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Research article

Muscle Oxygen Saturation Dynamics During Back Squat Exercise: The Influence of Intensity and Velocity Loss on Deoxygenation and Reoxygenation

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Abstract

Resistance training plays a key role in enhancing muscular performance; however, the effects of different combinations of loading intensity and velocity loss (VL) thresholds on muscle oxygen saturation (SmO_2) dynamics during exercise remain insufficiently understood. This study aimed to investigate the influence of intensity (60% vs. 80% one-repetition maximum [1RM]) and VL (20% vs. 40%) on SmO_2 responses during the back squat exercise. Eighteen resistance-trained males (age: 20.06 ± 1.63 years; height: 176.78 ± 6.45 cm; body mass: 70.26 ± 9.56 kg) performed four back squat protocols - 60%1RM-VL20% (60 - 20), 60%1RM-VL40% (60 - 40), 80%1RM-VL20% (80 - 20), and 80%1RM-VL40% (80 - 40) - using a repeated-measures, counterbalanced design. Each protocol comprised three sets with 5-minute inter-set rest periods. SmO_2 of the vastus lateralis was continuously monitored to determine changes in its magnitude and slope during exercise and recovery phases. Results revealed no significant differences were observed in the magnitude of SmO_2 decline across conditions, with values ranging from 47.28% to 57.67% across all sets ($p > .05$). The SmO_2 decline slope was significantly steeper (more negative) in the 80-20 condition (-1.71 to -2.04 $\%\cdot s^{-1}$) compared to both 60-20 (-0.80 to -1.13 $\%\cdot s^{-1}$) and 60-40 (-0.53 to -1.00 $\%\cdot s^{-1}$) across all sets ($p < .001$). No significant differences were observed in SmO_2 recovery slope during rest (range: 0.36 - 0.61 $\%\cdot s^{-1}$; $p > .05$). The present study demonstrated that combining 60% 1RM with a 40% VL% threshold elicited the slowest SmO_2 decline rate, potentially delaying fatigue onset and allowing greater repetition volume. Although both training intensity and velocity loss thresholds influenced muscle oxygenation dynamics, the rate of SmO_2 desaturation was particularly sensitive to changes in VL% thresholds under the 80% 1RM. These findings underscore the importance of integrating training intensity, VL% magnitude, and oxygenation dynamics when designing individualized resistance training protocols.

Key words: Strength training, velocity-based training, muscle deoxygenation, muscle fatigue.

Introduction

Resistance training (RT) is widely recognized as an effective method for developing muscle strength, hypertrophy, power output, speed, and muscular endurance (Kraemer and Ratamess, 2004). The design of an RT program involves multiple training variables, including exercise selection and sequence, intensity, volume, rest intervals, and movement velocity. Among these variables, intensity and volume are considered key determinants of the type and extent of neuromuscular adaptations (Bird et al., 2005; Fry, 2004). The combination of these two variables is commonly referred to as the "level of effort" (Pareja-Blanco et al., 2019). However, previous studies have demonstrated that even under the same percentage of one-repetition maximum (%1RM), there is significant individual variability in the maximum number of repetitions performed (Richens and Cleather, 2014). This variability is influenced by several factors, including the individual's training status and the specific exercise performed. These factors suggest that traditional repetition-based protocols may result in inconsistent fatigue levels due to differences in repetitions in reserve, which refers to the estimated number of additional repetitions an individual can perform before reaching momentary muscular failure. These discrepancies can diminish the overall effectiveness of traditional RT prescriptions, highlighting the need for more individualized and precise fatigue management strategies.

Velocity-based training (VBT) is an innovative and individualized approach to resistance training that leverages the natural decline in movement velocity as neuromuscular fatigue accumulates (Weakley et al., 2021). VBT has been predominantly studied and applied in multi-joint exercises, such as squats, bench presses, and deadlifts. By monitoring the percentage of velocity loss (VL%) during exercise, the set is terminated once the barbell velocity reaches a predetermined threshold. This method allows for dynamic adjustment of training volume based on individual fatigue levels, providing a more objective and personalized measure of effort (Rodriguez-Rosell et al., 2020b). Research has shown a significant positive correlation between VL% and the percentage of completed repetitions (i.e., actual repetitions performed relative to the maximum possible repetitions) ($r^2 = 0.93 - 0.97$) (Rodriguez-Rosell et al., 2020b). This relationship enables dynamic adjustments without relying on fixed repetition counts, while still allowing practitioners to anticipate a reasonable range of repetitions based on the selected VL%. As a result, training volume can be dynamically adjusted according to individual fatigue levels, ensuring consistent effort across sessions. Studies suggest that setting VL between 10% and 20% is optimal for maximizing performance improvements (Pareja-Blanco et al., 2017b; Pareja-Blanco et al., 2020; Rodriguez-Rosell et al., 2020a). In contrast, training with a VL above 20% has been shown to elicit greater muscle hypertrophy (Pareja-Blanco et al., 2020). Notably,

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when VL exceeds 40%, it may promote muscle fiber-type transitions from fast-twitch (Type IIX) to slow-twitch (Type I) fibers (Pareja-Blanco et al., 2017a), leading to adaptations that favor muscular endurance rather than strength. Despite the lower training volume associated with VL20% compared to VL40%, both conditions result in similar increases in maximal strength (Pareja-Blanco et al., 2017a). This suggests that VL% settings can be tailored to specific training objectives, such as maximizing performance or inducing hypertrophy. By precisely adjusting VL%, VBT allows for optimized management of training intensity and fatigue, providing a scientific basis for customized resistance training programs to achieve specific physiological adaptations and performance outcomes.

Monitoring fatigue is essential for optimizing training outcomes. It involves both central mechanisms, such as reduced neural drive, and peripheral factors like metabolic disturbances that impair muscle function (Gandevia, 2001; Fitts, 1994; McMahon and Jenkins, 2002). Research has indicated that localized ischemia may also contribute to muscle fatigue, particularly during the early stages of exercise, where reduced oxygen availability plays a critical role (Hogan et al., 1994). To monitor such physiological responses, near-infrared spectroscopy (NIRS) has emerged as a valuable, non-invasive method for assessing SmO_2 and microvascular circulation during exercise. NIRS operates by measuring the absorption and scattering of near-infrared light, allowing for the estimation of changes in tissue oxygenation and blood flow (Boushel et al., 2001). Previous studies have investigated acute SmO_2 responses during various resistance training exercises and intensities (Baudry et al., 2013; Guardado et al., 2021; Timón et al., 2017). A recent systematic review indicated that SmO_2, as measured by NIRS, is a sensitive marker of acute changes in muscle oxygenation during resistance training, regardless of whether moderate or high intensities are applied (Miranda-Fuentes et al., 2021). Nevertheless, existing research has predominantly focused on fixed repetition or traditional RT protocols, with limited attention to how SmO_2 responds specifically to individualized, velocity-based prescriptions. Consequently, the physiological characteristics of muscle oxygenation under varying combinations of VL% and load intensities remain insufficiently elucidated.

A clear understanding of how different combinations of training intensities and velocity loss thresholds influence muscle oxygenation dynamics - specifically, the magnitude and slope of SmO_2 responses - is crucial for elucidating physiological mechanisms during resistance exercise. Such insights may clarify fatigue development, metabolic stress, and recovery patterns, thereby supporting the refinement of individualized RT prescriptions. Accordingly, the present study investigates the effects of different intensities (60% vs. 80% 1RM) and velocity loss thresholds (20% vs. 40%) on SmO_2 dynamics. The findings are expected to inform the design of more precise and effective individualized resistance training strategies.

Methods

Participant characteristics

Eighteen male participants with prior resistance training experience were recruited for this study (age: 20.06 ± 1.63 years; height: 176.78 ± 6.45 cm; body mass: 70.26 ± 9.56 kg; back squat 1RM: 123.17 ± 24.41 kg). All participants had a training background ranging from 1.5 to 3 years (1-3 sessions per week) and were familiar with proper technique. Exclusion criteria included any physical limitations, health problems, or musculoskeletal injuries that could affect performance or testing, as well as the use of drugs, medications, or dietary supplements known to influence physical performance. All participants provided written informed consent after receiving a detailed explanation of the experimental procedures and potential risks. A comprehensive health examination was conducted prior to participation to ensure eligibility. This study was approved by the Institutional Review Board of Fu Jen Catholic University Hospital (Approval No.: C108083), and all procedures were conducted in accordance with the Declaration of Helsinki.

Experimental procedures

This study employed repeated measures and a counterbalanced design. The 18 participants performed four different back squat resistance training conditions: (1) 60 - 20: 60% 1RM with VL 20%; (2) 60 - 40: 60% 1RM with VL40%; (3) 80 - 20: 80% 1RM with VL20%; (4) 80 - 40: 80% 1RM with VL 40%. All back squat exercises were performed using a Smith machine to ensure consistent movement patterns and reduce inter-trial variability. The Smith machine also provided a controlled barbell path and enhanced safety, particularly when participants executed each repetition with maximal voluntary effort. Each protocol consisted of three sets, with a 5-minute rest interval between sets to allow adequate recovery. Throughout the exercise and inter-set rest periods, real-time monitoring of SmO_2 in the vastus lateralis was conducted using a NIRS device. SmO_2 dynamics, including changes in saturation magnitude and slope, were recorded continuously to capture both exercise-induced deoxygenation and reoxygenation patterns (Figure 1).

(1) Execution of the back squat

Before testing, participants performed a bodyweight squat to a depth where their thighs were parallel to the ground. A resistance band was positioned between the uprights of the squat rack to serve as a consistent depth marker. During the execution of the back squat, participants descended at a controlled tempo until their thighs contacted the band, then completed the concentric phase with maximal voluntary effort to return to a standing position. Throughout the movement, participants were instructed to maintain full foot contact with the ground and to keep the barbell securely positioned across the shoulders. An experienced trainer provided verbal cues to ensure adherence to the standardized technique. The execution emphasized a controlled descent to parallel thigh position, an upright torso, and proper bar bell placement - consistent with established guidelines for back squat technique (Schoenfeld, 2010).

(2) One-Repetition Maximum (1RM) test

The 1RM test for back squat was performed on a Smith machine, following a standardized protocol (Dorrell et al., 2020). During each repetition, participants were instructed to control the eccentric phase, descending steadily until

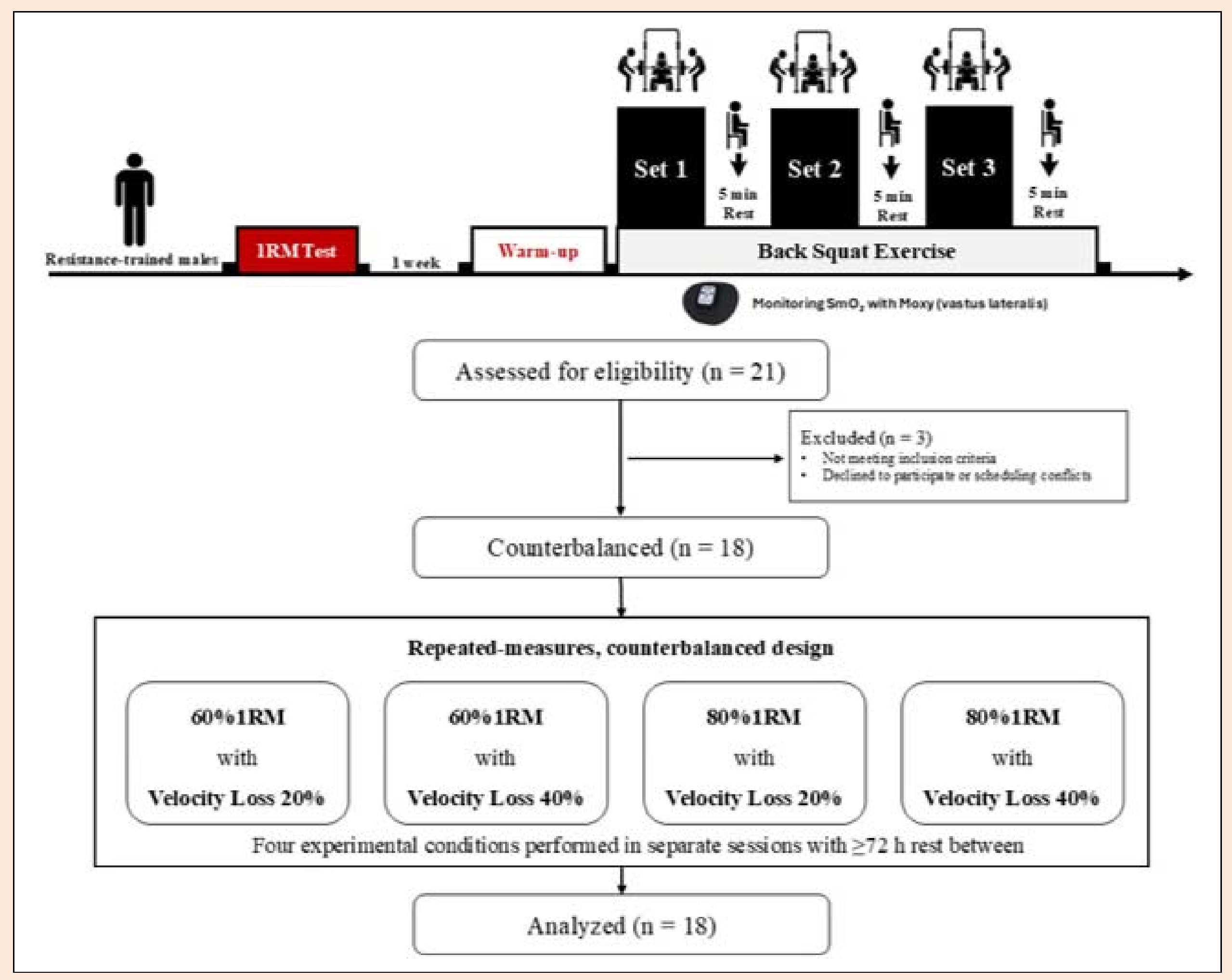

Figure 1. Overview of the experimental design and participant flow.

their thighs touched the resistance band. Upon reaching the designated depth, they performed the concentric phase with maximal voluntary effort to return to a standing position. Participants were required to maintain foot contact with the floor and keep the barbell on their shoulders throughout the movement. An experienced-trainer positioned at the side of the squat rack provided verbal cues to ensure participants maintained proper form and adhered to the standardized movement pattern. The test initiated with a standardized warm-up and progressive loading sequence. Participants performed a bodyweight squat without additional load for 8 - 10 repetitions to familiarize themselves with the squat depth and movement pattern. Following the warm-up, they performed 5 - 6 repetitions at 50% of their estimated 1RM, 3 - 5 repetitions at 70%, and a single repetition at 90% of estimated 1RM. For 1RM testing, participants performed single repetitions with progressively increasing loads until their 1RM was determined. If a participant failed to lift a certain load, the weight was reduced by 5%, and another attempt was performed. The 1RM was determined within 3 to 5 attempts. Each series of repetitions throughout the full protocol was interspersed with 3–5 minutes of rest to minimize fatigue and ensure optimal performance. To ensure consistency, a GymAware linear position transducer was used to monitor squat depth throughout the test, verifying that the designated depth was reached for every repetition. To minimize the potential effects of fatigue or muscle damage on subsequent performance, a one-week rest period was scheduled after the 1RM test and before the start of the resistance exercise protocols.

(3) Resistance exercise protocol

All four back squat conditions were performed on a Smith machine. Throughout the exercise, a GymAware linear position transducer (GymAware PowerTool, Kinetic Performance Technologies, Canberra, Australia) was used to monitor the mean velocity of the barbell, which has been shown to demonstrate acceptable reliability and validity (Dorrell et al., 2019). The device was securely mounted on the right side of the Smith machine, with its tether attached to the barbell via Velcro approximately 5 cm from the outer edge. The device's position was carefully adjusted to ensure the tether remained perpendicular to the ground throughout the movement. Real-time velocity feedback was displayed to participants via an iPad (Apple Inc., Cupertino, CA, USA). Once the pre-assigned velocity loss (VL%) threshold was reached, researchers instructed participants to terminate the set. During all repetitions, participants were encouraged to perform the concentric phase with maximal voluntary effort.

(4) Muscle oxygen saturation measurement and data analysis

Muscle oxygen saturation was monitored using a near-infrared spectroscopy device (Moxy Monitor, Hutchinson, MO, USA), which has been shown to be reliable and valid for assessing muscle oxygenation parameters (Feldmann et al., 2019). Following the procedure described by Gómez-Carmona et al. (2020), the sensor was placed on the belly of the vastus lateralis, with its lower edge positioned 15 cm above the patella. To minimize sweat interference and avoid direct skin contact, the device was wrapped in a transparent film, fixed with double-sided adhesive tape, and covered with a dark elastic band to prevent ambient light contamination. Sensor placement was kept consistent across all testing sessions.

The Moxy device continuously recorded SmO_2 as the ratio of oxyhemoglobin to total hemoglobin, providing real-time muscle oxygen saturation data. SmO_2 signals were segmented into three distinct phases: (1) the exercise phase, characterized by progressive deoxygenation; (2) the recovery phase, defined by reoxygenation occurring during the first 60 seconds post-exercise; and (3) the maintenance phase, during which SmO_2 values stabilized prior to the subsequent set. Three variables were extracted for analysis: (1) the magnitude of SmO_2 decline, calculated as the percentage decrease from the value measured 1 second before the start of the set (SmO_2start) to the value immediately after the final concentric repetition (SmO_2stop), using the formula: $[(SmO_2\text{stop} \times 100 / SmO_2\text{start}) - 100] \times -1$; (2) the SmO_2 decline slope ($\%\cdot s^{-1}$), defined as the linear rate of decrease from SmO_2start to the end of the last concentric repetition during the exercise phase; and (3) the SmO_2 recovery slope ($\%\cdot s^{-1}$), computed as the linear rate of increase in SmO_2 during the first 60 seconds of the rest period, from the minimum to the peak value. The 60-second window for recovery slope calculation was chosen based on prior literature suggesting that the majority of reoxygenation occurs within this timeframe, minimizing the influence of hyperemia and gravitational factors. All SmO_2 data were visually inspected for motion artifacts and processed using custom spreadsheet scripts (Gómez-Carmona et al., 2020; Muñoz-López et al., 2022).

Statistical analysis

A priori power analysis was conducted using G*Power (version 3.1.9.7) to estimate the minimum required sample size for a repeated-measures ANOVA with four measurements. Assuming a medium-to-large effect size (f = 0.3), an alpha level of 0.05, statistical power of 0.80, a correlation among repeated measures of 0.5, and a nonsphericity correction $\varepsilon = 1$, the analysis indicated a required sample size of 17 participants. The final sample size of 18 exceeded this requirement, ensuring adequate statistical power (actual power = 0.81).

All statistical analyses were performed using SPSS (version 22.0; IBM Corp., Armonk, NY, USA). A two-way repeated-measures ANOVA was used to evaluate the effects of condition (60 - 20, 60 - 40, 80 - 20, 80 - 40) and set (1 - 3) on SmO_2 responses. When significant main or interaction effects were observed, Bonferroni-corrected post hoc comparisons were conducted. Effect sizes were reported as partial eta squared (η^2_p), with values of 0.01, 0.06, and 0.14 interpreted as small, medium, and large, respectively (Cohen, 1988). The statistical significance was set at $\alpha = 0.05$.

Results

Table 1 presents the VL% and number of repetitions for each experimental condition. No significant differences were observed between the targeted (VL20%, VL40%) and actual velocity losses at both intensities (60%1RM: 23.81 ± 5.41% [VL20], 41.49 ± 8.46% [VL40]; 80%1RM: 24.42 ± 5.98% [VL20], 37.69 ± 11.94% [VL40]). A significant interaction effect was observed for fastest MV across conditions ($F = 42.345$, $p < .001$, $\eta^2_p = .714$). Specifically, the fastest MV was consistently higher in the 60% 1RM conditions (60-20 and 60-40) compared to the 80% 1RM conditions (80-20 and 80-40) across all sets (all $p < .001$). For slowest MV, a significant interaction was also found ($F = 19.828$, $p < .001$, $\eta^2_p = .538$). In Set 1, the 80-40 condition exhibited significantly lower slowest MV compared to all other conditions (all $p < .05$). Additionally, the slowest MV in both the 60 - 40 and 80-20 conditions was significantly lower than in the 60 - 20 condition (both $p < .05$). In sets 2 and 3, the slowest MV was consistently higher in the 60-20 condition than in all other conditions (all $p < .01$). A significant interaction was also found for repetitions across conditions ($F = 3.185$, $p = .030$, $\eta^2_p = .158$).

Table 1. Comparison of Fastest and Slowest Mean Velocity, and Repetition Count Across Experimental Conditions.

		Set 1	Set 2	Set 3	Overall
Fastest MV ($m\cdot s^{-1}$)	60-20	0.68 ± 0.09	0.66 ± 0.08	0.65 ± 0.09	0.66 ± 0.09
	60-40	0.68 ± 0.09	0.65 ± 0.09	0.63 ± 0.10	0.66 ± 0.10
	80-20	0.54 ± 0.08*†	0.53 ± 0.08*†	0.50 ± 0.08*†	0.52 ± 0.08*†
	80-40	0.55 ± 0.08*†	0.53 ± 0.09*†	0.51 ± 0.10*†	0.53 ± 0.09*†
Slowest MV ($m\cdot s^{-1}$)	60-20	0.49 ± 0.08	0.50 ± 0.08	0.50 ± 0.08	0.50 ± 0.08
	60-40	0.40 ± 0.07*	0.39 ± 0.08*	0.39 ± 0.07*	0.39 ± 0.07*
	80-20	0.41 ± 0.07*	0.40 ± 0.06*	0.38 ± 0.07*	0.40 ± 0.07*
	80-40	0.34 ± 0.06*†‡	0.35 ± 0.06*	0.33 ± 0.10*	0.34 ± 0.08*†‡
REPs (n)	60-20	12.94 ± 4.88	12.39 ± 3.91	10.72 ± 3.80	12.04 ± 4.25
	60-40	16.50 ± 5.59	13.44 ± 3.55	11.50 ± 3.22	13.81 ± 4.66
	80-20	5.67 ± 2.30*†	5.78 ± 2.46*†	5.28 ± 2.32*†	5.57 ± 2.33*†
	80-40	10.28 ± 4.69†‡	8.67 ± 4.00*†‡	7.11 ± 3.01*†	8.69 ± 4.10*†‡

Data are presented as mean ± standard deviation. Fastest MV = The highest mean velocity within each set (typically occurring on the first repetition). Slowest MV = The lowest mean velocity within each set. REPs = number of repetitions performed. 60-20 = 60%1RM with 20% velocity loss; 60-40 = 60%1RM with 40% velocity loss; 80-20 = 80%1RM with 20% velocity loss; 80-40 = 80%1RM with 40% velocity loss. *Significantly different from 60-20 ($p < .05$); †Significantly different from 60-40 ($p < .05$); ‡Significantly different from 80-20 ($p < .05$).

Specifically, repetition counts systematically decreased as loading intensity increased. Participants completed significantly more repetitions in the 60 - 40 condition compared to the 80-20 condition (all sets: $p < .001$) and the 80-40 condition (sets 1 - 3: $p = .036$, .004, and .004, respectively). Additionally, repetitions were significantly greater in the 80-40 compared to the 80-20 condition in sets 1 ($p = .019$) and 2 ($p = .025$).

Table 2 presents the SmO_2 values at the start and stop of each set across the four experimental conditions. No significant differences were observed in SmO_2 start values among the 60-20, 60-40, 80-20, and 80-40 conditions across all sets (all $p > .05$). Likewise, SmO_2 stop values did not differ significantly between conditions in any of the three sets (all $p > .05$).

Figure 2 shows SmO_2 decline magnitudes across conditions. No significant interaction (F = 0.509, p = .680, $\eta^2_p = .029$) or main effects for experimental condition ($F = 0.915$, $p = .440$, $\eta^2_p = .051$) and set ($F = 1.852$, $p = .172$, $\eta^2_p = .098$) were detected. Post hoc analyses confirmed no differences among conditions within any set (set 1: 47.28%, 56.70%, 54.84%, 55.13%, $p = .432$; set 2: 49.50%, 56.91%, 54.72%, 57.67%, $p = .488$; set 3: 49.86%, 56.66%, 54.89%, 57.55%, $p = .472$).

Figure 3 depicts the slope of SmO_2 decline during exercise across different experimental conditions. No significant interaction effect between treatment and set was detected for the SmO_2 decline slope ($F = 0.279$, $p = .869$, $\eta^2_p = .016$). However, significant main effects were observed for the experimental condition (i.e., the four configurations; $F = 20.717$, $p < .001$, $\eta^2_p = .549$) and set (i.e., sets 1, 2, and 3; $F = 20.479$, $p < .001$, $\eta^2_p = .546$). Post hoc analyses indicated that the SmO_2 decline slope was significantly steeper (more negative) in the 80-20 condition compared to the 60-20 condition across all three sets (set 1: -1.71 vs. −0.80 %·s⁻¹, $p < .001$; set 2: -1.91 vs. -0.88 $\%\cdot s^{-1}$, $p = .001$; set 3: -2.04 vs. -1.13 $\%\cdot s^{-1}$, $p < .001$).

Similarly, the slope was significantly steeper in the 80-20 condition than in the 60-40 condition across all sets (set 1: -1.71 vs. -0.53 $\%\cdot s^{-1}$, $p < .001$; set 2: -1.91 vs. -0.80 $\%\cdot s^{-1}$, $p < .001$; set 3: -2.04 vs. -1.00 $\%\cdot s^{-1}$, $p < .001$). Within-condition comparisons further revealed that, in the 60-40 condition, the SmO_2 decline slope was significantly steeper in set 3 compared to set 1 ($p = .001$) and set 2 ($p = .037$), and also steeper in set 2 compared to set 1 ($p = .007$). Additionally, in the 80 - 40 condition, the slope in set 3 was significantly steeper compared to set 1 ($p = .013$).

Figure 4 presents the SmO_2 recovery slope (increase) during the resting phase across different experimental conditions. No significant interaction effect between treatment and set was observed for the SmO_2 recovery slope ($F = 1.393$, $p = .225$, $\eta^2_p = .076$). Additionally, neither the main effect of experimental condition ($F = 1.689$, $p = .181$, $\eta^2_p = .090$) nor the main effect of set ($F = 1.213$, $p = .296$, $\eta^2_p = .067$) was significant. Post hoc analyses further confirmed no significant differences in SmO_2 recovery slopes among the four experimental conditions in any of the three sets (set 1: 0.48, 0.42, 0.61, and 0.58 $\%\cdot s^{-1}$, $p = .123$; set 2: 0.46, 0.48, 0.55, and 0.58 $\%\cdot s^{-1}$, $p = .457$; set 3: 0.36, 0.48, 0.54, and 0.53 $\%\cdot s^{-1}$, $p = .108$).

Table 2. Comparison of muscle oxygen saturation at set start and stop across experimental conditions.

		Set 1	Set 2	Set 3
SmO_2 start (%)	**60-20**	67.15 ± 7.94	68.98 ± 6.24	70.54 ± 5.63
	60-40	67.44 ± 5.59	69.71 ± 7.35	71.43 ± 3.95
	80-20	69.14 ± 6.84	70.51 ± 6.68	71.59 ± 4.31
	80-40	65.44 ± 8.03	67.66 ± 6.26	69.58 ± 5.53
SmO_2 stop (%)	**60-20**	35.06 ± 11.03	34.83 ± 11.11	35.38 ± 10.94
	60-40	29.78 ± 14.15	30.70 ± 12.52	31.12 ± 11.52
	80-20	30.96 ± 11.60	31.81 ± 11.37	32.14 ± 10.64
	80-40	29.08 ± 12.08	28.68 ± 12.51	29.16 ± 12.93

Data are presented as mean ± standard deviation.

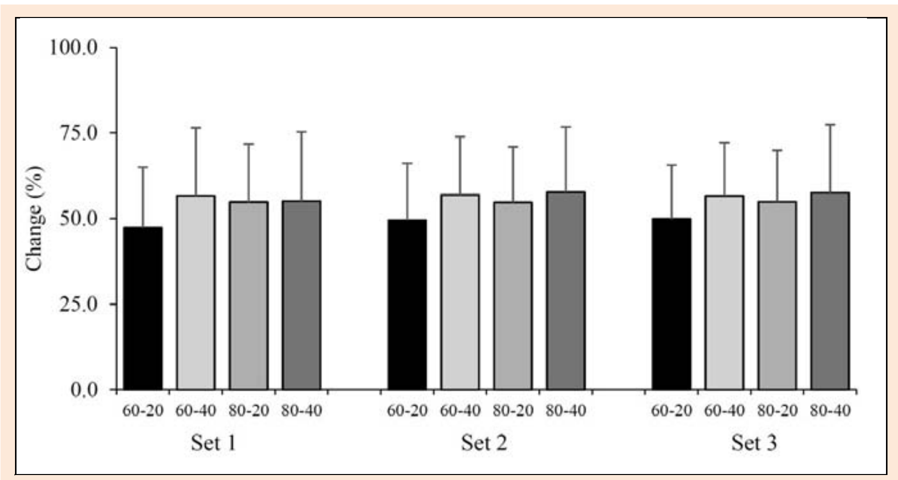

Figure 2. Comparison of SmO_2 Decline Magnitude Across Three Sets Under Different Experimental Conditions. *Significantly different from 60-20 ($p < .05$); †Significantly different from 60-40 ($p < .05$); ‡Significantly different from 80-40 ($p < .05$); §Significantly different from set 1 of 60-40 ($p < .05$); ||Significantly different from set 2 of 60-40 ($p < .05$); ¶Significantly different from set 1 of 80-40 ($p < .05$).

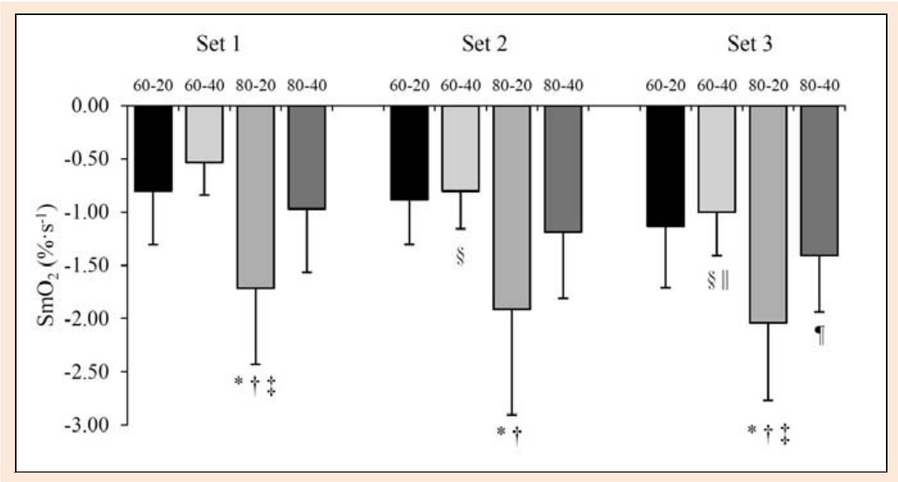

Figure 3. **Comparison of SmO_2 decline slope across three sets under different experimental conditions.**

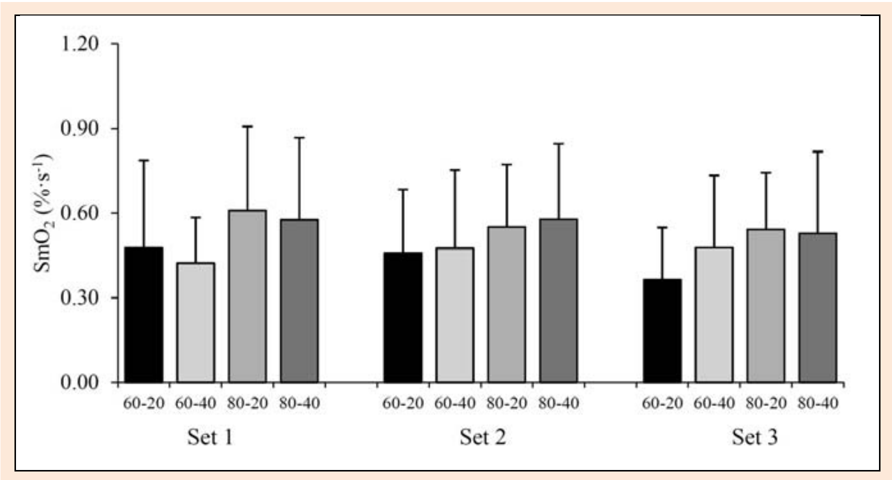

Figure 4. **Comparison of SmO_2 recovery slope during inter-set rest periods under different experimental conditions.**

Discussion

This study aimed to investigate the effects of different resistance exercise intensities (60% vs. 80% 1RM) and velocity loss thresholds (VL20% vs. VL40%) on lower-limb muscle oxygen saturation. The primary findings revealed no significant differences in the magnitude of SmO_2 decline among the four experimental conditions during the exercise phase. However, the SmO_2 decline slope was consistently steeper (more negative, indicating faster muscle deoxygenation) in the higher intensity 80 - 20 condition compared to both lower intensity conditions (60 - 20 and 60 - 40) across all three sets. During inter-set recovery, no significant differences in SmO_2 recovery slope were observed among conditions. These results suggest that both exercise intensity and velocity loss thresholds influence muscle oxygenation dynamics.

In addition to SmO_2-related findings, differences in repetition performance were also observed. Although 60-40 showed a higher mean repetition count than 60 - 20, the difference was not statistically significant. This may be explained by substantial inter-individual variability in muscular endurance under light-load conditions (60% 1RM), which led to wide variation in the first set of both conditions. However, fatigue accumulated during the first set likely resulted in more uniform fatigue levels in sets two and three, reducing variability and causing repetition counts to converge between the two groups. Nonetheless, across the broader set of conditions, more pronounced differences in repetition numbers were observed (e.g., 5 vs. 16 reps per set). However, even under these contrasting workloads, the magnitude of SmO_2 decline in the vastus lateralis did not significantly differ. This velocity-based approach suggests muscle deoxygenation is not strictly volume-dependent but rather governed by reaching an individual fatigue threshold. Consistent with prior studies (Muñoz-López et al., 2022), our findings indicate that even under substantially different repetition counts, terminating sets based on VL% yields comparable levels of muscle oxygen desaturation. Moreover, this study extends previous findings by demonstrating this consistency in muscle oxygen desaturation across both moderate (60% 1RM) and high intensities (80% 1RM).

Further, the SmO_2 plateau observed may reflect the activation of autoregulatory mechanisms. Prior research by Dech et al., 2021, which employed resistance exercise at 60% of maximal voluntary isometric contraction, has proposed that a threshold level of muscle oxygen saturation - approximately 59% - may trigger compensatory microvascular adjustments such as increased blood filling or capillary recruitment. These mechanisms serve to preserve a minimal level of tissue oxygenation, thereby preventing further desaturation. Once this physiological "floor" is reached, SmO_2 may stabilize regardless of additional repetitions performed. Thus, the observed uniformity in SmO_2 decline magnitude likely represents an interaction between exercise intensity, velocity loss thresholds, and intrinsic autoregulatory responses, rather than a simple reflection of repetition volume or time under tension. These findings support using VL% as a more individualized and fatigue-sensitive training prescription method, particularly for investigating muscle oxygenation dynamics during resistance exercise.

A further comparison of SmO_2 decline slopes during the exercise phase revealed a significant difference between VL20% and VL40% in the 80% 1RM condition, whereas no significant difference was observed between VL20% and VL40% in the 60% 1RM condition. This finding is consistent with the study by Muñoz-López et al. (2022), which reported that during 60% 1RM back squat exercises, the vastus lateralis SmO_2 decline slope significantly differed in between VL20% and VL40% only in the set 1. These results suggest that in moderate-intensity conditions, the impact of VL% on SmO_2 decline slope is relatively smaller. Additionally, the present study found that among the four experimental conditions, the 60 - 40 condition exhibited the least negative SmO_2 slope, reflecting a slower desaturation rate during exercise. This indicates that under the same SmO_2 decline magnitude, the 60 - 40 protocol prolonged hypoxic duration, thereby increasing the time under tension during exercise. Prolonged time under tension, especially under hypoxic conditions, is known to enhance anabolic signaling by extending the hypoxic duration of type I muscle fibers, which may facilitate superior muscle hypertrophy (Ogborn and Schoenfeld, 2014; Grgic et al., 2018).

It is important to note that while significant differences were observed in the slope of SmO_2 decline across conditions and sets, no differences were found in the overall magnitude of SmO_2 deoxygenation. This apparent discrepancy arises because slope and magnitude represent distinct physiological characteristics. Specifically, the slope reflects the rate of oxygen desaturation, whereas the magnitude indicates the total decrease in oxygen saturation. Therefore, a steeper slope does not necessarily imply a greater overall reduction in SmO_2 but rather indicates a faster rate of deoxygenation. These divergent characteristics highlight the necessity of examining both metrics to fully understand muscle oxygenation dynamics, as they capture different aspects of the physiological response to resistance exercise.

Previous research has predominantly focused on physiological adaptations associated with VL (Pareja-Blanco et al., 2017a; Pareja-Blanco et al., 2020; Rodríguez-Rosell et al., 2021; Sanchez-Medina and González-Badillo, 2011). Notably, this study is the first to simultaneously investigate the interaction between different loading intensities (60% 1RM and 80% 1RM) and VL% conditions, offering new insights into how these variables jointly influence muscle oxygenation kinetics. The present findings indicate that both VL% and exercise intensity may differentially affect the rate of muscle deoxygenation. For example, in the 60 - 20 and 80-20 conditions, the SmO_2 decline slopes were $-0.84\ \%\cdot s^{-1}$ and $-1.67\ \%\cdot s^{-1}$, respectively, suggesting that higher intensity may accelerate the loss of muscle oxygenation despite comparable VL thresholds. In contrast, lower intensity protocols led to more prolonged contraction durations. These observations may have meaningful implications for understanding the acute physiological stress imposed by different resistance training prescriptions and warrant further investigation in future studies.

In the present study, no significant differences were observed in the SmO_2 recovery slope among the four experimental conditions during the inter-set recovery phase. This finding is consistent with the results of Muñoz-López et al. (2022), who reported similar recovery slopes in conditions where the magnitude of SmO_2 decline during exercise was not markedly different. In this study, SmO_2 recovery slopes were calculated based on the first minute of post-exercise recovery, providing a stable representation of early reoxygenation. However, this short-term indicator may not fully capture the entire neuromuscular recovery process. Although no differences in recovery slopes were found across conditions, absolute SmO_2 values at the start of each set returned to or slightly exceeded the baseline of the previous set, indicating that peripheral reoxygenation was largely restored after the standardized 5-minute rest period. Nonetheless, the number of repetitions performed declined progressively across sets, suggesting that SmO_2 recovery alone may not accurately reflect complete neuromuscular readiness. This discrepancy may be explained by the persistence of other fatigue mechanisms, such as central fatigue or the accumulation of metabolic byproducts, which can impair excitation–contraction coupling and muscle force production (Carroll et al., 2017). These findings emphasize the need for integrating additional physiological markers and performance metrics for comprehensive recovery evaluation.

This study focused exclusively on SmO_2 responses in the vastus lateralis, which may limit the applicability of the findings to other muscle groups. Prior studies have shown that oxygenation dynamics can differ between muscles due to variations in fiber type composition, anatomical location, and recruitment patterns during exercise (Muñoz-López et al., 2022). In addition, the participant sample consisted solely of healthy, resistance-trained young adults. As muscle oxygen saturation responses are known to be influenced by factors such as age, training history, and fitness level (Costilla et al., 2023; Gepner et al., 2019), the results may not generalize to untrained individuals, older adults, or athletic populations. Another important consideration is that while this study captured SmO_2 kinetics, it did not assess intracellular metabolic variables such as inorganic phosphate accumulation or hydrogen ion concentration, both of which are relevant to muscle fatigue and contractile performance (Keyser, 2010). Future studies should therefore integrate these biochemical markers with NIRS-derived SmO_2 data to better elucidate the physiological mechanisms underpinning resistance training adaptations. To enhance generalizability and further clarify physiological interpretations, future investigations are recommended to include diverse participant groups (e.g., varying age ranges and training backgrounds), assess multiple muscle groups, and explore long-term adaptations across different resistance training protocols.

Conclusion

In the context of back squat exercises, the slope of SmO_2 change, which reflects the rate of muscle oxygen desaturation, differed across combinations of exercise load and velocity loss thresholds. Specifically, the condition involving 60% 1RM combined with a 40% velocity loss threshold exhibited the slowest rate of SmO_2 decline, potentially delaying fatigue and allowing more repetitions, thereby increasing total contraction time as a result of the protocol allowing more repetitions. This extended time under tension may help promote hypertrophic adaptations. In contrast, SmO_2 desaturation was more sensitive to VL% changes under the 80% 1RM condition, while remaining relatively stable at 60% 1RM. From a practical standpoint, when muscle metabolic stress is comparable (i.e., similar SmO_2 magnitude), the 80-20 protocol may provide a stronger resistance stimulus due to a steeper desaturation slope, even under a lower total training volume - offering a more time-efficient yet physiologically demanding training approach. Furthermore, muscle reoxygenation during inter-set recovery was comparable across all conditions. These findings underscore the importance of integrating training intensity, velocity loss, and oxygenation responses when designing individualized resistance training protocols.

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Key points

- The magnitude of muscle oxygen saturation decline during the back squat exercise is not influenced by training intensity or velocity loss magnitude.
- The 60%1RM-VL40% condition exhibited the slowest rate of SmO_2 decline, potentially delaying fatigue and allowing more repetitions, thereby increasing total contraction time without inducing abrupt physiological stress.
- Both training intensity and velocity loss settings influence muscle oxygenation dynamics, with the rate of muscle oxygen desaturation being particularly sensitive to changes in velocity loss thresholds under 80% 1RM conditions.

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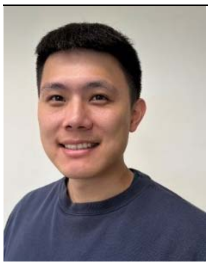

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