Oxygen Uptake Slow Component and the Efficiency of Resistance Exercises

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Abstract

Garnacho-Castaño, MV, Albesa-Albiol, L, Serra-Payá, N, Gomis Bataller, M, Pleguezuelos Cobo, E, Guirao Cano, L, Guodemar-Pérez, J, Carbonell, T, Domínguez, R, and Maté-Muñoz, JL. Oxygen uptake slow component and the efficiency of resistance exercises. *J Strength Cond Res* 35(4): 1014–1022, 2021—This study aimed to evaluate oxygen uptake slow component ($\dot{V}O_2sc$) and mechanical economy/efficiency in half squat (HS) exercise during constant-load tests conducted at lactate threshold (LT) intensity. Nineteen healthy young men completed 3 HS exercise tests separated by 48-hour rest periods: 1 repetition maximum (1RM), incremental-load HS test to establish the %1RM corresponding to the LT, and constant-load HS test at the LT. During the last test, cardiorespiratory, lactate, and mechanical responses were monitored. Fatigue in the lower limbs was assessed before and after the constant-load test using a countermovement jump test. A slight and sustained increase of the $\dot{V}O_2sc$ and energy expended (EE) was observed ($p < 0.001$). In blood lactate, no differences were observed between set 3 to set 21 ($p > 0.05$). A slight and sustained decrease of half squat efficiency and gross mechanical efficiency (GME) was detected ($p < 0.001$). Significant inverse correlations were observed between $\dot{V}O_2$ and GME ($r = -0.93$, $p < 0.001$). Inverse correlations were detected between EE and GME ($r = -0.94$, $p < 0.001$). Significant losses were observed in jump height ability and in mean power output ($p < 0.001$) in response to the constant-load HS test. In conclusion, $\dot{V}O_2sc$ and EE tended to rise slowly during constant-load HS exercise testing. This slight increase was associated with lowered efficiency throughout constant-load test and a decrease in jump capacity after testing. These findings would allow to elucidate the underlying fatigue mechanisms produced by resistance exercises in a constant-load test at LT intensity.

Key Words gross mechanical efficiency, lactate threshold, mechanical fatigue, energy expended, half squat

Introduction

Recently, several studies have focused on incremental resistance exercise tests (10,13) designed to identify the point of transition between aerobic and anaerobic metabolism, recognized as the lactate threshold (LT) (3). The LT is defined as the load intensity during incremental exercise at which blood lactate concentrations increase exponentially (39). This is considered the load intensity that supports the prescription of resistance training and monitoring of training progress for the healthy population, athletes, and those undergoing rehabilitation (39).

During prolonged constant-load resistance exercises tests conducted at a load intensity equivalent to the LT, a stabilization is observed in blood lactate levels and in cardiorespiratory response in leg press (10) and half squat (HS) exercise (14), as also occurs in endurance exercises (13). It is known that oxygen uptake ($\dot{V}O_2$) tends to slowly rise during any constant work rate exercise test involving sustained lactic acidosis, surpassing the primary component initiated at exercise onset. This $\dot{V}O_2$ response, known as the "$\dot{V}O_2$ slow component" ($\dot{V}O_2sc$), is defined as the continued increase in $\dot{V}O_2$ beyond the third minute of exercise (12) until a delayed steady state is attained or maximal $\dot{V}O_2$ is reached (43). During long-term constant-load exercise, the $\dot{V}O_2sc$ kinetics increases the energy expenditure above that predicted from the submaximal $\dot{V}O_2$ work-rate relationship, leading to a reduced work efficiency and premature fatigue.

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Thus, a limited $\dot{V}O_2sc$ might be an important parameter to determine endurance performance (12).

The scientific literature indicates several physiological factors that individually or jointly could influence on the $\dot{V}O_2sc$ behavior, including muscle fiber type (34), type of muscle action and contraction (35), pattern of motor unit recruitment, and type of exercise (6). It has been reported that the $\dot{V}O_2sc$ is lower in running compared with cycling exercise (6) and higher in arm-crank than leg-cycle exercises (19), indicating that the $\dot{V}O_2sc$ is exercise-dependent.

Although these studies have focused on evaluating the $\dot{V}O_2sc$ in endurance exercises, the $\dot{V}O_2sc$ phenomenon in resistance exercises during a long-term constant-load exercise test has not been explored. It is tempting to suggest that knowledge of $\dot{V}O_2sc$ behavior in resistance exercises might help to elucidate the underlying fatigue mechanisms produced during prolonged constant-load testing. Garnacho-Castaño et al. (13) observed significant losses in height and mean power during the countermovement jump (CMJ) test only in HS exercise (not in cycling) measured at the end of a constant-load exercise test at LT intensity. This decrease in jumping ability after the constant-load HS test could be related to a slow rise in $\dot{V}O_2$, and the corresponding increase in energy cost would be associated with progressive fatigue (16). This mechanical fatigue, presumably prompted during a constant-load HS test, would stimulate a preferential glycogen depletion of type I fibers and induce a forced recruitment of type II fibers (21). In addition, a key determinant of the $\dot{V}O_2sc$ is the change in gross mechanical efficiency (GME), which estimates the effects of blood alkalinization on the gradual loss of muscle efficiency (12).

TABLE 1. Descriptive data related to 1RM incremental- and constant-load tests.*

Variables	Mean	*SD*
1RM in HS (kg)	204.9	45.9
Load at LT intensity (kg)	51.0	17.2
LT intensity (%1RM)	25.3	5.0
Lactate in constant test ($mmol\cdot L^{-1}$)	3.3	0.9
$\dot{V}O_2$ at LT intensity ($L\cdot min^{-1}$)	1.6	0.2
$\dot{V}O_2$ at LT intensity ($ml\cdot Kg^{-1}\cdot min^{-1}$)	20.0	2.3
HR at LT intensity ($b\cdot min^{-1}$)	128.6	12.0
RER at LT intensity	0.93	0.0
HSE at LT ($W\cdot L^{-1}\cdot min^{-1}$)	155.7	6.6
GME at LT (%)	44.9	2.0
EE at LT intensity ($Kcal\cdot min^{-1}$)	8.0	0.4

*1RM = 1 repetition maximum; HS = half squat; LT = lactate threshold; $\dot{V}O_2$ = oxygen uptake; HR = heart rate; RER = respiratory exchange ratio; HSE = half squat efficiency; GME = gross mechanical efficiency; EE = energy expended.

Half squat is one of the most popular exercises in resistance training programs. In scientific literature, the $\dot{V}O_2sc$ and economy/efficiency responses to constant-load HS exercise performed at LT intensity are still unknown.

We hypothesized that, as $\dot{V}O_2sc$ increases in a prolonged constant-load test at LT intensity, work efficiency in resistance exercises such as HS should be reduced, and therefore, it would be plausible to propose a causal inverse relationship between the $\dot{V}O_2sc$, energy expended (EE), and mechanical efficiency. This study aimed to evaluate the $\dot{V}O_2sc$ kinetic, EE, and mechanical efficiency in HS exercise during prolonged constant-load tests conducted at an intensity equivalent to the LT.

METHODS

Experimental Approach to the Problem

Subjects performed 3 different tests between 9:00 AM and 15:00 PM (±3 hours) each day under the same environmental conditions (temperature: 21–25° C, atmospheric pressure: 715–730 mm Hg, and relative humidity: 40–50%), with a rest period between each test of 48 hours. The test protocols followed the guidelines established by our research group in previous studies (14): (a) 1 repetition maximum (1RM) HS test to determine the % loads to be used in the incremental test, (b) incremental-load HS test to establish the %1RM corresponding to the LT, and (c) constant-load HS test at the LT. In the HS constant-load test, acute cardiorespiratory and metabolic responses were recorded. A Smith machine (Matrix G1-FW161; Matrix Fitness, Johnson Health Tech, Cottage Grove, WI) was used to ensure controlled movements. Mechanical fatigue in the lower limbs was assessed before and after the constant-load tests.

Subjects

The study subjects were 19 young (aged 19–25 years), healthy men, all students of the Physical Activity and Sport Sciences (age 21.7 ± 1.7 years; height, 180.5 ± 5.1 cm; body mass, 81.9 ± 9.5 kg; body mass index, 25.1 ± 2.2, data are provided as mean ± standard deviation). Subjects had at least 6 months of experience in strength training and all were accustomed to HS exercise. Four exclusion criteria were applied: (a) the use of any medication or performance-enhancing drugs, (b) any cardiovascular, metabolic, neurological, pulmonary, or orthopedic disorders that could limit exercise performance, (c) being an elite athlete, and (d) a 1RM of less than or equal to 150 kg in HS exercise.

Before the study outset, subjects were informed of the tests, and written consent was obtained from each subject. The study protocol was approved by the Ethics Committee of the Alfonso X el Sabio University (Madrid, Spain) and adhered to the tenets of the Declaration of Helsinki.

Procedures

One Repetition Maximum Half Squat Test. The HS test protocol included a standard warm-up for all subjects, involving 5 minutes of low-intensity running and 5 minutes of joint mobility and dynamic stretching exercises. This was

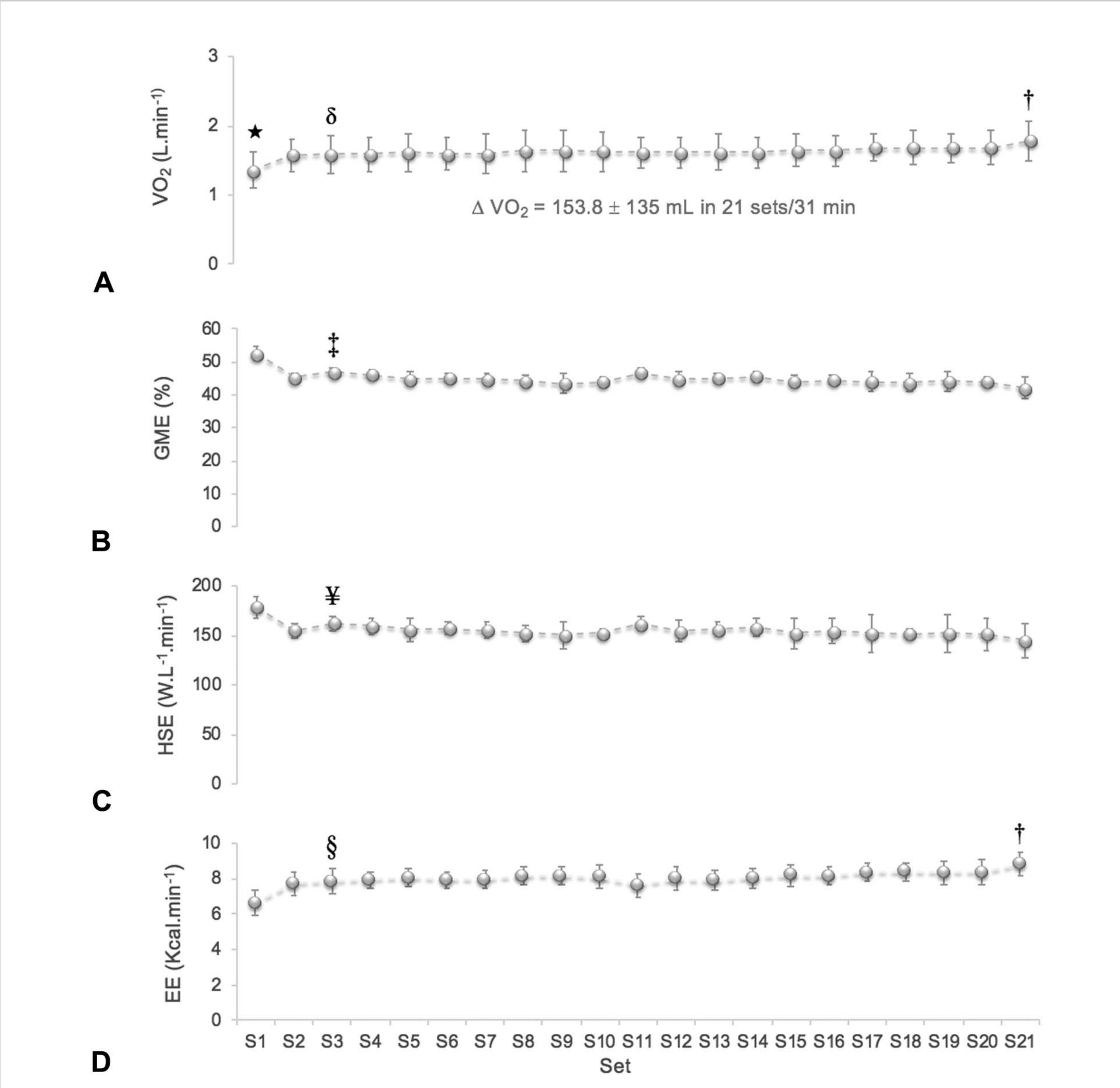

Figure 1. Slow component kinetics (A); gross mechanical efficiency (GME) (B); half squat efficiency (HSE) (C); and energy expended (EE) (D) during constant-load half squat (HS) test at lactate threshold intensity. ★Significant differences vs. checkpoints S3, S6, S9, S12, S15, S18, S21 ($p < 0.001$). δSignificant differences vs. checkpoints S6, S12, S15, S18, S21 ($p < 0.05$). ‡Significant differences vs. checkpoints S6, S9, S12, S15, S18, S21 ($p < 0.05$). ¥Significance differences vs. checkpoints S9, S12, S15, S18, S21 ($p < 0.05$). §Significant differences vs. checkpoints S6, S18, S21 ($p \leq 0.004$). † Significant differences vs. checkpoints S6, S12, S15 ($p < 0.05$).

followed by a specific warm-up consisting of 1 set of 3–5 HS repetitions at a relative intensity of 40–60% of the maximum perceived effort. Subjects commenced the 1RM test after a 2-minute rest. This involved 3–5 lifting attempts using increasing weights. The 1RM was defined as the last load lifted by the subject while completing a knee extension to the required position. The rest period between each attempt was 4 minutes.

The HS technique was specified in the protocol. The subjects positioned themselves under the barbell in a standing position with the knees and hips fully extended, and legs spread at shoulder width. The barbell was placed on the upper back (trapezius muscle), approximately at the level of the acromion. The subject flexed the knees and hips (eccentric action) to lower the barbell in a controlled manner, until 90° flexion of the knees. From this position,

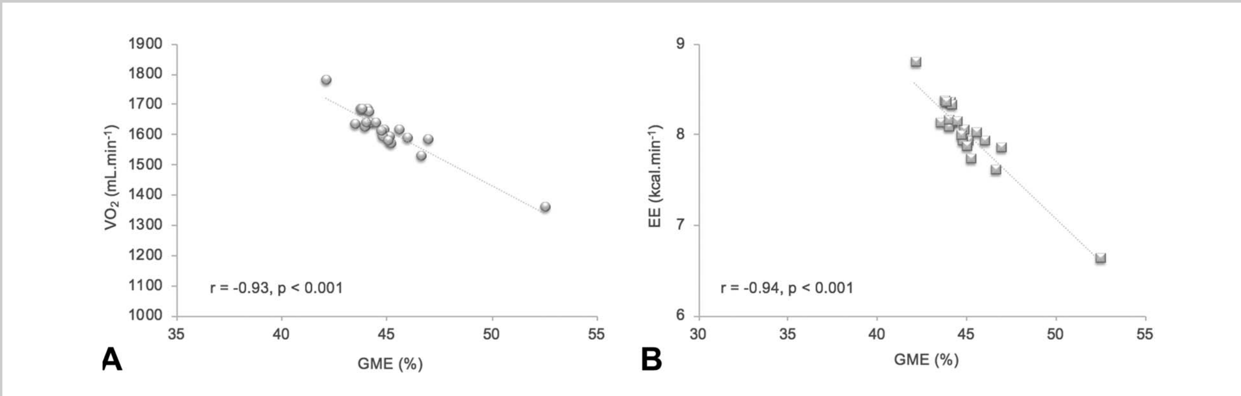

Figure 2. Relationship between (A) $\dot{V}O_2$ and gross mechanical efficiency (GME); (B) energy expended (EE) and GME.

the propulsive (concentric) muscle action was initiated until the knees and hips were fully extended.

Incremental Half Squat Test. Subjects performed the same warm-up as in 1RM HS test. After a 2-minute rest, the incremental HS test was performed in sets at relative intensities of 10, 20, 25, 30, 35, and 40% 1RM as in previous studies (14,27). Each set lasted 1 minute and involved 30 repetitions of 2 seconds each (1 second for the eccentric phase and 1 second for the concentric phase). This rhythm was monitored with a metronome while an observer provided visual and verbal cues. A passive rest of 2 minutes was established between sets while the relative load (%1RM) was increased and blood samples were collected for lactate determination. The test was completed when the subject did not correctly perform repetitions or was unable to continue executing repetitions at the rhythm set for each set at the corresponding relative intensity (%1RM).

Blood samples (5 μL) were obtained by finger pricking 30 seconds after the end of each set/relative intensity (10, 20, 25, 30, 35, and 40% of 1RM), and lactate levels determined using a portable lactate analyzer (Lactate Pro LT-1710; Arkray Factory Inc., KDKCorporation, Shiga, Japan). The reliability of this device has been previously evaluated (28). All measurements were rigorously performed by the same expert evaluator.

The LT was established using the algorithm adjustment method based on the procedure described by Orr et al. (31), as the work intensity at which lactate concentrations start to increase in an exponential manner (42). The LT was located through computerized 2-segment linear regression by fixing both linear regression equations emerging for each segment at the point of intersection between a plot of blood lactate concentration and relative intensity. Data treatment was performed using the software package Matlab version 7.4 (MathWorks, Natick, MA).

Constant-Load Half Squat Test at Lactate Threshold Intensity. Subjects performed the same warm-up as in 1RM HS test. After 2 minutes, the constant-load HS test was conducted as 21 sets of 15 repetitions of 2 seconds (1 second of concentric exercise and 1 second of eccentric) guided by metronome, visual, and verbal cues. The duration of each set was 30 seconds, with a 1-minute rest period between sets; the complete constant-load test took 31 minutes.

Respiratory exchange data were recorded using a breath-by-breath open-circuit gas analyzer (Vmax spectra 29; Sensormedics, Corp., Yorba Linda, CA), which had been previously calibrated. The following variables were monitored: minute ventilation (VE), volume oxygen consumed ($\dot{V}O_2$), volume carbon dioxide expired ($\dot{V}CO_2$), and respiratory exchange ratio (RER). Heart rate was monitored every 5 seconds by telemetry (RS-800CX; Polar Electro OY, Kempele, Finland).

Blood samples were obtained at rest and 30 seconds after the end of the HS sets (S) S3, S6, S9, S12, S15, S18, and S21, when lactate concentrations were determined as described above for the incremental test. The checkpoints of the lactate samples coincided with the following minutes of testing (M): S3/M4, S6/M8.5, S9/M13, S12/M17.5, S15/M22, S18/M26.5, and S21/M31 (test end).

The $\dot{V}O_2$sc was identified as the difference between $\dot{V}O_2$ at the end of exercise and at the end of the third minute of constant-load exercise ($\Delta\dot{V}O_2$, in $mL \cdot min^{-1}$). The latter was taken as the average $\dot{V}O_2$ from 2 minutes 30 seconds to 3 minutes 30 seconds (set 2 to set 3), whereas end exercise values were taken as the average of the last 2 minutes of the tests (29 minutes 0 seconds to 31 minutes 0 seconds/set 20 to set 21).

Mean HS efficiency (HSE) during constant load was expressed in $W \cdot L^{-1} \cdot min^{-1}$, whereas GME was calculated as the ratio of work accomplished per minute (i.e., W in $kcal \cdot min^{-1}$) to energy consumed per minute (i.e., in

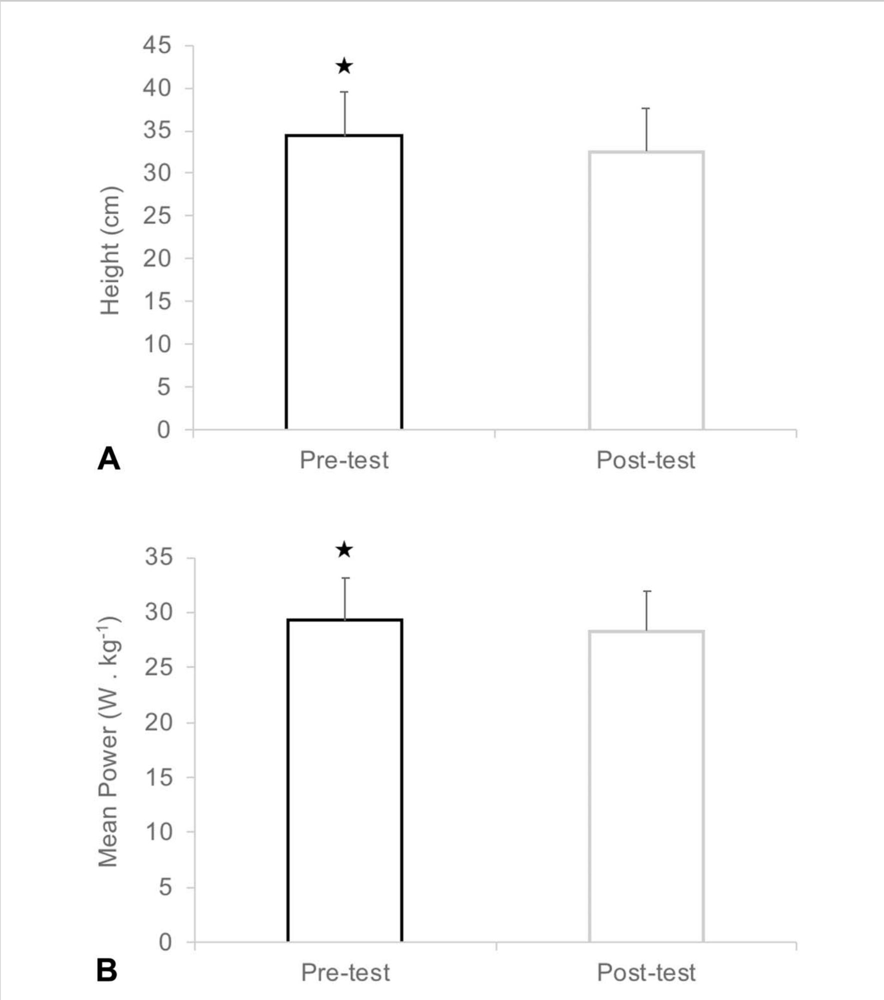

Figure 3. Mechanical fatigue measured as jump height losses (A) and mean power output losses (B) in a countermovement jump test. ★Significant differences vs. post-test ($p < 0.001$).

kcal·min^{-1}), as described elsewhere (8). Energy expenditure was calculated from $\dot{V}O_2$ and the RER using the tables of Lusk (25). To determine the GME and HSE, a linear position transducer, Tendo Weightlifting Analyzer System (Trencin, Slovak Republic) was used to measure bar velocity during constant-load HS exercise testing. The reliability and validity of this device has been previously demonstrated (15). The power output was calculated for each repetition based on bar velocity as follows:

velocity (m·s^{-1}) = vertical movement of the bar (m) × time (s^{-1})

acceleration (m·s^{-2}) = vertical bar velocity (m·s^{-1}) × time (s^{-1})

force (N) = system mass (kg) × [vertical acceleration of the bar (m·s^{-2}) + acceleration due to gravity (m·s^{-2})]

power (W) = vertical force (N) × vertical bar velocity (m·s^{-1}).

The mean power output was calculated as the average of all repetitions.

Lower Limbs Fatigue. Mechanical fatigue was determined using a CMJ test following a method previously described (14). Briefly, the test was performed using a force plate (Quattro Jump model 9290AD; Kistler Instruments, Winterthur, Switzerland) before and after the constant-load HS test at the LT intensity. Pre-test and post-test jumps were exactly performed before starting the HS test (after warm-up) and after the last blood lactate collection, respectively. Subjects performed 3 jumps separated by a rest time of 30 seconds, and the mean values of height and mean power recorded in the 3 jumps were used in the subsequent analyses.

Statistical Analyses

The Shapiro-Wilk test was used to check the normal distribution of data, which are provided as mean ± *SD*. Repeated-measures analysis of variance was used to compare $\dot{V}O_2$ kinetics, lactate, EE, GME, and HSE responses. When significant differences emerged, Bonferroni test was used to determine between which checkpoints these occurred. Effect sizes were calculated using partial eta-squared (η_p^2). Statistical power (SP) and intraclass correlation coefficients were also determined.

Pearson product-moment correlation coefficients were calculated to determine a significant relationship between $\dot{V}O_2$ and GME, and between EE and GME. To determine mechanical fatigue, student *t*-test for paired samples was used to evaluate CMJ height and power losses produced in response to the constant-load test at LT intensity. All statistical tests were performed using the software package SPSS Statistics version 23.0 for Mackintosh (SPSS, Chicago, IL). Significance was set at $p \leq 0.05$.

Results

Descriptive data related to incremental- and constant-load tests are shown in Table 1.

A significant difference in blood lactate levels was observed ($F_{7,\ 126} = 36.51$, $p < 0.001$, $\eta_p^2 = 0.670$, SP = 1), and Bonferroni test confirmed differences between resting and all checkpoints ($p < 0.001$). Although no significant changes ($p > 0.05$) were observed between S3 to S21, a slight rise was detected in the blood lactate kinetics.

The behavior of $\dot{V}O_2sc$ kinetics, GME, HSE, and EE during constant-load HS test at LT intensity is shown in Figure 1. A significant $\dot{V}O_2$ increase was detected ($F_{7,\ 126} = 22.09$, $p < 0.001$, $\eta_p^2 = 0.551$, SP = 1), and a slight and sustained increase of the $\dot{V}O_2sc$ was observed (Figure 1A). In GME, a significant slight and sustained decrease was observed throughout the constant-load HS test ($F_{6,\ 108} = 10.06$, $p < 0.001$, $\eta_p^2 = 0.359$, SP = 1), and Bonferroni test confirmed changes between S3 and all checkpoints ($p < 0.05$) (Figure 1B). A significant slight and sustained decrease was observed throughout the constant-load test in HSE ($F_{6,\ 108} = 8.56$, $p < 0.001$, $\eta_p^2 = 0.322$, SP = 1), and significance differences were found between S3 and S9, S12, S15, S18, S21 checkpoints ($p < 0.05$) (Figure 1C). A significant slight and sustained increases of EE was identified ($F_{6,\ 108} = 10.54$, $p < 0.001$, $\eta_p^2 = 0.369$, SP = 1), and Bonferroni test determined significant differences between S21 vs. S3, S6, S12, S15 ($p < 0.05$) (Figure 1D).

Significant inverse correlations were found between $\dot{V}O_2$ and GME ($r = -0.93$, $p < 0.001$) (Figure 2A). Significant inverse correlations were detected between EE and GME ($r = -0.94$, $p < 0.001$) (Figure 2B).

Intraclass correlation coefficients were 0.964 (confidence interval [95% CI]: 0.932–0.984) for lactate, 0.973 (95% CI: 0.959–0.988) for $\dot{V}O_2sc$, 0.994 (95% CI: 0.989–0.997) for HSE, and 0.994 (95% CI: 0.990–0.998) for GME.

In response to the constant-load HS test, significant losses were observed in jump height ability ($p < 0.001$) and in mean power output ($p < 0.001$) (Figure 3A, B).

Discussion

The principal finding of this study was that $\dot{V}O_2sc$ (small magnitude) and EE tended to rise slowly during constant HS exercise testing conducted at a load intensity equivalent to the LT. In addition, GME and HSE were slightly decreased throughout the HS constant test (Figure 1). Consequently, $\Delta\dot{V}O_2$ and EE were inversely correlated with GME (Figure 2) because the GME was diminishing as $\dot{V}O_2$ and EE were increased throughout the long-term constant-load test.

Although comparable conclusions have been observed in several studies analyzing the relationship between $\dot{V}O_2$ and GME during prolonged constant-load cycling exercise (18), no data are available about the $\dot{V}O_2sc$, EE, HSE, or GME of humans able to sustain 21 sets of 15 repetitions for at least 31 minutes with relatively low circulating lactate levels (~3.3 mMol) in HS exercise.

Our results were slightly higher in absolute values (153.8 ml in 28 minutes vs. 130 ml in 17 minutes) and slightly lower in relative values (5.49 $ml\cdot min^{-1}$ vs. about 8 $ml\cdot min^{-1}$) than those obtained by professional cyclists (22), although our findings clearly differed from those reported by others (330 ml in 15 minutes or 22 $ml\cdot min^{-1}$) in nonprofessional cyclists (17), both studies during 20 minutes of constant-load test at 80% of $\dot{V}O_2$max. Carter et al. (6) found that the absolute magnitude of $\dot{V}O_2sc$ was significantly higher for cycling than for running at 2 intensities (50%Δ, 334 ± 183 vs. 205 ± 84 $ml\cdot min^{-1}$; 75%Δ, 430 ± 159 vs. 302 ± 154 $ml\cdot min^{-1}$). These data verify the assumptions that the precise amplitude of $\dot{V}O_2sc$ is influenced by the experimental conditions, characteristics of the subjects including fitness and muscle fiber type (2,33), exercise modalities (19), training status (22), and the exercise intensity (5).

Although similar $\dot{V}O_2sc$ performance could be observed in different exercise modalities (i.e., HS in our study vs. cycling), the etiology of resistance exercise at LT intensity is uncertain because the power output at LT intensity signifies the highest power output or load that will not induce $\dot{V}O_2sc$ (5). In theory, at LT intensity, the $\dot{V}O_2sc$ should be nonexistent or very low; however, in our study, a slow rise of $\dot{V}O_2sc$ was observed, similar to that reported in professional cyclists at an intensity above LT (80% $\dot{V}O_2$max) (22).

Although our study did not compare HS to cycling exercises, we suspected that HS exercise could induce higher levels of fatigue than cycling at the same relative intensity (LT), elevating the $\dot{V}O_2sc$; this idea is supported by our previous findings (13) that significant losses in jump capacity height and power output production occur only in HS exercise and not in cycling at the end of constant-load testing at LT intensity. Again, this study corroborates a mechanical fatigue (approx. losses of 5% in height and power) induced in lower limbs evaluated by CMJ capacity immediately after constant-load HS exercise test at LT intensity. We suggest a causal relationship between the mechanical mechanisms that induce loss of force in lower extremities and the increased O_2 cost of exercise at the end of constant-load test. The increased pulmonary $\dot{V}O_2sc$ cost of exercise likely appears at intensities at which muscle fatigue has been reported (9). Probably, ATP cost of muscle contraction progressively increased while force production of lower limbs was gradually decreasing (4) throughout the constant-load HS test. Thus, the intensity-dependent decline in muscle efficiency is believed to be associated with the progressive development of muscle fatigue (45).

In addition, Poole et al. (33) proposed that 86% of the $\dot{V}O_2sc$ could be determined by an increase in leg oxygen uptake, suggesting that $\dot{V}O_2sc$ is mainly activated within the contracting muscle, and the central factors have a minor influence of its amplitude (29). From a mechanical perspective, this means a delayed recruitment of less oxidatively efficient, larger motor units to compensate for attenuated force production in those already active motor units (12), as well as a reduction in the efficiency of skeletal muscle contraction and mitochondrial energy production (20). In support of this assumption, the magnitude of $\dot{V}O_2$sc has been correlated with the percentage (2) and recruitment of type II muscle fibers (37). It has been assumed that the ratio of phosphate produced per oxygen consumed is 18% higher in isolated mitochondria from type I compared with type II muscle, which suggests uncoupling of mitochondrial respiration (44). In this regard, $\dot{V}O_2$sc reveals a gradual recruitment of type II fibers with exercise duration (33,35), whereas type II fibers are less efficient than type I fibers. The purpose of this study was not to assess the physiological mechanisms responsible for the gradual recruitment of type II fibers; therefore, these assumptions are purely speculative. However, some of these physiological mechanisms may justify the need for recovery time in resistance exercises to continue maintaining a predominantly aerobic metabolism at LT intensity.

The exact mechanisms that cause $\dot{V}O_2$sc during submaximal intensity exercise are not yet fully understood. We hypothesized that the $\dot{V}O_2$sc phenomenon might be explained, at least in part, by the change in GME, which estimates the effects of blood alkalinization on the gradual loss of muscle efficiency (12).

Unfortunately, our results cannot be reinforced by previous findings because no data are available about GME and efficiency in resistance exercises during long-term constant-load exercise testing at LT intensity. The GME results reported in this study are higher than those obtained in word class cyclist (23) and professional riders (24) (both ~24%) at the power outputs eliciting the LT and the respiratory compensation point during a ramp test. In well-trained cyclists were observed lower values (~18%) during 2-hour constant-load cycling exercise at 60% of maximal minute power output (18). Other studies in cyclists who were not highly trained (30) have found lower values of GME (~20%) in healthy general population, values of 18–22% have been observed, and values of 16% were reported in chronic patients with severe exercise intolerance during leg cycling exercise (1).

The physiological mechanisms of GME reduction in resistance exercises during constant-load test at LT intensity are fully unknown. The high values found in our study, compared with others, are likely attributable to the characteristics of resistance training. Performing a set of HS or other resistance exercise is usually a brief and intense task in which recovery time is required to execute added series. Probably, making 21 sets of HS exercise causes a relative lack of O_2 supply to muscle loci, further suggesting that a large portion of the energy comes from anaerobic system that could not be determined by measuring metabolic gas exchange. This may have happened from a theoretical perspective because resistance training is chiefly fueled by anaerobic metabolism, generally inducing an important release of anaerobic sources to EE (40) that preclude the use of steady-state $\dot{V}O_2$ to accurately estimate EE (36). As a result, a high-efficiency ratio (work accomplished/EE) could occur.

In addition, Villagra et al. (41) found a higher $\dot{V}O_2$ and a lower GME (approximately 13–20%) as the load increased in 2 forms of squatting exercise. Gross mechanical efficiency differences observed between our results and those of Villagra et al. (41) could be attributed to the experimental protocols used in both studies. Subjects in their study performed 24 knee flexions per minute and 96 flexions in 4 minutes with full recovery between sets in 2 forms of squatting exercise. In our study, unlike several studies that used different resistance exercises and protocols (10,38), an experimental protocol of 15 repetitions/30 seconds per set was achieved in which blood lactate levels and $\dot{V}O_2$ responses remained stable during HS constant-load test at LT intensity (13,14). In both studies, light loads were used, and therefore, the differences could be produced by the repetitions/duration established in each set and the type of exercise (HS vs. full squat). In preliminary test, we detected that the blood lactate concentrations and $\dot{V}O_2$ were exponentially increased by rising the repetitions/duration (approximately more than 20 repetitions or 35–40 seconds per series). It can reasonably be expected that if a set of 1 minute in squatting exercises is performed (41), probably, EE will mostly come from anaerobic sources to a greater extent than in our study, triggering a different oxygen consumption and GME. We advocate a protocol of 15 repetitions/30 seconds per set to request mostly aerobic sources in a constant protocol. These postulates should be supported by other experimental designs that analyze the etiology of GME in resistance exercises in both aerobic and anaerobic metabolism.

Significantly higher lactate values were observed during the HS exercise than at baseline, but once they had increased to ~3.3 $mmol \cdot L^{-1}$ at S3, there were no further increases, although GME and HSE were smoothly diminishing as the $\dot{V}O_2$ was slowly rising as the time of the test was extended. Effectively, an inverse relationship between GME and $\Delta\dot{V}O_2$ was observed. It has been reported that a decrease in efficiency coincides with significant increases in oxygen uptake during repeated submaximal exercise (32).

Other possible explanations that would justify the high GME observed could be related to the stretch-shortening cycle in HS exercise. The stretch-shortening cycle involves the active stretching of a muscle (eccentric contraction) followed by its immediate shortening (concentric contraction). Previous findings (41) have demonstrated that the gross, net, and apparent efficiency of rebound squats was significantly greater than that of no rebound squats. The authors concluded that the mechanical work performed in both protocols (rebound vs. no rebound) was the same; however, no rebound exercise induced a greater oxygen cost. It is likely that the rebound HS exercise requires less oxygen due to the contribution of elastic recoil (41). During eccentric phase (prestretching or negative work), a storage of elastic energy in the series elastic components is produced in muscles and tendons. Energy produced is reused during the concentric phase (positive work), possibly decreasing oxygen uptake to a greater extent than resistance exercises with a single concentric phase.

Most of the studies used to evaluate GME have been in cycling test, and cycle pedaling mainly involves concentric muscle actions (11). Various factors affect efficiency and fatigue during exercise, including muscle properties (22), the type of muscle contraction, the type of muscle action, and the exercise methodology (maximal vs. submaximal force generation and duration) (26). Studies comparing GME of the cycle ergometer and resistance exercise are needed to sustain such claims. In addition, differences in power measurement between a linear position transducer and a cycle ergometer should be taken into consideration.

Although GME might be linked to the percent distribution of oxidative, fatigue-resistant (type I) fiber, it certainly is not an accurate measure of muscle efficiency (8). However, GME could be considered as a practical and suitable marker of whole-body efficiency (7), reliable throughout laboratory tests (30), reflecting the ability to perform exercise at the lowest possible metabolic cost.

This study had some limitations that need to be discussed. The 1RM of the subjects could vary from the initial test session to the next; therefore, a test-retest would have been convenient for improving reliable test results by reducing the effects of a systematic bias. This means that the load used (% 1RM) during incremental test session and the power output developed in each repetition of HS exercise could also be slightly altered during the constant-load test at LT intensity.

Future research should be conducted to determine what type of exercises (resistance or endurance exercises) could be more efficient to apply both in sports performance and in health-related exercise programs in diverse populations (e.g., healthy adults, sedentary lifestyle, elderly, athletes, diseases, etc.). It would be essential to analyze other resistance exercises (e.g., bench press, leg press, etc.) and compare or combine them with endurance exercises (e.g., cycling, walking, running, etc.) to determine what type of exercises are more suitable for each population according to the objective of the exercise program.

Practical Applications

The etiology of fatigue in resistance exercise is not completely understood. However, better knowledge of the behavior of $\dot{V}O_2sc$, EE, HSE, and GME (typically used in endurance exercises) would allow us to increase performance and discover the potential of resistance exercises in a predominantly aerobic metabolism.

As previously discussed, it is plausible to speculate that resistance training at LT intensity could be a very useful complementary training at a certain time of the season, especially when we refer to fitness training programs and sport performance by improving local muscular resistance and cardiorespiratory fitness in both athletes and healthy adults. It is likely that when performing 21 series in resistance exercises with a short recovery time as described in this study, local muscle endurance could be improved using a predominantly aerobic metabolism without producing the metabolites (e.g., H^+) that generate the most purely anaerobic metabolism. It is suspected that, by the decrease in jumping ability, the load used in resistance exercises at LT intensity may be great enough to increase local muscle endurance. In preliminary tests (unpublished data), our research group have observed how the combination of resistance exercises in a circuit training at LT intensity could maintain stable and low blood lactate concentrations, slightly increasing the $\dot{V}O_2sc$ and maintaining a high mechanical efficiency. More research is needed to confirm these preliminary findings.

A further possible application could be the prescription of resistance exercises in patients with some sort of disorder. For example, resistance training conducted at an intensity equivalent to the LT would help optimize glucose entry into the muscle, probably improving cardiorespiratory fitness and local muscle endurance.

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