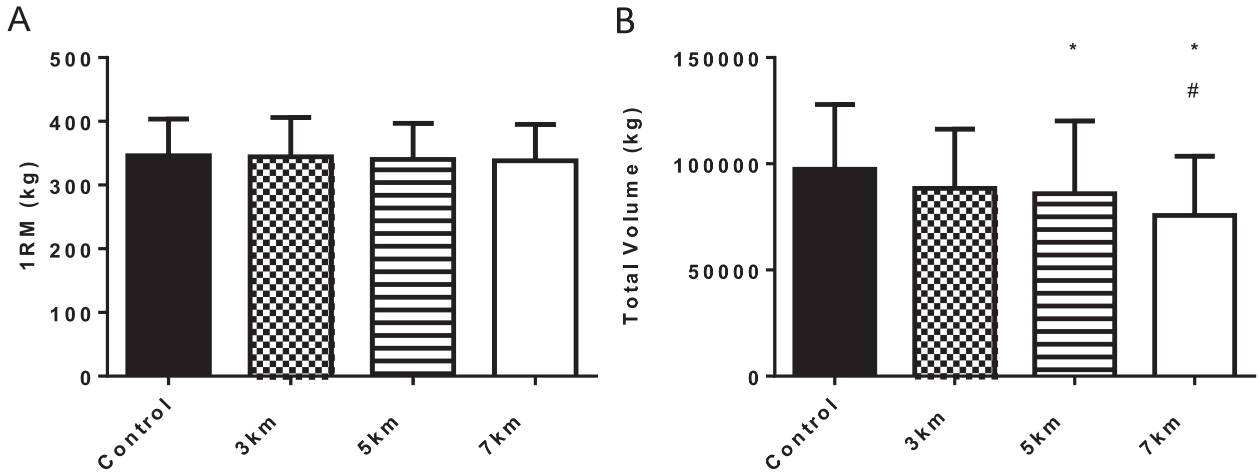

Figure 2. A Maximum dynamic strength (1RM, kg) performance in the control condition and after 3 km, 5 km, and 7 km. B Strength-endurance performance (total volume load, TV) in the control condition and after 3 km, 5 km, and 7 km. *Different from control condition ($p < 0.05$); #Different from 3 km and 5 km ($p < 0.05$).

The data were presented as means and SDs and analyzed using SAS statistical package (SAS 9.3, SAS Institute Inc., Cary, NC, USA). Statistical significance was set at $p \leq 0.05$.

Results

No significant differences were observed in 1RM values among conditions (Figure 2(A)). Total volume load (TV) was significantly lower after 5 km and 7 km runs when compared to the control condition (i.e. no previous run) (12%, $p < 0.05$ and 22%, $p < 0.001$, respectively). In addition, TV after 7 km was lower than after 3 km (14%, $p < 0.01$) and 5 km (12%, $p < 0.05$). No significant differences were observed in TV when comparing 3 km with 5 km and 3 km with control (Figure 2(B)).

There was a significant main time effect for MVIC ($p < 0.001$), in which values were reduced at time 2 (i.e. post-aerobic exercise) (~8% $p < 0.001$) and time 3 (i.e. post-strength test) (~15% $p < 0.001$) for all aerobic exercise volumes when compared to time 1 (i.e. pre-assessment). Additionally, MVIC values were significantly lower in time 3 than in time 2 (~8% $p < 0.01$). There was a significant strength test by time interaction for MVIC ($p < 0.001$), in which at time 3 MVIC values were lower after the strength-endurance test than the 1 RM test (~7% $p < 0.001$) (Table 1). There was a significant main time effect for VA and RMS ($p < 0.001$ and $p <$

Table 1. Neuromuscular parameters of the knee extensors muscle assessed before and after aerobic exercise (3 km, 5 km or 7 km) and after the strength test (strength-endurance or 1RM).

		3 km		5 km		7 km	
Neuromuscular parameters	Time	SE	1 RM	SE	1 RM	SE	1 RM
MVIC (N·m)	1	265.9 ± 34.7	266.1 ± 38.4	269.8 ± 40.2	262.3 ± 32.8	268.2 ± 34.3	267.6 ± 36.4
	2 †	246.9 ± 31.9	253.9 ± 33.5	247.1 ± 39.9	237.9 ± 36.2	239.6 ± 32.1	242.1 ± 33.9
	3 §	214.9 ± 42.1**	233.6 ± 34.7	221.5 ± 34.5**	235.0 ± 39.5	215.6 ± 37.2**	232.7 ± 30.1
VA (%)	1	91.1 ± 9.3	93.5 ± 6.2	92.3 ± 7.8	91.5 ± 7.4	91.7 ± 7.1	91.7 ± 7.8
	2 †	86.9 ± 11.3	90.5 ± 10.5	88.1 ± 11.1	84.3 ± 11.5	85.9 ± 8.2	86.4 ± 9.6
	3 †	87.6 ± 7.5	88.1 ± 12.2	87.3 ± 9.5	88.9 ± 6.8	84.7 ± 10.5	84.0 ± 9.6
RMS (mV)	1	0.32 ± 0.12	0.37 ± 0.09	0.35 ± 0.10	0.34 ± 0.12	0.32 ± 0.12	0.32 ± 0.14
	2 †	0.33 ± 0.13	0.32 ± 0.10	0.30 ± 0.09	0.29 ± 0.13	0.29 ± 0.12	0.26 ± 0.12
	3	0.35 ± 0.12	0.31 ± 0.15	0.30 ± 0.11	0.30 ± 0.12	0.28 ± 0.10	0.36 ± 0.12

Data are Mean ± SD ($n = 18$); significant at $p < 0.05$. Time: 1 = pre-aerobic exercise neuromuscular assessment, 2 = post-aerobic exercise neuromuscular assessment and 3 = post-strength test neuromuscular assessment; SE = strength-endurance; 1RM = maximum dynamic strength; MVIC = maximum voluntary isometric contraction; VA = voluntary activation level; RMS = root mean square.
† Different from time 1.
§ Different from times 1 and 2.
** Different from 1RM test (main strength test effect).

Table 2. Contractile properties of the knee extensors muscle assessed before and after aerobic exercise (3 km, 5 km or 7 km) and after the strength test (strength-endurance or 1RM).

		3 km		5 km		7 km	
Contractile parameters	Time	SE	1 RM	SE	1 RM	SE	1 RM
PT (N·m)	1	94.9 ± 20.0	94.5 ± 15.7	95.6 ± 16.1	96.8 ± 16.6	94.8 ± 15.5	92.6 ± 16.2
	2 †	83.4 ± 15.6	83.8 ± 13.7	82.4 ± 14.2	80.0 ± 14.0	80.8 ± 15.5	78.4 ± 12.6
	3 §	64.5 ± 16.1**	75.6 ± 11.8	64.8 ± 10.0**	76.8 ± 12.8	64.8 ± 13.2**	76.1 ± 13.5
TPT (ms)	1	124.1 ± 12.9	122.4 ± 10.3	123.5 ± 9.6	122.1 ± 10.8	123.2 ± 9.4	124.0 ± 9.4
	2 †	116.1 ± 9.0	112.7 ± 7.8	110.2 ± 7.0	110.9 ± 10.0	112.3 ± 7.8	108.9 ± 7.4
	3 †	109.0 ± 9.0**	113.9 ± 8.1	110.8 ± 6.7**	113.6 ± 9.9	109.1 ± 6.6**	115.8 ± 9.0
RTD ($N{\cdot}m{\cdot}s^{-1}$)	1	778.2 ± 209.6	778.6 ± 158.2	780.0 ± 157.8	799.7 ± 165.3	773.8 ± 144.6	750.5 ± 147.4
	2 †	722.2 ± 149.1	748.6 ± 145.9	752.0 ± 142.8	729.6 ± 162.6	724.7 ± 159.8	723.5 ± 130.5
	3 §	595.8 ± 161.1**	667.6 ± 117.7	586.0 ± 90.4**	683.5 ± 144.2	596.1 ± 125.4**	664.1 ± 144.5
1/2 RT (ms)	1	50.9 ± 11.0	52.4 ± 13.2	51.2 ± 9.5	53.2 ± 13.1	51.3 ± 13.1	51.9 ± 10.2
	2 † ‡	46.4 ± 9.1	47.9 ± 8.1	46.7 ± 9.8	47.5 ± 10.9	45.3 ± 6.5	47.7 ± 9.8
	3	53.6 ± 13.4	48.8 ± 8.9	49.2 ± 10.9	49.3 ± 10.8	50.0 ± 9.2	45.8 ± 6.6

Data are Mean ± SD ($n = 18$); significant at $p < 0.05$. Time: 1 = pre-aerobic exercise neuromuscular assessment, 2 = post-aerobic exercise neuromuscular assessment and 3 = post-strength test neuromuscular assessment; SE = strength-endurance; 1RM = maximum dynamic strength; MVIC = maximum voluntary isometric contraction; PT = peak twitch torque; TPT = time to peak twitch torque; RTD = average rate of twitch torque development; 1/2 RT = half relaxation time.
† Different from time 1.
§ Different from times 1 and 2.
‡ Different from time 3.
** Different from 1RM test (main strength test effect).

0.01, respectively), in which at time 2 both variables were significantly lower than at time 1 (~5% $p < 0.001$ and ~11% $p < 0.01$, respectively) and at time 3 only VA was reduced compared to time 1 (~6% $p < 0.001$) (Table 1). There was a significant main time effect for PT, TPT and RTD ($p < 0.001$, $p < 0.001$ and $p < 0.001$, respectively), in which values were reduced at time 2 (~14% $p < 0.001$, ~9% $p < 0.001$, ~6% $p < 0.05$, respectively) and time 3 (~26% $p < 0.001$, ~9% $p < 0.001$, ~19% $p < 0.001$, respectively) when compared to time 1. Additionally, PT and RTD values were significantly lower in time 3 than in time 2 (~14% $p < 0.001$ and ~14% $p < 0.05$, respectively). There was a significant strength test by time interaction for PT, TPT and RTD ($p < 0.001$, $p < 0.001$ and $p < 0.001$, respectively), in which at time 3 PT, TPT and RTD values were lower after the strength-endurance test than the 1RM test (~15% $p < 0.001$, ~4% $p < 0.001$, ~12% $p < 0.05$, respectively) (Table 2). There was a significant main time effect for 1/2 RT ($p < 0.001$), in which values were reduced at time 2 when compared to time 1 (~9% $p < 0.001$) and lower in time 2 than in time 3 (~5% $p < 0.05$) (Table 2).

Discussion

The main findings of this study were the following: a) strength-endurance performance (TV) was impaired by previous aerobic exercise in a volume-dependent manner, while maximum dynamic strength (1RM) performance was not affected by previous aerobic exercise; b) central drive declined similarly after all aerobic-exercises and remained reduced after both strength tests; c) both aerobic exercise and strength tests induced peripheral fatigue; however, peripheral fatigue was greater after the strength-endurance tests than the maximum dynamic strength ones, regardless of TV.

The impairments on strength-endurance performance observed herein are in agreement with studies that used similar protocols to investigate the effects of a previous aerobic exercise on maximum dynamic strength and strength-endurance (De Salles Painelli et al., 2014; De Souza et al., 2007). For example, De Souza et al. (2007) and De Salles Painelli et al. (2014) investigated the effects of a 5-km run (90% of AnT or 1:1 min at $\dot{V}O_2$max velocity) on acute maximum dynamic strength and strength-endurance tests (maximum repetitions with 80% 1RM) performed on the 45° leg press exercise. Similar to the current study they observed reductions (~22–27%) only in strength-endurance performance.

The magnitude of the interference on strength-endurance was dependent on the aerobic exercise volume; as TV decreased after 5 km and 7 km, but not after 3 km trials. Additionally, reductions observed in TV after 7 km were larger compared to the ones observed after 5 km, supporting that higher volumes induce greater negative interference in subsequent strength tasks. Thereby, it is plausible to suggest that aerobic exercises with low volume

(~3 km) at moderate intensity do not affect the subsequent strength performance.

Partially contradicting our hypothesis, central drive (i.e. VA and RMS reductions) declined similarly after all aerobic exercises and remained reduced after the strength tests. However, contractile properties (i.e. PT, TPT and RTD) impairments were greater after aerobic exercises followed by strength-endurance tests than followed by 1RM tests. Regarding the peripheral fatigue indices, PT reductions may indicate impairments in excitation–contraction coupling (Allen, Lamb, & Westerblad, 2008; Fitts, 1994; Place, Yamada, Bruton, & Westerblad, 2010), while TPT reductions possibly occurred in consequence of the lower PT values. Reductions observed on RTD may indicate impairments in cross-bridge force rate (Andersen & Aagaard, 2006; Metzger, Greaser, & Moss, 1989). These physiological events are important for muscle contraction process and may have occurred as a result of metabolic acidosis (e.g. pH reduction and/or P_i accumulation), impairments on the action potential propagation (e.g. K^+ accumulation extracellular) and decreases in Ca^{2+} release or sensitivity, which is critical for the conversion of electrical stimuli to mechanical responses (Fitts, 2016; Place et al., 2010). Thus, we can conclude that strength was impaired by both central and peripheral fatigue, but strength-endurance test hampered the excitation-contraction coupling more than the maximum strength one.

Even though strength-endurance TV was affected by the aerobic exercise volume, we did not find significant differences in central and peripheral fatigue between the aerobic exercise volumes. These findings are hard to reconcile, as changes in central and peripheral fatigue indices were very similar between aerobic exercise volumes. A possible explanation could be that the tests used in the present study to measure functional performance and fatigue (central and peripheral) had limited mechanical resemblance. Accordingly, the maximum dynamic strength and strength-endurance assessments were performed in a multi-joint exercise (i.e. 45° leg press exercise), while fatigue tests were performed in a single-joint leg extension exercise using an isometric contraction. As fatigue assessments require the stimulation of a specific nerve branch or muscle belly, using a multi-joint exercise could negatively affect the specificity and sensibility of the tests. There are suggestions in the literature that single-joint isometric exercises have lower neural involvement than multi-joint dynamic exercises, as they are less complex and consequently require less coordination (Chilibeck, Calder, Sale, & Webber, 1997; Rutherford & Jones, 1986). Thus, one may suggest that the absence of differences in fatigue location after aerobic exercise with distinct volumes may have been due to the lack of mechanical similarity between the maximum dynamic strength and strength-endurance tests, and the fatigue tests.

This study is not without limitations. One may suggests that psychological factors (i.e. perceived effort and affection) associated with the distinct volumes of aerobic exercise (i.e. duration of the 3 km, 5 km, and 7 km trials) may have affected the performance in the subsequent maximum strength or strength-endurance tests, and fatigue test. Finally, it is worth noting that the present results should not be extrapolated to different aerobic exercise intensities (e.g. high-intensity intermittent training or self-selected intensity), exercise mode (e.g. cycle ergometer), and population (e.g. elderly, trained individuals, and athletes).

In conclusion, strength-endurance performance is impaired when performed after aerobic exercise and the magnitude of this interference is dependent on the aerobic exercise volume. However, peripheral and central fatigue indices could not explain the different TV observed herein.

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References

Allen, D. G., Lamb, G. D., & Westerblad, H. (2008). Skeletal muscle fatigue: Cellular mechanisms. *Physiological Reviews*, *88* (1), 287–332.

Allen, G. M., Gandevia, S. C., & Mckenzie, D. K. (1995). Reliability of measurements of muscle strength and voluntary activation using twitch interpolation. *Muscle & Nerve*, *18*(6), 593–600.

Andersen, L. L., & Aagaard, P. (2006). Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *European Journal of Applied Physiology*, *96*(1), 46–52.

Balabanis, C. P., Psarakis, C. H., Moukas, M., Vassiliou, M. P., & Behrakis, P. K. (2003). Early phase changes by concurrent endurance and strength training. *Journal of Strength and Conditioning Research*, *17*(2), 393–401.

Bell, G. J., Syrotuik, D., Martin, T. P., Burnham, R., & Quinney, H. A. (2000). Effect of concurrent strength and endurance training on skeletal muscle properties and hormone concentrations in humans. *European Journal of Applied Physiology*, *81*(5), 418–427.

Cadore, E. L., Izquierdo, M., Alberton, C. L., Pinto, R. S., Conceição, M., Cunha, G., … Kruel, L. F. M. (2012). Strength prior to endurance intra-session exercise sequence optimizes neuromuscular and cardiovascular gains in elderly men. *Experimental Gerontology*, *47*(2), 164–169.

Chilibeck, P. D., Calder, A. W., Sale, D. G., & Webber, C. E. (1997). A comparison of strength and muscle mass increases during resistance training in young women. *European Journal of Applied Physiology*, *77*(1-2), 170–175.

Craig, B. W., Lucas, J., & Pohlman, R. (1991). The effects of running, weightlifting and a combination of both on growth hormone release. *The Journal of Applied Sport Science Research*, *5*(4), 198–203.

De Salles Painelli, V., Alves, V. T., Ugrinowitsch, C., Benatti, F. B., Artioli, G. G., Lancha, Jr., A. H., … Roschel, H. (2014). Creatine supplementation prevents acute strength loss induced by concurrent exercise. *European Journal of Applied Physiology*, *114*(8), 1749–1755.

De Souza, E. O., Tricoli, V., Aoki, M. S., Roschel, H., Brum, P. C., Bacurau, A. V. N., … Ugrinowitsch, C. (2014). Effects of concurrent strength and endurance training on genes related to myostatin signaling pathway and muscle fiber responses. *Journal of Strength and Conditioning Research*, *28*(11), 3215–3223.

De Souza, E. O., Tricoli, V., Franchini, E., Paulo, A. C., Regazzini, M., & Ugrinowitsch, C. (2007). Acute effect of two aerobic exercise modes on maximum strength and strength endurance. *Journal of Strength and Conditioning Research*, *21*(4), 1286–1290.

Fitts, R. H. (1994). Cellular mechanisms of muscle fatigue. *Physiological Reviews*, *74*(1), 49–94.

Fitts, R. H. (2016). The role of acidosis in fatigue: Pro perspective. *Medicine and Science in Sports and Exercise*, *48*(11), 2335–2338.

Garber, C. E., Blissmer, B., Deschenes, M. R., Franklin, B. A., Lamonte, M. J., Lee, I. M., … Swain, D. P. (2011). American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: Guidance for prescribing exercise. *Medicine and Science in Sports and Exercise*, *43*(7), 1334–1359.

Heck, H., Mader, A., Hess, G., Mucke, S., Muller, R., & Hollmann, W. (1985). Justification of the 4-mmol/l lactate threshold. *International Journal of Sports Medicine*, *6*(3), 117–130.

Howley, E. T., Bassett, Jr., D. R., & Welch, H. G. (1995). Criteria for maximal oxygen uptake: Review and commentary. *Medicine and Science in Sports and Exercise*, *27*(9), 1292–1301.

Kraemer, W. J., Patton, J. F., Gordon, S. E., Harman, E. A., Deschenes, M. R., Reynolds, K., … Dziados, J. E. (1995). Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *Journal of Applied Physiology*, *78*(3), 976–989.

Leveritt, M., & Abernethy, P. J. (1999). Acute effects of high intensity endurance exercise on subsequent resistance activity. *Journal of Strength and Conditioning Research*, *13*(1), 47–51.

Leveritt, M., Abernethy, P. J., Barry, B. K., & Logan, P. A. (1999). Concurrent strength and endurance training. A review. *Sports Medicine*, *28*(6), 413–427.

Leveritt, M., MacLaughlin, H., & Abernethy, P. J. (2000). Changes in leg strength 8 and 32 h after endurance exercise. *Journal of Sports Sciences*, *18*(11), 865–871.

Metzger, J. M., Greaser, M. L., & Moss, R. L. (1989). Variations in cross-bridge attachment rate and tension with phosphorylation of myosin in mammalian skinned skeletal muscle fibers. Implications for twitch potentiation in intact muscle. *The Journal of General Physiology*, *93*, 855–883.

Millet, G. Y., & Lepers, R. (2004). Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. *Sports Medicine*, *34*(2), 105–116.

Millet, G. Y., Martin, V., Lattier, G., & Ballay, Y. (2003). Mechanisms contributing to knee extensor strength loss after prolonged running exercise. *Journal of Applied Physiology*, *94*(1), 193–198.

Neyroud, D., Vallotton, A., Millet, G. Y., Kayser, B., & Place, N. (2014). The effect of muscle fatigue on stimulus intensity requirements for central and peripheral fatigue quantification. *European Journal of Applied Physiology*, *114*(1), 205–215.

Panissa, V. L. G., Julio, U. F., Silva, C. M. P., Andreato, L. V., Hardt, F., & Franchini, E. (2012). Effects of interval time between high-intensity intermittent aerobic exercise on strength performance: Analysis in individuals with different training background. *Journal of Human Sport and Exercise*, *7*(4), 815–825.

Panissa, V. L. G., Tricoli, V. A. A., Julio, U. F., Ribeiro, N., De Azevedo Neto, R. M. A., Carmo, E. C., & Franchini, E. (2015). Acute effect of high-intensity aerobic exercise performed on treadmill and cycle ergometer on strength performance. *Journal of Strength and Conditioning Research*, *29*(4), 1077–1082.

Place, N., Lepers, R., Deley, G., & Millet, G. Y. (2004). Time course of neuromuscular alterations during a prolonged running exercise. *Medicine and Science in Sports and Exercise*, *36*(8), 1347–1356.

Place, N., Maffiuletti, N. A., Martin, A., & Lepers, R. (2007). Assessment of the reliability of central and peripheral fatigue after sustained maximal voluntary contraction of the quadriceps muscle. *Muscle & Nerve*, *35*, 486–449.

Place, N., Yamada, T., Bruton, J. D., & Westerblad, H. (2010). Muscle fatigue: From observations in humans to underlying mechanisms studied in intact single muscle fibres. *European Journal of Applied Physiology*, *110*(1), 1–15.

Reed, J. P., Schilling, B. K., & Murlasits, Z. (2013). Acute neuromuscular and metabolic responses to concurrent endurance and resistance exercise. *Journal of Strength and Conditioning Research*, *27*(3), 793–801.

Ross, E. Z., Goodall, S., Stevens, A., & Harris, I. (2010). Time course of neuromuscular changes during running in well-trained subjects. *Medicine and Science in Sports and Exercise*, *42*(6), 1184–1190.

Rutherford, O. M., & Jones, D. A. (1986). The role of learning and coordination in strength training. *European Journal of Applied Physiology and Occupational Physiology*, *55*(1), 100–105.

Sale, D. G., MacDougall, J. D., Jacobs, I., & Garner, S. (1990). Interaction between concurrent strength and endurance training. *Journal of Applied Physiology*, *68*(1), 260–270.

Sporer, B. C., & Wenger, H. A. (2003). Effects of aerobic exercise on strength performance following various periods of recovery. *Journal of Strength and Conditioning Research*, *17*(4), 638–644.

Thomas, K., Goodall, S., Stone, M., Howatson, G., Gibson, A. S. C., & Ansley, L. (2015). Central and peripheral fatigue in male cyclists after 4-, 20-, and 40-km time trials. *Medicine and Science in Sports and Exercise*, *47*(3), 537–546.

Wilson, J. M., Marin, P. J., Rhea, M. R., Wilson, S. M. C., Loenneke, J. P., & Anderson, J. C. (2012). Concurrent training: A meta-analysis examining interference of aerobic and resistance exercises. *Journal of Strength and Conditioning Research*, *26*(8), 2293–2307.