# Lower-limb Dynamics of Muscle Oxygen Saturation During the Back-squat Exercise: Effects of Training Load and Effort Level

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**Abstract**

Gómez-Carmona, CD, Bastida-Castillo, A, Rojas-Valverde, D, de la Cruz Sánchez, E, García-Rubio, J, Ibáñez, SJ, and Pino-Ortega, J. Lower-limb dynamics of muscle oxygen saturation during the back-squat exercise: effects of training load and effort level. *J Strength Cond Res* XX(X): 000–000, 2019—The aim of this study was to analyze the effect of strength training on lower limb muscle oxygenation. The sample consisted of 12 male subjects (22.4 ± 1.73 years; 1.81 ± 0.08 cm height and 77.76 ± 8.77 kg body mass). Six different strength training stimuli were analyzed, based on the training variables: load (60–75% 1 repetition maximum [1RM]) and level of effort (LE) (E1: 4 × 8 [20RM], E2: 4 × 12 [20RM], E3: 4 × 16 [20RM], E4: 4 × 4 [10RM], E5: 4 × 6 [10RM], and E6: 4 × 8 [10RM]) in the squat exercise up to 90° with a 2-second stop between repetitions to avoid the myotatic reflex. Oxygen saturation at the beginning of the series ($SmO_2$start), oxygen saturation at the end of the series ($SmO_2$stop), percentage of oxygen saturation loss ($\nabla\%SmO_2$), and reoxygenation time ($SmO_2$recT) were assessed using a near-infrared spectroscopy device. In addition, the percentage of mean propulsive velocity loss (%MPVL) was recorded using a linear transducer. The results suggested an influence of LE and training load on muscle oxygenation. A greater LE was directly associated with $SmO_2$recT ($r = 0.864$), $\nabla\%SmO_2$ ($r = 0.873$), and %MPVL ($r = 0.883$) and inversely with $SmO_2$stop ($r = -0.871$). When the same LE was used (E1 vs. E4, E2 vs. E5, and E3 vs. E6), it was found that the stimuli with a higher load had a lower $SmO_2$recT, $\nabla\%SmO_2$, and %MPVL and a higher $SmO_2$stop. Muscle oxygen saturation was found to be minimal ($\%SmO_2 = 0$) in stimuli with a LE greater than 60% (E3 and E6). The $SmO_2$ variables studied in the present research could be considered as an easier and more useful method for understanding skeletal muscle fatigue during resistance training.

**Key Words:** strength training, velocity-based, near-infrared spectroscopy

## Introduction

The adaptations produced by strength training depend on the interaction of different variables such as intensity, level of effort (LE), rest interval, frequency, and volume (33,37). The interaction of the variables involved in resistance training hinders the analysis of their individual contribution in the improvement of strength performance and specific training programming (29). The understanding and manipulation of these training variables could influence performance; and there is a direct relationship with fatigue mechanisms (32). The study of the complex interaction of these multiple variables could lead to optimal loading strategies for improving responses to strength exercise (38).

In strength training, various indicators have been used to control intensity and fatigue during exercise (41). Intensity parameters such as relative load are commonly used (1 repetition maximum [1RM] percentage) or maximum load with which a certain number of repetitions can be performed (nRM) (14,17,23,35). Among commonly used fatigue indicators during training, LE and mean propulsive velocity loss (MPVL) are the most popular nowadays. The level of effort is expressed as the percentage of the repetition performed compared with the maximum possible, and it shows a relation with the execution velocity loss that is understood as the loss of execution velocity compared with the maximum possible (18,36). This finding makes it possible to estimate from the monitoring of repetition velocity how many repetitions could be made in a given exercise set. In addition, these variables are used for designing strength training programs and have been related to training intensity and fatigue markers such as ammonium and lactate (17,19).

Peripherical fatigue has been reported to have multiple etiologies, and one of these causes could be oxygen availability (29). In this sense, related to training intensity, it has been shown that when the numbers of repetitions are increased compared with the total of possible repetitions with submaximal loads, there is a restriction in the blood flow in the effector muscle and, consequently, a relative lack of oxygen supply (2,43). This pattern of blood flow restriction, anoxia, and reoxygenation is observed even when low-intensity strength training protocols are performed (19). There are differences in muscle oxygen saturation according to the fitness level (42), and it

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can be improved with training (21). Although this phenomenon is known, there is a lack of studies aimed at understanding muscle oxygenation during strength training, which may be due to the difficulty of monitoring variables such as $SmO_2$ during the execution of strength training exercises (16).

Previous evidence suggests that there are changes in muscle oxygen saturation ($SmO_2$) and reoxygenation time depending on the exercise characteristics. For example, eccentric protocols caused a greater decrease in $SmO_2$ and longer reoxygenation time than concentric exercises (45). The velocity and the intensity of the execution (44) and the number of repetitions until volitional fatigue (19) and between series recovery strategies could also influence $SmO_2$ (4).

Near-infrared spectroscopy (NIRS) is a noninvasive method of measuring local blood oxygen saturation using near-infrared rays (11), providing real-time physiological feedback (29). This technology has been used previously to check the changes in the oxygenation of a specific muscle tissue during endurance and resistance training (16,30) because intramuscular oxygen dynamics and blood volume can vary for different muscles (24,39). This real-time muscle oxygen availability assessment could explain how the change in load variables such as intensity, volume, rest, and frequency could influence fatigue (29). Thus, the objective of this study was to evaluate the dynamics of $SmO_2$, both during execution and recovery phases, depending on the load and LE during strength training.

## Methods

### Experimental Approach to the Problem

A cross-sectional repeated-measures design was used, using STROBE guidelines (quality checklist of experimental designs, www.equator.com). All athletes attended the laboratory 8 times (first familiarization and second 1RM evaluation), for about an hour each session, and 6 stimuli were performed in a randomized order. The stimuli consisted of the squat exercise (4 sets of 4–16 repetitions at 60–75% 1RM and 40–80% of LE). The distribution of the tests is shown in Table 1. To detect fatigue, the MPVL and the $SmO_2$ were assessed using a lineal transducer and a local NIRS device, respectively. All measurements were performed before and after series and stimuli.

### Subjects

A total of 12 well-trained male subjects participated voluntarily in this study (mean ± *SD*: age, 21.63 ± 1.17 years; height: 1.81 ± 0.08 m; body mass: 77.76 ± 8.77 kg; and body mass index: 23.59 ± 1.85 $kg \cdot m^{-2}$). All the subjects met the following inclusion criteria: (a) A minimum of 2 years of experience in strength training; (b) No health problems, and (c) normalized strength (NS) greater than 1.5 in the back-squat exercise (ratio between the 1RM and their body mass). The testing protocol, which was conducted according to the Declaration of Helsinki, was approved by the University of Extremadura Bioethics Committee (register number 67/2017). Subjects were informed of the risks and discomforts associated with testing and signed informed consent documents were obtained for all subjects.

### Procedures

The study lasted 4 weeks. In the first week, 2 sessions were performed: The first one for familiarization and the second one for evaluating the 1RM for the squat exercise (1RM: 131.40 ± 11.92 kg and NS: 1.71 ± 0.15). Subsequently, in the 3 remaining weeks, the proposed stimuli were performed with a minimum of 72 hours of rest to ensure recovery (40). To avoid biases, all sessions began at 9:00 AM, and the athletes had to meet the following requirements: (a) suppression of alcohol and caffeine intake 24 hours before each session and (b) not to perform high-intensity physical activity 72 hours before performing the different stimuli; so none of these factors interfered in the investigation (27).

**Table 1**
**Temporal distribution of the different tests and stimuli performed by the athletes.***

| Session | Objective |
|---|---|
| 1 | Familiarization of athletes with the squat exercise. |
| 2 | Evaluation of the 1RM of the athletes in the squat exercise. |
| 3 | Stimulus 1 (60% 1RM and 40% LE) = 4 × 8 (20RM). |
| 4 | Stimulus 2 (60% 1RM and 60% LE) = 4 × 12 (20RM). |
| 5 | Stimulus 3 (60% 1RM and 80% LE) = 4 × 16 (20RM). |
| 6 | Stimulus 4 (75% 1RM and 40% LE) = 4 × 4 (10RM). |
| 7 | Stimulus 5 (75% 1RM and 60% LE) = 4 × 6 (10RM). |
| 8 | Stimulus 6 (75% 1RM and 80% LE) = 4 × 8 (10RM). |

*1RM = 1 repetition maximum; LE = level of effort; 10RM = 10 repetitions maximum; 20RM = 20 repetitions maximum.

Each stimulus was composed of 4 series of a number of repetitions as a function of the load and LE that are considered in this study as follows:

- Intensity: load (%1RM). One repetition maximum is the load that allows the athlete to perform just 1 repetition. In this study, submaximum loads were used. The loads used were 60% 1RM (≈20RM) and 75% 1RM (≈10RM) (40).
- Volume: The level of effort is considered as the real endeavor in relation to the actual possibilities of training (36). Volume is expressed by the number of repetitions performed (nRpf) in relation to the maximum number of repetitions that could be executed with this load per series (nRrb). This variable has a relation with physiological stress measures such as the amount of metabolites produced (ammonium and lactic acid), MPVL, and loss of $SmO_2$ after finishing each series (19,34).

$$LE = \frac{nRpf}{nRrb}$$

Active rest of 2 minutes was established between series (4). The structure of each of the sessions followed the distribution described in Table 2.

*Anthropometric Equipment.* The height of the subjects was measured with a wall height stadiometer (SECA, Hamburg, Germany), whereas the body mass was obtained using a body mass scale (model BC-601; TANITA Corporation, Tokyo, Japan).

*Back Squat Exercise.* The exercise performed in the study was the back squat up to 90° of flexion with a complete stop to avoid the myotatic reflex (28). In strength training, the squat exercise has traditionally been considered one of the main performance indicators and, therefore, is included in the training plan of different sports (47). In this study, the assessment of the vastus lateralis (VL) was selected because it is where the greater activation occurs (10). A Smith machine (Technogym, Cesena, Italia) was used with calibrated disks of 2.5, 5, 10, and 20 kg (Salter, Barcelona, Spain) in all sessions to ensure the smooth vertical displacement of the bar along a fixed pathway in the back-squat exercise.

**Table 2**
**Temporal distribution of the strength stimuli sessions.***

| Exercise | Duration | Objective |
|---|---|---|
| 1 | 5 min | General warm-up: Pedaling on a cycle ergometer with a rate of perceived exertion (RPE) of 5–6 of 10. |
| 2 | 10 min | Specific warm-up: 3 sets of 8 squat repetitions at 40% 1RM with a rest between sets of 2 min. |
| 3 | 10 min | 1 RM confirmation |
| 4 | 15 min | Squat exercise (4 sets of *n* repetitions, with active rest between repetitions of 2 min, according to stimulus). |
| 5 | 5 min | Recovery: Work on a cycle ergometer with an RPE of 3–4 of 10. |

*RPE = rate of perceived exertion.

The squat exercise was performed according to the following specifications shown in Figure 1: (a) body placed under the Smith machine; (b) bar gripped in the prone position, with spacing slightly greater than the width of the shoulders (comfortable position); (c) bar resting on the trapezium and feet shoulder-width apart (without rotation); and (d) back maintained in its normal curvature during the entire movement with the subject looking to the front. During the execution, (e) controlled velocity bending until reaching an angle of 90° (a WIMU inertial device verified the correct angulation) (25); (f) complete stop in the 90° position for between 2 seconds; and (g) extension at maximum velocity to the initial position. The subjects were familiarized with the procedure and with the measuring instruments before the execution.

*One Repetition Maximum Assessment Through Velocity-Based Estimation.* For the estimation of 1RM, a general and specific warm-up was performed before the stimuli execution (Table 2). Monitoring of the mean propulsive velocity (MPV) allowed the estimation of 1RM of each of the subjects from the first repetition performed (back squat: $(100 \cdot \text{load})/(-2.185 \times \text{MPV}^2) - (61.53 \times \text{MPV}) + 122.5$), extracted from Franco-Márquez et al. (13). So the starting load at the 1RM confirmation represented 70% 1RM. From this load, a progressive increase was applied until reaching a load in which the MPV was around 80% 1RM ($0.67 \pm 0.02$ m·s$^{-1}$) because from this 1RM percentage, 100% of the movement is within the propulsive phase and the estimation of 1RM has a very low bias (35). For the estimation of 1RM, the supplementary weight and the mass of the bar (17 kg) were considered.

*Velocity-Based Assessment and Data Analysis.* A cable-extension linear velocity transducer (ChronoJump, Barcelona, Spain) was

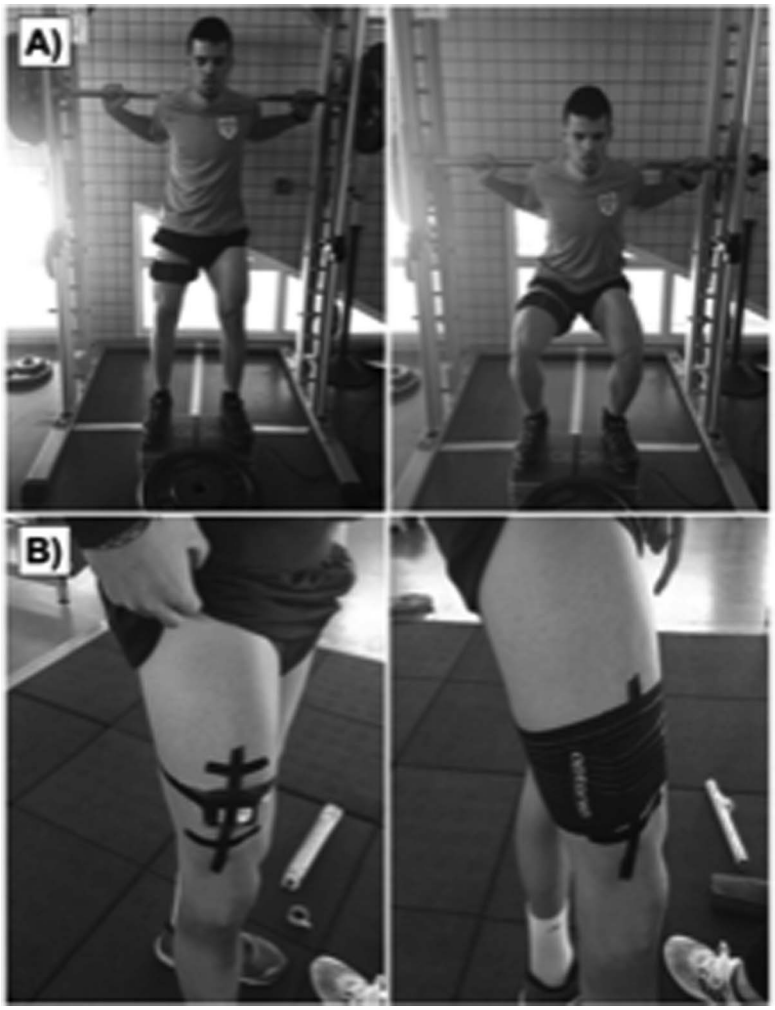


**Figure 1.** A) Initial and final position of the squat up to 90° of knee flexion; (B) position and attachment method of the NIRS device. NIRS = near-infrared spectroscopy.

used with a 1,000-Hz sampling frequency to measure bar velocity. The measured variable was MPVL. This variable determines the difference between the MPV of the repetition performed at the highest velocity and the MPV of the repetition performed at the lowest velocity. The lowest velocity repetition coincides with the last repetition performed by the athletes in each series (34). This is expressed as a percentage and is calculated with the following formula, where $MPV_{max}$ is the MPV of the fastest repetition in each series and $MPV_{min}$ is the MPV of the slowest repetition in each series. At the end of each of the repetitions, the MPV performed by the athlete was indicated.

$$MPVL = \frac{MPV_{min}}{MPV_{max}} \times 100$$

*Muscle Oxygen Saturation ($SmO_2$) Assessment and Data Analysis.* This represents the changes in the concentration of oxyhemoglobin [$HbO_2$] and deoxyhemoglobin [HHb]. A NIRS device was used for real-time muscle oxygen saturation monitoring in the VL (MOXY, Hutchinson, MO). The MOXY device automatically calculates the relative concentration of $HbO_2$ in relation to the total amount of hemoglobin (tHb) ($SmO_2 = HbO_2/tHb$). This device has been used in a recent research that studied the $SmO_2$ dynamics using a 3 × 8 protocol at 75–80% RM in barbell and flywheel back squat exercise (45).

The device was placed in the middle of the VL, leaving its lower edge 15 cm from the crack of the kneecap (39) (Figure 1). Before placing the device, (a) the respective skin area was shaved, (b) the device was wrapped in a transparent paper to eliminate direct contact with the skin and avoid the interference of sweat, and (c) after fixing the device with a tape, it was covered with a dark band to prevent ambient light pollution (39,48). Instantaneous muscle oxygen saturation was sampled at 4 Hz. An inertial device (WIMU PRO; RealTrack Systems, Almería, Spain) was used to receive and store raw data of NIRS (by Ant+ technology) (3), and the subsequent analysis was performed with S PRO software (RealTrack Systems).

Typical monitoring of muscle oxygenation kinetics during the squat exercise is shown in Figure 2. Muscle oxygen saturation decreased after each series and returned to baseline levels before the recovery time, which was set at 2 minutes at the end of the execution. It can be observed how the $SmO_2$ graph of the subject follows a similar pattern in the deoxygenation and reoxygenation after the series. Thus, 3 differentiated phases were defined: (a) the execution phase (phase 1), where a deoxygenation process was observed, represented by a descending slope; (b) a recovery phase (phase 2) or reoxygenation of the muscle tissue, where an ascending inclination slope was observed; and (c) a maintenance phase (third phase) in which there were no significant variations in oxygenation and which was maintained until the beginning of the new series. To analyze the muscle oxygenation dynamics produced, 3 variables were designed that reflected the results obtained in magnitude and time. The variables analyzed from the $SmO_2$ were as follows:

- $SmO_2$ at the start ($SmO_2$start) and at the end ($SmO_2$stop) of the execution. Percentage of oxyhemoglobin of the total hemoglobin available in the blood at the start and end of the execution. The $SmO_2$start value was considered 1 second previous to start each series, whereas the $SmO_2$stop value was determined when the athlete finished the concentric phase at the end of the last repetition of each series.
- Reoxygenation time ($SmO_2$recT). The amount of time to recover the muscle oxygenation from the end of the execution of the series until the recovery of the muscle oxygen saturation of the subject stagnates at a value for more than 5 seconds. This criterion was due to the fact that in previous tests, a significant increase was not observed after that time point.
- Loss of $SmO_2$ ($\nabla$% $SmO_2$): This is the relationship between $SmO_2$ at the beginning of the series ($SmO_2$start) and $SmO_2$ at the end of the series ($SmO_2$stop). This variable was calculated with the following formula:

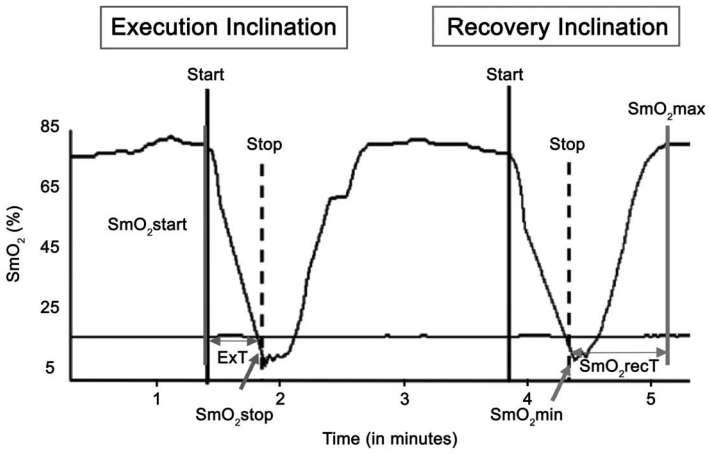


**Figure 2.** Parameters used in the calculation of the variables for the analysis of muscle oxygen saturation, where $SmO_2$start is the muscle oxygen saturation at the start of the series, start is the moment when the athlete begin to realize the squat exercise series, E × T is the execution time, $SmO_2$stop is the muscle oxygen saturation at the end of the execution, stop is the moment when the athlete finishes the series, $SmO_2$min is the minimum muscle oxygen saturation value, $SmO_2$max is the maximum muscle oxygen saturation value, and $SmO_2$recT is the recovery time between $SmO_2$min and $SmO_2$max.

$$\nabla\%\ \mathrm{SmO_2} = \left(\left(\frac{\mathrm{SmO_2stop} \times 100}{\mathrm{SmO_2start}}\right) - 100\right) \times -1$$

### Statistical Analyses

Data showed normal distribution as confirmed by the Shapiro-Wilk test analysis (12). A first descriptive analysis with mean, *SD*, and 95% confidence intervals (CIs) was performed to characterize the sample. To calculate the data of series in each variable, the separate average of first, second, third, and fourth series performed in the 6 stimuli was calculated. Instead, to calculate the data of each stimulus, the average of the 4 series performed in each stimulus was calculated. A multivariant analysis of variance (MANOVA) was conducted to identify the mean of differences between each series and each stimulus. Bonferroni correction was used for 2-by-2 comparisons (12). In addition, the magnitude of the differences for MANOVA was calculated using the partial omega squared ($\omega_p^2$) that is classified as ≤0.01 small, ≤0.06 medium, and ≤0.14 large following Cohen (6) and for 2-by-2 comparisons using Cohen's *d* following Hopkins et al. (20), classified as very low (0–0.2), low (0.2–0.6), moderate (0.6–1.2), high (1.2–2.0), and very high (>2.0), with mean differences and CIs. The relationship between kinematical and physiological analyzed variables was studied using the Pearson correlation coefficient.

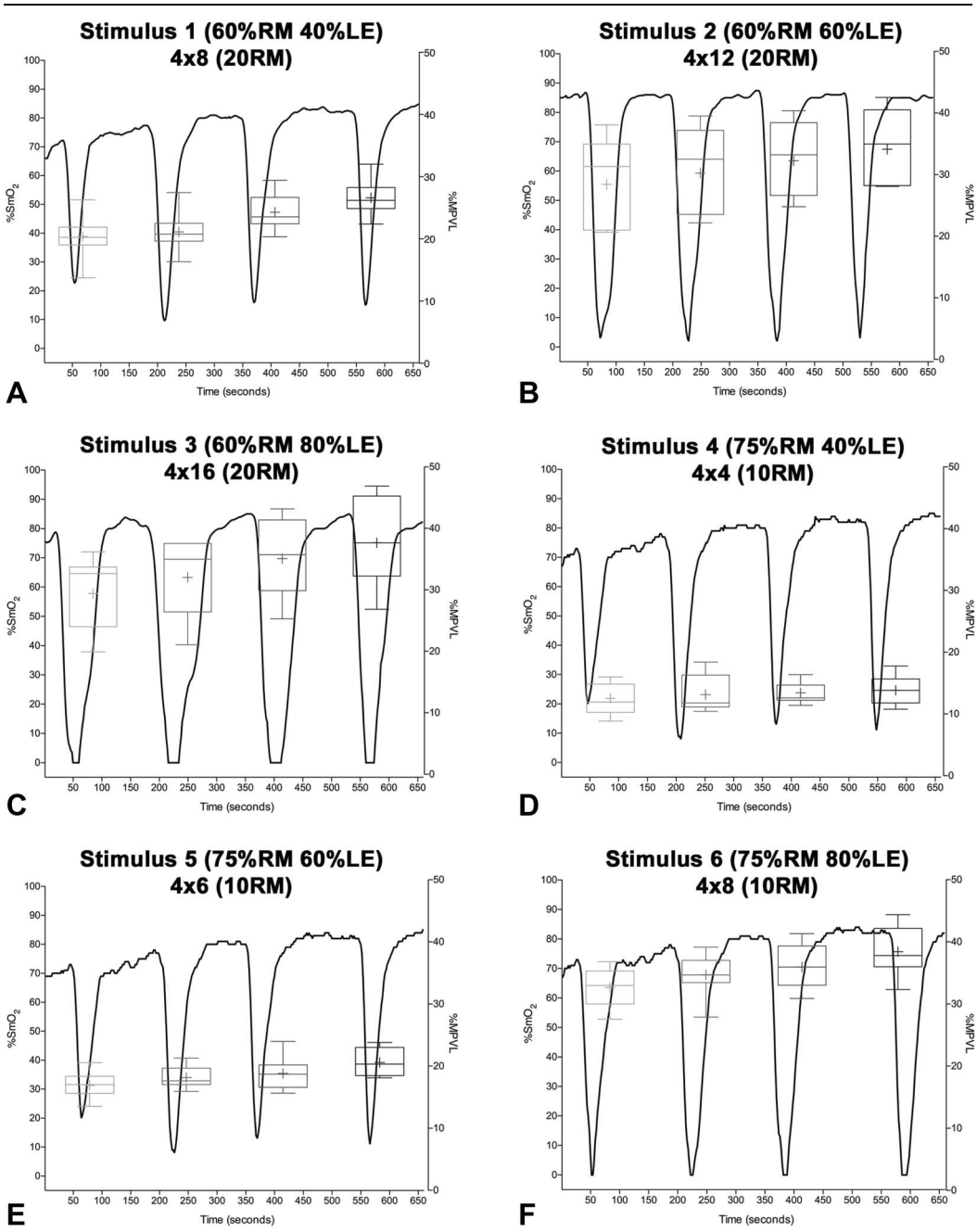


**Figure 3.** Dynamics of muscle oxygen saturation (% SmO2) and loss of mean propulsive velocity (% MPVL) in the 4 series performed in each of the stimuli: (A) stimulus 1, (B) stimulus 2, (C) stimulus 3, (D) stimulus 4, (E) stimulus 5, and (F) stimulus 6.

**Table 3**

**Mean ± *SD*s, 95% CIs (in parentheses), and MANOVA's post hoc with partial omega squared ($\omega_p^2$) of physical and physiological variables analyzed per series and stimuli.***

| | MPVL (%) | $SmO_2$start (%) | $SmO_2$stop (%) | $SmO_2$recT (s) | ▽%$SmO_2$ (%) |
|---|---|---|---|---|---|
| Series | | | | | |
| Series 1 | 21.69 ± 8.58 (19.67–23.70) | 77.30 ± 7.00 (75.65–78.94) | 9.50 ± 9.70 (7.20–11.74) | 62.97 ± 14.25 (59.62–66.31) | 87.26 ± 13.16 (84.17–90.35) |
| Series 2 | 23.93 ± 9.48 (21.70–26.16) | 76.89 ± 6.30 (75.41–78.37) | 8.40 ± 9.30 (6.23–10.60) | 65.70 ± 15.61 (62.03–69.36) | 88.81 ± 12.30 (85.92–91.71) |
| Series 3 | 25.87 ± 10.50 (23.40–28.33) | 76.82 ± 5.63 (75.50–78.15) | 8.00 ± 9.20 (5.87–10.17) | 68.82 ± 17.67 (64.66–72.97) | 89.45 ± 12.05 (86.62–92.28) |
| Series 4 | 27.76 ± 11.41 (25.08–30.44) | 76.34 ± 5.44 (75.06–77.62) | 7.30 ± 9.30 (5.14–9.52) | 71.93 ± 19.08 (67.45–76.41) | 90.45 ± 12.11 (87.61–93.30) |
| *F* | 78.41 | 34.56 | 0.43 | 2.55 | 3.7 |
| *p* | <0.01† | <0.01† | 0.73 | 0.05 | 0.01† |
| $\omega_p 2$ | 0.46, large | 0.27, large | 0, none | 0.02, small | 0.03, small |
| Stimulus | | | | | |
| Stimulus 1 | 17.46 ± 2.74 (16.67–18.26) | 76.98 ± 7.81 (74.71–79.25) | 14.20 ± 9.80 (11.38–17.08) | 50.56 ± 2.74 (49.77–51.36) | 81.93 ± 11.90 (78.47–85.39) |
| Stimulus 2 | 24.84 ± 3.22 (23.91–25.78) | 82.74 ± 4.61 (81.40–84.08) | 3.40 ± 3.00 (2.58–4.32) | 74.66 ± 6.18 (72.87–76.46) | 95.85 ± 3.63 (94.79–96.90) |
| Stimulus 3 | 39.36 ± 5.69 (37.71–41.01) | 75.17 ± 6.19 (73.37–76.97) | 0.00 ± 0.00 (0.00–0.00) | 89.77 ± 10.14 (86.83–92.72) | 100.00 ± 0.00 (100.00–100.00) |
| Stimulus 4 | 13.23 ± 2.28 (12.57–13.89) | 73.15 ± 4.24 (71.91–74.38) | 22.00 ± 2.90 (21.21–22.87) | 44.63 ± 4.83 (43.22–46.03) | 69.83 ± 3.88 (68.71–70.96) |
| Stimulus 5 | 18.53 ± 2.66 (17.76–19.30) | 74.73 ± 4.25 (73.50–75.96) | 10.10 ± 4.70 (8.78–11.51) | 66.95 ± 6.07 (65.19–68.71) | 86.36 ± 6.44 (84.49–88.23) |
| Stimulus 6 | 35.44 ± 3.90 (34.31–36.57) | 78.25 ± 3.44 (77.25–79.25) | 0.00 ± 0.00 (0.00–0.00) | 77.54 ± 8.20 (75.16–79.92) | 100.00 ± 0.00 (100.00–100.00) |
| *F* | 851.05 | 447.16 | 21.46 | 164.91 | 196.17 |
| *p* | <0.01† | <0.01† | <0.01† | <0.01† | <0.01† |
| $\omega_p 2$ | 0.94, large | 0.89, large | 0.27, large | 0.75, large | 0.78, large |
| Interaction | | | | | |
| *F* | 5.76 | 2.76 | 0.68 | 3.08 | 0.64 |
| *p* | <0.01† | <0.01† | 0.80 | <0.01† | 0.84 |
| $\omega_p 2$ | 0.20, large | 0.08, moderate | 0, none | 0.10, moderate | 0, none |

*M = mean; CI = confidence interval; MANOVA = multivariant analysis of variance; MPVL = mean propulsive velocity loss; $SmO_2$start = $SmO_2$ first repetition percentage; $SmO_2$stop = $SmO_2$ last repetition percentage; ▽%$SmO_2$ = $SmO_2$ lost percentage; $SmO_2$recT = reoxygenation time, *F* = main effects *F* value, *p* = *p* value, $\omega_p^2$ = partial omega squared.
†Significant differences.

The magnitude of the correlation coefficients was deemed as trivial ($r^2 < 0.1$), small ($0.1 < r^2 < 0.3$), moderate ($0.3 < r^2 < 0.5$), large ($0.5 < r^2 < 0.7$), very large ($0.7 < r^2 < 0.9$), nearly perfect ($r^2 > 0.9$), and perfect ($r^2 = 1$) (20). All analyses were conducted using SPSS 24.0 software (SPSS, Inc., Chicago, IL). Statistical significance was established at $p \leq 0.05$.

## Results

Figure 3 shows the dynamics of the analyzed variables. The execution of the different stimuli provoked a decrease of the $SmO_2$ from basal levels (73.15–82.74 %$SmO_2$) that increased again after the end of the series. In addition, Table 3 shows the results of the series vs. stimuli analysis. Significant interaction was found in MPVL, $SmO_2$recT, and $SmO_2$start, but there was no significant interaction in $SmO_2$stop and ▽%$SmO_2$. After main effects analysis, there was a significant difference between series in MPVL, $SmO_2$start, and ▽%$SmO_2$ and stimuli in MPVL, $SmO_2$start, $SmO_2$stop, $SmO_2$recT, and ▽%$SmO_2$ (Table 3).

Table 4 shows the pairwise comparison analysis between the stimuli and the series analyzed. In the comparison among series, no differences were found in the variables analyzed, except between series 1 and series 4 in MPVL ($p < 0.01$; $d = -0.60$) and in $SmO_2$recT ($p < 0.01$; $d = -0.53$). In pairwise analysis between stimuli, the MPVL was different in all groups ($p < 0.01$; $d = 0.80$–$6.95$), except between 1 and 5 ($p = 1.00$; $d = 0.40$). In $SmO_2$start, stimulus 2 and stimulus 6 showed differences with the rest of the groups (S2: $p < 0.01$, $d = 0.90$–$2.17$; S6: $p < 0.05$, $d = 0.21$–$1.32$, respectively). All stimuli revealed differences in $SmO_2$stop ($p < 0.01$; $d = 0.53$–$10.73$), except between stimuli 3 and 6 ($p = 1.00$; $d = 0.00$). A very high effect size was identified between stimulus 3 and 4 and between 4 and 6 (MD = 22.04, $d = 10.73$). In the Bonferroni post hoc comparison, significant differences were found among all stimuli in $SmO_2$recT ($p < 0.01$; $d = 1.26$–$5.68$), except between 2 and 6 ($p = 0.57$; $d = -0.40$), which was the largest effect size found in all oxygen saturation variable comparisons ($p < 0.01$; $F = 304.67$; $d = 1.47$). Finally, in ▽%$SmO_2$, significant differences were found in all groups ($p < 0.01$; $d = 0.46$–$10.99$), except between 3 and 6 ($p = 1.00$; $d = 0.00$).

Finally, in Table 5, an associative analysis using the Pearson correlation coefficient showed a very large direct relationship ($r > 0.70$) between the external load variables (RTLoad, MPVL, and LE) and the internal load variables (▽%$SmO_2$, $SmO_2$recT, and $SmO_2$stop). Besides, a very large inverse relationship was found between MPVL and LE with respect to $SmO_2$stop. There was no relationship between $SmO_2$start and the external and internal load variables analyzed.

## Discussion

The purpose of this study was to evaluate the dynamics of muscle oxygen saturation ($SmO_2$), both during execution and recovery phases, depending on the load and LE during strength training. To the best of our knowledge, previous studies have verified the effect of the load on muscle oxygenation at 20, 30, and 40% of 1RM (2), at 60 and 90% of 1RM (19,43), and at 75–80% of 1RM in barbell and flywheel training (45). Conversely, different LEs have never been studied on the $SmO_2$ dynamics. Overall, both variables significantly influence muscle oxygen saturation with moderate to very high effect sizes.

Based on our results, the $SmO_2$stop, MPVL, and $SmO_2$start decreases and $SmO_2$, $SmO_2$recT, and ▽%$SmO_2$ increases compared with basal levels are due to cumulative fatigue. A regular result of resistance training is neuromuscular fatigue (7), this is represented regularly as a loss in muscle tone, which may lead to excess laxity in the myotendinous tissues and cause

**Table 4**

**Univariate differences.*†**

| | MPVL (%) | | | | $SmO_2$start (%$SmO_2$) | | | | $SmO_2$stop (%$SmO_2$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *p* | MD (95% CI) | *d* (95% CI) | magnitude | *p* | MD (95% CI) | *d* (95% CI) | magnitude | *p* | MD (95% CI) | *d* (95% CI) | magnitude |
| Series | | | | | | | | | | | | |
| 1 vs. 2 | 1.00 | −2.24 (−6.69 to 2.20) | −0.25 (−0.57 to 0.08) | low | 1.00 | 0.40 (−2.30 to 3.12) | 0.06 (−0.27 to 0.39) | very low | 1.00 | 1.05 (−3.08 to 5.19) | 0.11 (−0.21 to 0.44) | very low |
| 1 vs. 3 | 0.08 | −4.17 (−8.62 to 0.27) | −0.44 (−0.77 to −0.11) | low | 1.00 | 0.47 (−2.23 to 3.18) | 0.08 (−0.25 to 0.40) | very low | 1.00 | 1.45 (−2.69 to 5.59) | 0.16 (−0.16 to 0.49) | very low |
| 1 vs. 4 | 0.00 | −6.07 (−10.52 to −1.62) | −0.60 (−0.94 to −0.27) | moderate | 1.00 | 0.95 (−1.75 to 3.67) | 0.15 (−0.17 to 0.48) | very low | 1.00 | 2.13 (−2.04 to 6.28) | 0.23 (−0.10 to 0.56) | low |
| 2 vs. 3 | 1.00 | −1.93 (−6.38 to 2.51) | −0.19 (−0.52 to 0.13) | very low | 1.00 | 0.06 (−2.64 to 2.77) | 0.01 (−0.32 to 0.34) | very low | 1.00 | 0.39 (−3.74 to 4.53) | 0.04 (−0.28 to 0.37) | very low |
| 2 vs. 4 | 0.14 | −3.83 (−8.28 to 0.61) | −0.37 (−0.70 to −0.04) | low | 1.00 | 0.55 (−2.16 to 3.26) | 0.09 (−0.23 to 0.42) | very low | 1.00 | 1.08 (−3.06 to 5.22) | 0.11 (−0.21 to 0.45) | very low |
| 3 vs. 4 | 1.00 | −1.89 (−6.34 to 2.55) | −0.17 (−0.50 to 0.16) | very low | 1.00 | 0.48 (−2.22 to 3.19) | 0.09 (−0.24 to 0.41) | very low | 1.00 | 0.68 (−3.45 to 4.83) | 0.08 (−0.25 to 0.40) | very low |
| Stimuli | | | | | | | | | | | | |
| 1 vs. 2 | 0.00 | −7.37 (−9.55 to −5.21) | −2.47 (−2.90 to −2.04) | very high | 0.00 | −5.76 (−8.96 to −2.55) | −0.90 (−1.24 to −0.56) | moderate | 0.00 | 10.78 (7.90–13.65) | 1.49 (1.12–1.86) | high |
| 1 vs. 3 | 0.00 | −21.89 (−24.07 to −19.72) | −4.90 (−5.56 to −4.25) | very high | 1.00 | 1.80 (−1.39 to 5.01) | 0.26 (−0.07 to 0.59) | low | 0.00 | 14.22 (11.35–17.10) | 2.05 (1.65–2.45) | very high |
| 1 vs. 4 | 0.00 | 4.23 (2.06–6.40) | 1.67 (1.30–2.06) | high | 0.01 | 3.83 (0.63–7.03) | 0.61 (0.28–0.94) | moderate | 0.00 | −7.81 (−10.68 to −4.93) | −1.08 (−1.43 to −0.73) | moderate |
| 1 vs. 5 | 1.00 | −1.06 (−3.24 to 1.11) | −0.40 (−0.73 to −0.07) | low | 0.58 | 2.25 (−0.95 to 5.45) | 0.36 (0.03–0.69) | low | 0.00 | 4.08 (1.20–6.95) | 0.53 (0.20–0.87) | low |
| 1 vs. 6 | 0.00 | −17.98 (−20.14 to −15.80) | −5.34 (−6.03 to −4.64) | very high | 1.00 | −1.27 (−4.47 to 1.93) | −0.21 (−0.54 to 0.12) | low | 0.00 | 14.22 (11.35–17.10) | 2.05 (1.65–2.45) | very high |
| 2 vs. 3 | 0.00 | −14.51 (−16.69 to −12.35) | −3.14 (−3.63 to −2.65) | very high | 0.00 | 7.56 (4.36–10.76) | 1.39 (1.02–1.75) | high | 0.00 | 3.44 (0.57–6.32) | 1.60 (1.23–1.98) | high |
| 2 vs. 4 | 0.00 | 11.61 (9.44–13.79) | 4.16 (3.58–4.74) | very high | 0.00 | 9.59 (6.39–12.79) | 2.17 (1.75–2.56) | very high | 0.00 | −18.59 (−21.46 to −15.72) | −6.30 (−7.10 to −5.51) | very high |
| 2 vs. 5 | 0.00 | 6.31 (4.14–8.49) | 2.14 (1.73–2.55) | very high | 0.00 | 8.01 (4.80–11.21) | 1.81 (1.42–2.19) | high | 0.00 | −6.69 (−9.57 to −3.82) | −1.69 (−2.08 to −1.32) | high |
| 2 vs. 6 | 0.00 | −10.59 (−12.77 to −8.42) | −2.96 (−3.44 to −2.49) | very high | 0.00 | 4.49 (1.28–7.69) | 1.10 (0.75–1.46) | moderate | 0.00 | 3.44 (0.57–6.32) | 1.60 (1.23–1.98) | high |
| 3 vs. 4 | 0.00 | 26.13 (23.96–28.31) | 6.03 (5.26–6.80) | very high | 0.93 | 2.02 (−1.17 to 5.22) | 0.38 (0.05–0.71) | low | 0.00 | −22.04 (−24.91 to −19.16) | −10.73 (9.45–12.01) | very high |
| 3 vs. 5 | 0.00 | 20.83 (18.66–23.01) | 4.69 (4.06–5.32) | very high | 1.00 | 0.44 (−2.75 to 3.64) | 0.08 (−0.24 to 0.41) | very low | 0.00 | −10.14 (−13.02 to −7.27) | −3.03 (−3.52 to −2.56) | very high |
| 3 vs. 6 | 0.00 | 3.92 (1.75–6.09) | 0.80 (0.46–1.14) | moderate | 0.07 | −3.07 (−6.27 to 0.12) | −0.62 (−0.95 to −0.28) | moderate | 1.00 | 0.00 (−2.87 to 2.87) | 0.00 (0.00–0.00) | none |
| 4 vs. 5 | 0.00 | −5.30 (−7.47 to −3.13) | −2.14 (−2.55 to −1.73) | very high | 1.00 | −1.58 (−4.78 to 1.61) | −0.37 (−0.70 to 0.04) | low | 0.00 | 11.89 (9.02–14.77) | 3.05 (2.57–3.53) | very high |
| 4 vs. 6 | 0.00 | −22.21 (−24.38 to −20.04) | −6.95 (−7.82 to −6.09) | very high | 0.00 | −5.10 (−8.31 to −1.90) | −1.32 (−1.68 to −0.96) | high | 0.00 | 22.04 (19.16–24.91) | 10.73 (9.45–12.01) | very high |
| 5 vs. 6 | 0.00 | −16.90 (−19.08 to −14.74) | −5.07 (−5.73 to −4.40) | very high | 0.02 | −3.52 (−6.72 to −0.31) | −0.91 (−1.25 to −0.57) | moderate | 0.00 | 10.14 (7.27–13.02) | 3.04 (2.56–3.52) | very high |

| | $SmO_2$recT (s) | | | | ▽%$SmO_2$ (%) | | | |
|---|---|---|---|---|---|---|---|---|
| | *p* | MD (95% CI) | *d* (95% CI) | magnitude | *p* | MD (95% CI) | *d* (95% CI) | magnitude |
| Series | | | | | | | | |
| 1 vs. 2 | 1.00 | −2.72 (−10.14 to 4.69) | −0.18 (−0.51 to 0.15) | very low | 1.00 | −1.55 (−7.05 to 3.94) | −0.12 (−0.45 to 0.21) | very low |
| 1 vs. 3 | 0.22 | −5.84 (−13.26 to 1.57) | −0.36 (−0.69 to 0.04) | low | 1.00 | −2.18 (−7.68 to 3.31) | −0.17 (−0.50 to 0.15) | very low |
| 1 vs. 4 | 0.00 | −8.96 (−16.83 to −1.54) | −0.53 (−0.86 to −0.20) | low | 0.74 | −3.19 (−8.69 to 2.30) | −0.25 (−0.58 to 0.08) | low |
| 2 vs. 3 | 1.00 | −3.11 (−10.53 to 4.29) | −0.19 (−0.52 to 0.14) | very low | 1.00 | −0.63 (−6.13 to 4.86) | −0.05 (−0.38 to 0.27) | very low |
| 2 vs. 4 | 0.15 | −6.23 (−13.65 to 1.18) | −0.36 (−0.69 to −0.03) | low | 1.00 | −1.63 (−7.13 to 3.85) | −0.13 (−0.46 to 0.19) | very low |
| 3 vs. 4 | 1.00 | −3.11 (−10.53 to 4.30) | −0.17 (−0.50 to 0.16) | very low | 1.00 | −1.00 (−6.51 to 4.49) | −0.08 (−0.41 to 0.24) | very low |
| Stimuli | | | | | | | | |
| 1 vs. 2 | 0.00 | −24.09 (−28.19 to −20.01) | −5.04 (−5.71 to 4.37) | very high | 0.00 | −13.91 (−17.50 to −10.32) | −1.58 (−1.96 to −1.21) | high |
| 1 vs. 3 | 0.00 | −39.21 (−43.30 to −35.11) | −5.27 (−5.97 to −4.59) | very high | 0.00 | −18.07 (−21.65 to −14.48) | −2.15 (−2.56 to −1.74) | very high |
| 1 vs. 4 | 0.00 | 5.93 (1.84–10.03) | 1.51 (1.14–1.88) | high | 0.00 | 12.09 (8.50–15.68) | 1.37 (1.01–1.73) | high |
| 1 vs. 5 | 0.00 | 16.38 (−20.48 to −12.28) | −3.48 (−3.99 to −2.96) | very high | 0.00 | −4.43 (−8.01 to −0.84) | −0.46 (−0.79 to −0.13) | low |
| 1 vs. 6 | 0.00 | −26.97 (−31.07 to −22.88) | −4.41 (−5.02 to −3.81) | very high | 0.00 | −18.07 (−21.65 to −14.48) | −2.15 (−2.56 to −1.74) | very high |
| 2 vs. 3 | 0.00 | −15.11 (−19.21 to −11.01) | −1.79 (−2.19 to −1.41) | high | 0.01 | −4.15 (−7.74 to −0.56) | −1.62 (−1.99 to −1.24) | high |
| 2 vs. 4 | 0.00 | 30.03 (25.94–34.13) | 5.41 (4.71–6.12) | very high | 0.00 | 26.01 (22.42–29.59) | 6.93 (6.06–7.80) | very high |
| 2 vs. 5 | 0.00 | 7.71 (3.61–11.81) | 1.26 (0.90–1.62) | high | 0.00 | 9.48 (5.89–13.07) | 1.82 (1.43–2.20) | high |
| 2 vs. 6 | 0.57 | −2.87 (−6.97 to 1.21) | −0.40 (−0.73 to −0.07) | low | 0.01 | −4.15 (−7.74 to −0.56) | −1.62 (−1.99 to −1.24) | high |
| 3 vs. 4 | 0.00 | 45.14 (41.05–49.24) | 5.68 (4.95–6.42) | very high | 0.00 | 30.16 (26.58–33.75) | 10.99 (9.69–12.31) | very high |
| 3 vs. 5 | 0.00 | 22.82 (18.72–26.92) | 2.73 (2.28–3.19) | very high | 0.00 | 13.63 (10.05–17.22) | 2.99 (2.52–3.47) | very high |
| 3 vs. 6 | 0.00 | 12.23 (8.13–16.32) | 1.33 (0.97–1.69) | high | 1.00 | 0.00 (−3.58 to 3.58) | 0.00 (0.00–0.00) | none |
| 4 vs. 5 | 0.00 | −22.32 (−26.41 to −18.22) | −4.07 (−4.64 to −3.50) | very high | 0.00 | −16.52 (−20.11 to −12.94) | −3.11 (−3.60 to −2.62) | very high |
| 4 vs. 6 | 0.00 | −32.91 (−37.01 to −28.81) | −4.89 (−5.54 to −4.24) | very high | 0.00 | −30.16 (−33.75 to −26.58) | −10.99 (−12.31 to −9.69) | very high |
| 5 vs. 6 | 0.00 | −10.59 (−14.69 to −6.49) | −1.47 (−1.84 to −1.10) | high | 0.00 | −13.63 (−17.22 to −10.05) | −2.99 (−3.47 to −2.52) | very high |

*MD = mean difference; MPVL = mean propulsive velocity loss; CI = confidence interval; d = Cohen's *d* effect size; *p* = *p* value.

†Mean differences, 95% interval confidence and post-hoc comparison with effect size between series and stimuli.

**Table 5**
**Physiological and kinematic variables correlation analysis with 95% confidence interval.***

| | MPVL, *r* (95% CI) | $SmO_2$recT, *r* (95% CI) | $SmO_2$start, *r* (95% CI) | $SmO_2$stop, *r* (95% CI) | ▽%$SmO_2$, *r* (95% CI) | %1RM, *r* (95% CI) |
|---|---|---|---|---|---|---|
| LE | 0.883† (0.852–0.905) | 0.864† (0.826–0.893) | 0.140 (0.029–0.252) | −0.871† (−0.902 to −0.827) | 0.873† (0.829–0.903) | 0 (−0.112 to 0.122) |
| MPVL | | 0.872† (0.834–0.899) | 0.240† (0.128–0.345) | −0.865† (−0.889 to −0.827) | 0.874† (0.838–0.896) | −0.273† (−0.383 to −0.159) |
| $SmO_2$recT | | | 0.182† (0.074–0.293) | −0.846† (−0.872 to −0.807) | 0.850† (0.810–0.876) | −0.266† (−0.377 to −0.231) |
| $SmO_2$start | | | | −0.161† (−0.271 to −0.042) | 0.200 (0.084–0.306) | −0.231† (−0.349 to −0.120) |
| $SmO_2$stop | | | | | −0.998† (−0.999 to −0.996) | 0.228† (0.114–0.345) |
| ▽%$SmO_2$ | | | | | | −0.241† (−0.359 to −0.124) |

*CI = confidence interval; MPVL = mean propulsive velocity loss; $SmO_2$start = $SmO_2$ first-repetition percentage; $SmO_2$stop = $SmO_2$ last-repetition percentage; ▽%$SmO_2$ = $SmO_2$ lost percentage; $SmO_2$recT = reoxygenation time; %1RM = percentage of 1 repetition maximum; LE = level of effort.
†Significant correlation between variables.

limitation in the return of elastic energy throughout the repetition and series, causing a decrease in force generation (1,22,26). In our study, this metabolic and neuromuscular limitation is represented as a large decrease in MPVL as a final result.

The loss of contractile efficiency and the greater metabolite accumulation resulted in an increase of intramuscular pressure that caused blood flow restriction (8). In addition, when an increase of LE with submaximal loads is produced, a restriction of blood flow to the effector muscle and a lack of oxygenation (anoxia) are found (43). This process provoked a decrease in local muscle oxygen uptake because of the absence of optimal oxygen transportation and metabolization (small increase in ▽%$SmO_2$ and $SmO_2$recT and large decrease in $SmO_2$start) (46), which could lead to difficulties in the myosin–actin bridge formation, resulting in a loss of force generation (decrease in MPVL). As results suggest, once the exercise is finished after the series execution, oxygen cost decreases but does not recover to baseline levels ($SmO_2$start large decrease throughout series).

Although resistance training causes neuromuscular and mechanical fatigue, the physiological responses could vary because of training methods, and these differences could affect the distribution of the load in intensity and volume (15,31). In our study, differences were found between stimuli in MPVL, $SmO_2$recT, and $SmO_2$start. This could be explained as the difference in the LE of each exercise; when a higher LE was found (stimuli third and sixth), there were higher MVPL, $SmO_2$start, and $SmO_2$recT compared with the lower LE (stimuli first and fourth). This evidence may suggest that completing a higher number of repetitions relating to the maximum repetitions performed with each load (LE) may be more of a determinant factor than intensity (%1RM) in resistance training, when considering muscle oxygen uptake. In support of this, Hoffman et al. (19) suggested that the total duration of maximal effort exercise could be more important than the relative intensity of exercise (%1RM) in affecting muscle oxygen recovery dynamics.

In addition, previous studies (19,34) have found a strong relationship between fatigue biomarkers and MPVL. Sánchez-Medina and González-Badillo (34) found an increase in fatigue markers when working with an LE close to 50, where the MPVL was between 25 and 30%. Stimuli 3 and 6 had a MPVL of 40 and 35%, respectively, producing this accumulation of metabolites and, for this reason, a greater recovery time between series. In this respect, it has been found that in stimuli that exceed 60% of the LE (stimuli 3:4 repetitions and stimuli 6:2 repetitions), the last repetitions are performed without muscle oxygen, working anaerobically. Besides, not only volume and LE affects muscle oxygenation but also, as Raeder et al. (31) and Timón et al. (45) found, greater fatigue markers ($SmO_2$, blood lactate, and rate of perceived exertion) and higher reoxygenation time in relation to type of muscle contraction (eccentric > concentric).

In this sense, the LE influenced the oxygenation of the muscle in the different variables analyzed. A greater LE provoked higher ▽%$SmO_2$ ($r = 0.873$) and $SmO_2$recT ($r = 0.864$) and lower $SmO_2$stop ($r = -0.871$) after each series. The load also had an effect on muscle oxygenation. It has been shown that by maintaining the LE and increasing the proposed load (stimulus 1 vs. 4, 2 vs. 5, and 3 vs. 6), a minor ▽%$SmO_2$ is produced because the athletes need to execute a smaller number of repetitions to reach the same LE. It has been reported that when a stimulus is executed at 90% 1RM (4 repetitions), a lower reoxygenation time and higher muscle oxygenation at the end of the series is found in relation to the athletes who performed 65% 1RM (16 reps.) (19), confirming that reoxygenation time increased when volume was higher (5).

Although the results of this study have provided information regarding the muscle oxygen dynamics in the lower limbs in relation to fatigue during strength training, some limitations to the study must be acknowledged. One of the limitations of this study concerns the sample ($n = 12$); it would be interesting to extend this research to include more subjects with different strength levels that could influence the number of repetitions performed at a given load, so would influence the statistical power of the results. Second, we must bear in mind that these findings can only be extrapolated to the back squat exercise with a muscle oxygen saturation assessment of the VL. Finally, only 1 MOXY to evaluate $SmO_2$ at a specific sampling rate was tested. The reliability and validity have not been evaluated for strength training, but it was evaluated during cycling in the same muscle (VL) obtaining a very strong reliability between trials (SROC: 0.842–0.993; intraclass correlation coefficient = 0.773–0.992) and a moderate validity with $\dot{V}O_2$ and HR ($r = -0.71$–$0.73$) (9). All processes were performed following the manufacturer's recommendations.

In conclusion, the volume and the intensity of each stimulus had a directly influence on the muscle oxygen saturation dynamics of the lower limbs, specifically in the VL. An increase in the LE, regardless of the %1RM used, will cause a greater MPVL and a greater $SmO_2$recT and ▽%$SmO_2$. However, if the LE was maintained with an increasing load, a minor MPVL was found due to needing a smaller number of repetitions to reach the same LE and, consequently, a shorter time of $SmO_2$recT and a lower percentage of ▽%$SmO_2$. Volume represented as LE was confirmed as the most sensitive load

component in resistance training considering the muscle oxygen uptake responses.

### Practical Applications

Considering the results obtained in this study, the LE is more sensitive to muscle oxygen fatigue (repetitions performed in relation of maximum repetitions performed with each load) than intensity (%1RM). Therefore, load increases throughout training sessions should be made in only 1 load factor (intensity or volume) depending on individual population characteristics, type of sport, and fatigue adaptations. If increasing volume is chosen, the rest time should be longer to achieve complete muscle oxygen reposition and reduce the MPVL.

For strength and conditioning coaches, the specific considerations analyzed in this study provide initial guidelines for the use of $SmO_2$ as an internal load index. Monitoring muscle oxygen saturation in athletes through an accessible, portable, and user-friendly NIRS device helps in understanding, with real-time feedback, the muscle oxygen saturation loss, the work-time with and without oxygen (anoxia), and the recovery-time for starting a new series (with or without complete recovery).

Future research could use the same muscle oxygen parameters to analyze the individual effect of load variations (different 1RM) at the same %1RM and LE. In addition, a multidevice assessment would be interesting to analyze the muscle oxygen dynamics of all lower limb muscles simultaneously and their relationship.

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