MANUSCRIPT UNDER REVIEW (PREPRINT)

The effects of different intra-set velocity loss thresholds on lower-limb adaptations to resistance training in young adults: A systematic review and meta-analysis

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Declarations of conflict of interest: All authors declare that they have no competing interests for this work

Acknowledgments: The authors thank Dr. Breno Quintella Farah for his support and contributions to data analysis.

Co-author agreement statement: All co-authors are agreed to share this preprint.

DOI: 10.31236/osf.io/v3tr9

Citation: Gantois, P., Nakamura, F.Y., Alcazar, J., Fortes, L.S., Pareja-Blanco, F., Fonseca, F.S. (2021). The effects of different intra-set velocity loss thresholds on lower-limb adaptations to resistance training in young adults: A systematic review and meta-analysis. Preprint available from SportRXiv. doi: 10.31236/osf.io/v3tr9

Abstract

Background: The level of effort seems to play a key role in determining neuromuscular adaptations; however, less is known regarding the optimal dose-response for intra-set levels of effort on chronic resistance training (RT) adaptations.

Objective: We aimed to synthesize the current literature on chronic RT adaptations in response to different intra-set velocity loss (VL) thresholds in the back squat exercise. We investigated changes in muscle strength, muscular endurance, sports-related physical performance, and muscle hypertrophy outcomes during resistance exercise to establish optimal dose-response relationships in physically active individuals.

Methods: We conducted a literature search using PubMed (Medline), Web of Science™, Scopus, and Cochrane up to April 2021, with no restriction on year of publication. The inclusion criteria were based on the PICO strategy. A random-effect meta-analysis was performed to determine the standardized mean differences (SMD $\pm$ 95% confidence intervals) for different intra-set VL thresholds (low VL [$< 15\%$], moderate VL [$\geq 15\%$ and $< 30\%$], and high VL [$\geq 30\%$]) in RT on maximum muscular strength, bar velocity against submaximal loads, endurance against a given load, countermovement jump height, running sprint time, and muscle hypertrophy.

Results: A total of 4,031 articles were found and 11 studies met our eligibility criteria. Pooled results revealed improvements between pre- and post-training intervention in 1RM strength (SMD = 0.78; $p < 0.001$); bar velocity outputs (light-loads [SMD = 0.79; $p < 0.001$] and heavy-loads [SMD = 2.08; $p < 0.001$]); endurance against a given load (SMD = 1.21; $p < 0.001$); countermovement jump height (SMD = 0.50; $p < 0.001$); running sprint time (SMD = - 0.28; $p = 0.001$); and muscle hypertrophy (SMD = 0.31; $p = 0.05$), with no significant difference between VL thresholds ($p > 0.05$). However, low VL elicited greater within-group SMD for 1RM strength than moderate and high VL thresholds (SMD = 0.93; 0.72; and 0.75; for low, moderate, and high VL thresholds, respectively). Low and moderate VL thresholds resulted in greater within-group SMD than high VL thresholds for velocity against light loads (SMD for low VL = 0.89; moderate VL = 0.90; high VL = 0.59); countermovement jump height (SMD for low VL = 0.51; moderate VL = 0.58; high VL = 0.36); and running sprint time (SMD for low VL = -0.49; moderate VL = -0.32; high VL = -0.09). Moderate and high VL thresholds induced higher within-group SMD for muscle hypertrophy than low VL (SMD for low VL = 0.14; moderate VL = 0.40; high VL = 0.44).

Conclusions: Low to moderate VL thresholds may provide more effective and efficient training stimuli for improving performance in strength-power tasks, due to the similar or even greater chronic adaptations achieved compared with high VL, despite the lower number of repetitions performed during the RT program. Conversely, moderate to high VL may provide more favorable training stimuli for inducing muscle hypertrophy. Strength coaches may apply these dose-response trends to design optimal RT stimuli based on their specific training goals.

Protocol registration: The study protocol was registered at the International Prospective Register of Systematic Reviews (PROSPERO) database (CRD42020189321).

1 Introduction

The appropriate manipulation of resistance training (RT) variables (e.g., selection and organization of exercises, number of sets per exercise, number of repetitions per set, intensity, rest duration, and movement velocity) represents a great challenge for strength and conditioning coaches aiming to develop athletes' strength, power, endurance and muscle hypertrophy, and athletic performance [1,2]. Among these RT prescription variables, the level of effort involved in every exercise set plays a key role in the magnitude and specificity of neuromuscular adaptations [3,4]. The level of effort relies on the interaction between training intensity and volume, and has been previously defined as the number of repetitions actually performed in each set with respect to the maximum number of repetitions that can be completed [3,5,6]. Accordingly, the level of effort will differ when performing, for example, 6 out of 12 repetitions with a given load (6[12]) compared to completing all possible repetitions (12[12]).

The level of effort has traditionally been determined by setting beforehand a specific number of repetitions to complete in each exercise set against a given relative load [i.e. %1RM] [6,7]. However, the maximum number of repetitions that can be performed against a given %1RM shows large inter-individual variability [8,9]. Therefore, it is not possible to ensure that the same level of effort will be attained across training sessions, since the number of repetitions that remain undone (i.e. repetitions left in reserve) may considerably vary over time [10,11]. This is likely to lead to different acute and chronic neuromuscular responses between individuals. Several studies have attempted to find strategies to objectively quantify the level of effort and to adequately control RT volume without disrupting the individual's daily RT routine with time-consuming tests [12–17].

Velocity-based training (VBT) has been proposed as an objective and accurate method to control RT variables such as intensity, volume, and level of effort by monitoring movement velocity (i.e. using bar displacement and time), and it has been reported to overcome the aforementioned limitations of other traditional approaches [18–20]. During an exercise set, by performing each repetition at maximal intended effort, a gradual and unintentional decrease in velocity is naturally observed as a result of increased fatigue [4,12,13,21]. The magnitude of the velocity loss (VL) experienced in a resistance exercise set (i.e., the percentage reduction in velocity relative to the fastest repetition) provides an objective tool for monitoring the level of effort during RT sessions [12,22,23] and can be manipulated by stopping the exercise sets when the participant reaches a certain VL threshold. Thus, while employing different VL thresholds (e.g., from VL0% to VL50%), the level of effort, degree of fatigue, and RT stimuli can be controlled to induce specific neuromuscular adaptations [22–24].

Recently, there has been an increase in the number of investigations analyzing the effects of RT performed under different intra-set VL thresholds on morphology, muscular strength, and sports-related performance. Acute studies have shown that performing resistance exercises under distinct VL thresholds can affect the degree of fatigue, leading to differences in post-exercise recovery of mechanical and neuromuscular variables such as countermovement jump (CMJ) height, force, velocity, and power output [12,25–27]. In addition, chronic adaptations in strength, power, speed, endurance, and muscle hypertrophy may differ when comparing programs with different VL thresholds [22,24,28,29]. It has been suggested that the selected VL threshold can modulate the adaptive responses in a dose-response fashion [22,23,28–30]. Evidence establishing the specific mechanical, neuromuscular, and hypertrophic adaptations that occur with different VL thresholds is essential to help coaches and strength and conditioning professionals to design and manage optimal dose-responses for RT [12,13,31].

An expanded and integrated analysis of studies investigating the chronic effects of different intra-set VL thresholds on muscle strength, physical performance, and muscle hypertrophy has important practical implications for managing the level of fatigue during RT and designing training stimuli targeting specific adaptations in a time-efficient manner [24,28,32]. However, there is still no critical review analyzing the results of the literature to derive the practical implications for RT programming. Considering that adaptations to RT are highly specific and determined by the characteristics of the stimuli applied to the organism, a systematic review with meta-analysis comparing the neuromuscular adaptations to RT performed under distinct VL thresholds could help strength and conditioning coaches to design optimal training volumes in RT programs according to their specific training goals.

Therefore, the purpose of the current study was threefold: (1) to perform a systematic review of studies that have compared different VL thresholds on muscle strength, physical performance, and muscle hypertrophy during RT; (2) to quantify and compare the findings with a meta-analysis; and (3) to draw evidence-based inferences to inform strength-power program prescriptions.

2 Methods

2.1 Search Strategy

This systematic review and meta-analysis followed the recommendations outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement and the study protocol was registered on the International Prospective Register of Systematic Reviews (PROSPERO) database (CRD42020189321). The same systematic search was carried out in PubMed

(Medline), Web of Science™, Scopus, and Cochrane up to April 2021, with no restriction on the year of publication. The search strategy employed the following terms and operators: "velocity-based training" OR "velocity-based" OR "velocity training" OR "velocity based training" OR "movement velocity" OR "velocity loss" OR "level of effort" with the operator AND to the keywords "physical performance" OR "functional performance" OR "athletic performance" OR "sport performance" OR "muscle fatigue" OR "muscular fatigue" OR "fatigue" OR "muscle strength" OR "strength" OR "force" OR "peak force" OR "power" OR "peak power" OR "power output" OR "mean velocity" OR "mean propulsive velocity" OR "mean propulsive power" OR "peak velocity" OR "mechanical" OR "neuromuscular" OR "jump*" OR "sprint*" OR "hypertrophy" OR "muscle size" OR "muscle fiber" OR "resistance" OR "endurance" AND "resistance trained" OR "physically active" OR "athlete*" OR "player*". In addition, hand searching and reference checking of each included study and other relevant reviews were performed to find other relevant reports [33]. Study titles and abstracts that did not provide sufficient information according to the inclusion criteria were retrieved for full-text assessment.

2.2 Eligibility Criteria

Eligible articles included controlled and non-controlled randomized trials, published in the English language and in a peer-reviewed journal. No restriction for the year of publication was established. A priori inclusion criteria were based on the Population, Intervention, Comparison, Outcome (PICO) approach to rate studies according to their eligibility as follows: i) population: physically active or resistance-trained young adults (18-40 years old; with no injuries in the last six months); ii) intervention: RT programs including the back-squat exercise (≥ 4 -week) that adopted movement velocity (peak velocity, mean velocity or mean propulsive velocity) to determine the intra-set VL and used it as an interruption criterion to prescribe RT volume; iii) comparison: groups using different VL thresholds in the RT session(s); and iv) outcome: adaptations in strength-related parameters (maximum muscular strength [1RM], velocity of the barbell attained against submaximal loads [i.e. light loads: $\geq 1.0 \text{ m}\cdot\text{s}^{-1}$; and heavy loads: $\text{MPV} < 1.0 \text{ m}\cdot\text{s}^{-1}$]), endurance against a given load), sports-related performance variables (jump height, and sprinting time), and muscle hypertrophy. Studies were included if bar displacement/velocity was assessed by validated and highly reproducible devices (i.e., linear position/velocity transducers) and if they reported sufficient information about the RT intervention: equipment used to measure bar displacement/velocity, volume, intensity, and exercise.

2.2.1 Study Selection

Two authors (P.G and F.S.F) independently performed the study selection based on title and abstract screening and subsequent full-text reading. Studies were included following agreement between these two authors (P.G and F.S.F). Disagreements were solved by the involvement of a third reviewer (F.Y.N). Data related to study design, participants' characteristics (age, sex, population, training status, study measurements (sets, intensity, intervention length for the pre-post longitudinal studies, velocity loss threshold, velocity parameter), and outcomes were extracted (Table 1). A PRISMA flow diagram providing a detailed description of the overall process is displayed in Fig. 1.

**** Fig. 1 here ****

2.3 Data Extraction

The mean and standard deviation (SD) values of the included outcomes were extracted by two independent researchers (L.S.F and F.P.B). Included studies were read to extract the following variables: authors, year of publication, descriptive information of sample, training program (exercise, intensity, volume, and rest time), assessment device, velocity parameter, outcomes evaluated, and main effects. When the data of interest could not be obtained directly from the articles, we contacted the authors to request the information.

2.4 Level of Evidence and Risk of Bias

The risk of bias in the included studies was assessed following a modified Cochrane Collaboration's Tools for Assessing Risk of Bias in Randomized Trials as previously reported [34]. The original Cochrane risk of bias tool consists of six domains of bias [35]: selection bias, performance bias, detection bias, attrition bias, reporting bias, and other sources of bias. The modified version used in this study removed the performance bias domain and added effort bias and familiarization bias to other sources of bias domain. The performance bias was removed since it is likely impossible to blind participants and researchers/assessors in this type of study [36,37]. Effort bias refers to whether the authors explicitly stated that participants were encouraged to exert their maximal effort in the concentric phase. A high risk of bias was considered when the authors did not explicitly state this aspect, since it is likely that the adaptations to the different interventions would be affected by the intended movement velocity of lifting [38–40]. Familiarization bias refers to whether the participants were familiarized with resistance exercise protocols. A high risk of bias was considered likely when the authors did not specify that participants were regularly performing the

resistance exercise used in the study or that a familiarization session had been included before the start of the study, since bias may occur from participants being unaccustomed to the resistance exercise protocol (i.e., proper technique and exert the maximal intended velocity). The methodological quality was independently assessed by two authors (F.S.F and L.S.F) and disagreement was resolved by a third reviewer (P.G).

2.5 Statistical Analysis

Quantitative data analysis was performed using the Review Manager Software (RevMan 5.4; Cochrane Collaboration, Oxford, United Kingdom). A random-effect meta-analysis was performed to determine the effectiveness of different intra-set VL thresholds in RT on the following outcomes: maximum muscular strength (1RM), velocity of the barbell attained against submaximal loads (i.e., light loads, defined as loads that could be lifted faster than $1.00 \text{ m} \cdot \text{s}^{-1}$; and heavy loads, defined as loads that could not be lifted faster than $1.00 \text{ m} \cdot \text{s}^{-1}$), endurance against a given load, countermovement jump (CMJ) height, running sprint time, and muscle hypertrophy. In order to compare the effect of VL magnitude on these parameters, the following thresholds were used: low VL ($< 15\%$), moderate VL ($\geq 15\%$ and $< 30\%$), and high VL ($\geq 30\%$). Differences between baseline and post-intervention were expressed as between-subject standardized mean differences (SMD) and their 95% confidence intervals (CI), with an adjustment for the total sample size as the following equation [41]:

$$SMD = \frac{M_{pre} - M_{post}}{SD_{pre - intervention}} \left(1 - \frac{3}{4n - 9} \right)$$

where M_{pre} is the mean value before the RT intervention, M_{post} is the mean value after the intervention, n is the sample size, and $SD_{pre-intervention}$ is the standard deviation in the baseline.

Threshold values for the SMD magnitude were interpreted as: small (0.20 – 0.49), moderate (0.50 – 0.79) or large (> 0.80) [42]. The level of between-study heterogeneity was evaluated using I^2 statistics. The magnitude of the I^2 statistic was expressed as: $< 25\%$ (low), 25–75% (moderate), and $> 75\%$ (high) [43]. The between-study variance was estimated by Tau-square (τ^2) [44]. Chi-square (Chi^2) statistics (p -value < 0.1 or large Chi^2 values) determined the presence of heterogeneity amongst studies for each outcome [44]. The statistical significance was set as a p -value of ≤ 0.05 .

3. Results

3.1 Search Results

The database search yielded a total of 4,031 articles, and 3,322 articles remained after duplicates were removed (using EndNote X9). After screening the title, abstract, and full-text (using Rayyan-web App, <http://rayyan.qcri.org>), 10 studies met our eligibility criteria. One study [45] was later included by tracking newly published articles. Thereby, a total of 11 studies were included in this systematic review (Table 1). The included and excluded studies (with reasons) are displayed in the PRISMA flowchart (Fig. 1).

3.2 Study Characteristics

Table 1 summarizes the studies' characteristics. The pooled number of participants across studies was 309. However, since it was observed that data from the same participants were used in two studies [22,32], the final number of participants included in the retained studies was 287. This represents a mean of ≈ 28 participants per study. The sample sizes varied from 11 [31] to 55 [23] participants. All studies included in this review recruited young adult men with at least one year of RT experience, except one study [31] that included both male and female participants. Two studies [31,46] recruited participants with at least two years of RT experience. Nine studies included physically active participants, whereas two studies [28,31] recruited athletes. The intra-set VL magnitude varied from 0% to 45%. Five studies [23,24,29,31,45] included low magnitudes of intra-set VL ($< 15\%$), eight [16,22–24,28,32,46,47] included moderate VL magnitudes ($\geq 15\%$ and $< 30\%$), and seven [22,23,28,29,32,45,46] included high percentages of VL ($\geq 30\%$). The total number of repetitions during the RT program ranged from ~ 48 [23] to ~ 501 [45]. The average number of total repetitions performed during the RT program across studies according to the intra-set VL magnitude was: low VL (~ 127 repetitions), moderate VL (~ 251 repetitions), and high VL (~ 352 repetitions). This indicates that the low VL and the moderate VL groups performed $\sim 36\%$ and $\sim 71\%$, respectively, of the total repetitions completed by the high VL group during the RT program. The total repetitions performed by the low VL group were $\sim 51\%$ of the repetitions completed by the moderate VL group. Most of the RT interventions lasted 8 weeks [16,22,23,29,31,32,45–47], with two studies including 6 weeks [28] and 7 weeks [24] of RT. The RT frequency varied from 2 to 4 sessions per week. The relative intensity ranged from 50% to 85% of 1RM with the rest intervals between sets varying from 2 to 4 minutes.

**** Table 1 here ****

3.3 Risk of Bias Assessment

The risk of bias assessment for each study is displayed in Fig. 2. Most of the studies included in this systematic review were classified as having an unclear risk of selection bias since they did not provide sufficient details about the randomization and allocation sequence. Three studies [29,46,47] were rated to be at low risk of bias since they provided further details about the randomization process. No studies provided information regarding allocation concealment. Only one study [22] was classified as being at low risk of outcome blinding bias, while the remaining studies were considered to be at unclear risk of bias due to the lack of information regarding the outcome blinding procedures. One study [46] was rated as having a high risk of effort bias since it did not report whether the participants were encouraged to exert maximum effort in lifting. Four studies [24,29,45,46] were classified to be at high risk of familiarization bias due to the lack of familiarization sessions and insufficient details about the participants' experience with the procedures of the study.

**** Fig. 2 here ****

3.4 Maximum Muscular Strength (1RM)

The effects of intra-set VL on 1RM were measured in 281 participants from 10 studies. The results of evaluations pre- and post-intervention showed a moderate positive effect ($p < 0.001$; SMD = 0.78, 95% CI: 0.61 to 0.96). Low between-study heterogeneity was detected for this analysis ($I^2 = 0\%$; $\tau^2 = 0\%$; $\text{Chi}^2 = 11.53$ [$p = 0.98$]) (Fig. 3). No statistically significant difference was observed among VL groups ($p = 0.61$). Within-group analysis showed that low VL resulted in a significant, large increase in 1RM strength ($p < 0.001$; SMD = 0.93; 95%CI: 0.59 to 1.27). However, there was also a significant moderate positive effect for both moderate ($p < 0.001$; SMD = 0.72; 95%CI: 0.47 to 0.98) and high VL ($p < 0.001$; SMD = 0.75; 95%CI: 0.42 to 1.07). There was an average low heterogeneity for each within-group analysis ($I^2 = 0\%$; $\tau^2 = 0\%$; $p > 0.68$).

**** Fig. 3 here ****

3.5 Velocity Outputs at Submaximal Loads (Light and heavy loads)

Eight studies involving 260 participants investigated the effects of VL on lifting velocity with light loads. The analysis of the overall changes, comparing pre- and post-training measurements, revealed significant improvements in velocity against light loads with moderate positive effects ($p <$

0.001; SMD = 0.79, 95% CI: 0.61 to 0.97) and a low level of heterogeneity of ($I^2 = 0\%$; $\tau^2 = 0\%$; $\text{Chi}^2 = 19.49$ [$p = 0.49$]) (Fig. 4). No significant between-group effects were observed among intra-set VL groups ($p = 0.33$). The within-group comparisons showed a large improvement in velocity with light loads from pre- to post-training intervention for both low VL ($p < 0.002$; SMD = 0.89, 95% CI: 0.33 to 1.46) and moderate VL ($p < 0.001$; SMD = 0.90, 95% CI: 0.64 to 1.17) groups. The high VL group showed a moderate positive effect on lifting velocity attained against light loads ($p < 0.008$; SMD = 0.59, 95% CI: 0.24 to 0.93). There was a low heterogeneity for within-group analysis for both moderate VL and high VL groups ($I^2 = 0\%$; $\tau^2 = 0\%$; $p > 0.70$). Conversely, there was a medium level of heterogeneity for the low VL group ($I^2 = 57\%$; $\tau^2 = 23\%$; $p = 0.05$).

Eight studies compared the pre- to post-training changes in intra-set VL on lifting heavy loads (pooled $n = 260$ participants). The overall analysis of pre- and post-intervention results showed a large positive effect on the velocity attained with heavy loads ($p < 0.001$; SMD = 2.08, 95% CI: 1.86 to 2.30). Low heterogeneity between studies was revealed for this analysis ($I^2 = 0\%$; $\tau^2 = 0\%$; $\text{Chi}^2 = 18.16$ [$p = 0.58$]) (Fig. 5). No significant differences among intra-set VL groups were observed ($p = 0.19$). Within-group analysis indicated a large positive effect on lifting velocity with heavy loads for all groups: low VL ($p < 0.001$; SMD = 2.16, 95% CI: 1.53 to 2.78), moderate VL ($p < 0.001$; SMD = 2.28, 95% CI: 1.95 to 2.62) and high VL ($p < 0.001$; SMD = 1.80, 95% CI: 1.39 to 2.20). Low heterogeneity was observed for both moderate VL and high VL groups ($I^2 = 0\%$; $\tau^2 = 0\%$; $p > 0.74$) and a moderate level of heterogeneity was found for the low VL group ($I^2 = 47\%$; $\tau^2 = 23\%$; $p = 0.11$).

**** Fig. 4 here ****

**** Fig. 5 here ****

3.6 Muscular Endurance Against a Given Load

Five studies investigated the effects of intra-set VL on the maximum number of repetitions (MNR) completed against a given load (pooled $n = 167$ participants). The overall analysis revealed a large improvement in MNR between pre- and post-intervention ($p < 0.001$; SMD = 1.21, 95% CI: 0.97 to 1.45). A low level of heterogeneity between studies was found in this analysis ($I^2 = 0\%$; $\tau^2 = 0\%$; $\text{Chi}^2 = 10.77$ [$p = 0.55$]) (Fig. 6). No significant differences were observed among VL groups ($p = 0.54$). The within-group comparison showed a significant, large improvement in MNR for low intra-set VL ($p < 0.001$; SMD = 1.46, 95% CI: 1.01 to 1.90), moderate VL ($p < 0.001$; SMD = 1.07, 95% CI: 0.50 to 1.63), and high VL ($p < 0.001$; SMD = 1.22, 95% CI: 0.82 to 1.62). An average low

heterogeneity was observed for both low and high VL groups ($I^2 = 0\%$; $\tau^2 = 0\%$; $p > 0.64$). Moderate between-study heterogeneity was found for the moderate VL group ($I^2 = 49\%$; $\tau^2 = 16\%$; $p = 0.12$).

**** Fig. 6 here ****

3.7 Vertical Jump Performance (CMJ)

Nine studies investigated the effects of VL between pre- and post-training on CMJ height (pooled $n = 278$ participants). The results of the overall effects observed between pre- and post-intervention showed a significant moderate positive effect on CMJ height ($p < 0.001$; $SMD = 0.50$, 95% CI: 0.33 to 0.67). Low between-study heterogeneity was detected for this analysis ($I^2 = 0\%$; $\tau^2 = 0\%$; $\text{Chi}^2 = 6.65$ [$p = 1.00$]) (Fig. 7). No significant differences were observed among VL groups ($p = 0.59$). When investigating within-group comparisons, there was a significant moderate improvement from pre- to post-intervention in CMJ height for both low ($p = 0.004$; $SMD = 0.51$, 95% CI: 0.16 to 0.85) and moderate VL ($p < 0.001$; $SMD = 0.58$, 95% CI: 0.33 to 0.82) groups. However, only a small increase was observed in the high VL group for CMJ height ($p = 0.030$; $SMD = 0.36$, 95% CI: 0.05 to 0.68). Low heterogeneity for each within-group analysis was revealed ($I^2 = 0\%$; $\tau^2 = 0\%$; $p > 0.83$).

**** Fig. 7 here ****

3.8 Sprint Performance

The effects of intra-set VL on running sprint time were investigated in eight studies (pooled $n = 277$ participants). Three studies included 20 m sprint times [16,22,24], one study included 30 m sprint times [28], and four studies measured sprint times for both 10 m and 20 m [23,29,45,46]. The results of the overall effects between pre- and post-intervention showed a significant, small improvement in sprint time ($p = 0.001$; $SMD = -0.28$, 95% CI: -0.45 to -0.11). Low between-study heterogeneity was detected for this analysis ($I^2 = 0\%$; $\tau^2 = 0\%$; $\text{Chi}^2 = 14.51$ [$p = 0.91$]) (Fig. 8). There were no differences between intra-set VL groups for sprint time ($p = 0.22$). A significant and small improvement from pre- to post-intervention in sprint time was observed for both low ($p = 0.01$; $SMD = -0.49$; 95% CI = -0.87 to -0.11) and moderate VL ($p = 0.020$; $SMD = -0.32$; 95% CI = -0.60 to -0.04) groups. Non-significant changes in sprint time were observed for the high VL group ($p = 0.540$; $SMD = -0.09$; 95% CI = -0.37 to 0.19). On average, a low heterogeneity for each within-group analysis was observed ($I^2 = 0\%$; $\tau^2 = 0\%$; $p > 0.24$).

**** Fig. 8 here ****

3.9 Muscle Hypertrophy

Two studies compared the effects of different intra-set VL on muscular hypertrophy (pooled $n = 77$ participants). The overall analysis revealed a significant, small increase between pre- and post-test for muscular hypertrophy ($p = 0.05$; SMD = 0.31, 95% CI: -0.01 to 0.63). The studies showed a low level of heterogeneity ($I^2 = 0\%$; $\text{Chi}^2 = 0.87$ [$p = 0.97$]) (Fig. 9). No significant differences were found between intra-set VL groups ($p = 0.70$). Within-group analysis revealed non-significant moderate improvements for both moderate ($p=0.16$; SMD = 0.40, 95% CI: -0.16 to 0.96) and high VL ($p = 0.14$; SMD = 0.44, 95% CI: -0.14 to 1.01) groups, while trivial changes were observed for the low VL group ($p = 0.61$; SMD = 0.14, 95% CI: -0.39 to 0.66). The level of heterogeneity of the studies was low for all groups ($I^2 = 0\%$; $\text{Chi}^2 = 0.87$ [$p > 0.75$]).

**** Fig. 9 here ****

4 Discussion

The present systematic review with meta-analysis aimed to investigate the effects of different intra-set VL thresholds on muscle strength (1RM and velocity against submaximal loads), muscular endurance, sports-related performance (jumping and sprinting ability), and muscle hypertrophy, and to identify which of these VL thresholds (low, moderate, and high) may be used to target specific training adaptations. The main findings of this study were: 1) all VL thresholds produced similar gains in muscular endurance and velocity against heavy loads; 2) low VL elicited greater within-group SMD for 1RM strength than moderate and high VL thresholds; 3) low and moderate VL thresholds resulted in greater within-group SMD for velocity against light loads, as well as for CMJ height and running sprint time; and 4) moderate and high VL thresholds induced higher within-group SMD for muscle hypertrophy. However, it should be noted that no statistically significant differences between groups were found for any of the variables analyzed, despite the considerable differences in the total volume accumulated during the RT program by each VL threshold (~127 vs. ~251 vs. ~352 repetitions for low, moderate, and high VL thresholds, respectively). Therefore, low and moderate VL thresholds provide effective and efficient training stimuli since they induce similar or even greater improvements in muscular strength and sports-related performance compared to training with high VL thresholds. By contrast, moderate and high VL thresholds may be required to provide sufficient stimuli for muscle hypertrophy gains.

4.1 Effects of Intra-Set Velocity Loss on Muscle Strength parameters (1RM, velocity at heavy and light loads) and muscular endurance

When examining the results of distinct VL thresholds on 1RM strength, velocity attained against submaximal loads, and endurance at a given load, overall moderate to large positive effects were observed. Our findings revealed that using higher VL thresholds in lower body exercises (i.e., squat) did not induce better 1RM strength gains than lower VL thresholds ($< 15\%$). Some authors have postulated that performing RT sets to a point close to muscle failure is necessary to maximize motor unit recruitment, and consequently, elicit superior muscular strength gains [48,49]. Notably, our findings showed that performing repetitions far below the point of muscle failure (i.e., $VL < 15\%$; $SMD = 0.93$), with maximum effort in every repetition, resulted in greater 1RM strength gains than moderate ($SMD = 0.72$) and high ($SMD = 0.75$) VL groups. In a study by Pareja-Blanco et al. [23], the authors noted 13.7%, 18.1%, 14.9%, and 12.3% increases in 1RM strength after 8 weeks of RT using 0%, 10%, 20%, and 40% VL, respectively. However, the 10% and 20% VL groups experienced earlier improvements in 1RM strength (session 2 and 3, respectively) compared with the 0% VL (session 6) and 40% VL (session 16 = end of the RT program) groups. The time course of adaptation to each VL needs to be further addressed in future studies, including longer intervention periods.

We also examined how these VL thresholds affected the different regions of the load-velocity curve by measuring the velocity attained with light ($AV > 1 \text{ m}\cdot\text{s}^{-1}$) and heavy ($AV < 1 \text{ m}\cdot\text{s}^{-1}$) loads. Interestingly, although no significant differences between groups were found, the low and moderate VL thresholds resulted in greater within-group SMD than high VL magnitudes for bar velocity attained against both light and heavy loads. Rodríguez-Rosell et al. [45] reported a significant positive correlation between relative changes in velocity outputs (i.e., light and heavy loads) and 1RM strength ($r = 0.60$ and 0.83 , respectively). Likewise, a significant positive association was observed between the average velocity attained during the RT program and relative changes in velocity for light ($r = 0.62$) and heavy loads ($r = 0.52$). By contrast, a negative correlation was found between the relative changes in velocity output and the total number of repetitions completed during the RT program ($r = -0.44$ and -0.43). This finding indicates that the unintentional decline in movement velocity (i.e., more fatiguing repetitions) experienced during the RT program using higher VL thresholds might be partially responsible for the lower within-group SMD in the muscle strength parameters observed in this systematic review in the high VL group ($\geq 30\%$) compared with the lower VL threshold groups ($< 30\%$). In fact, it has been reported that RT programs with high VL thresholds (40%), which are characterized by performing several extra slow and fatiguing repetitions, evoked a reduction in the IIX fiber type pool [22]. These physiological adaptations may not provide the optimal conditions for

improving force-generating capacity, especially at high velocities [50]. By contrast, the IIX fiber type pool was preserved when applying moderate VL thresholds (20%) [22].

Although it has been traditionally postulated that completing a high number of repetitions per set during RT should result in greater gains in muscular endurance [1,2], all VL thresholds produced similar large improvements in endurance against a given load (i.e., completing as many repetitions as possible with a given load), despite the considerable differences in total volume accumulated by each VL threshold. Rodríguez-Rosell et al. [29], reported 74.8% and 73.2% increases in muscular endurance after 8 weeks of RT using 10% and 30% VL, respectively. Notably, these adaptations were accompanied by 17.9% and 14.9% increases, respectively, in 1RM strength. Therefore, muscular endurance increments do not seem to depend on the training volume accumulated, but rather to the increase in maximal strength. In this regard, a positive relationship has been observed ($r = 0.63$ and 0.71) between the relative changes in 1RM and the relative changes in endurance against a given load [29,45], but not with the total number of repetitions completed during the RT program ($r = -0.16$) [45]. This phenomenon can be explained by the fact that a given absolute load (kg) will represent a lighter relative load (%1RM) following increases in 1RM strength. It is logical to assume that the lower the relative intensity (%1RM), the higher the maximal number of repetitions that can be completed. This statement is compatible with the large within-group SMD found in this systematic review for the 1RM strength and muscular endurance obtained by the low VL group (SMD = 0.93 and 1.46, respectively) compared with the moderate VL (SMD = 0.72 and 1.07, respectively) and high VL (SMD = 0.75 and 1.22, respectively) groups. Collectively, our results highlight that, in order to achieve greater muscle strength adaptations, a high volume of repetitions within the set is not necessary, since achieving high VL thresholds does not elicit further strength gains, despite the high levels of discomfort and fatigue experienced in those training routines.

4.2 Effects of Intra-Set Velocity Loss on Sports-Related Performance (CMJ and Sprint time)

The results of this systematic review showed a small (high VL: SMD = 0.36) to moderate (low VL: SMD = 0.51; and moderate VL: SMD = 0.58) increase in CMJ height. In addition, sprint performance only improved following RT with low (SMD = -0.49) and moderate VL (SMD = -0.32) thresholds, while RT using high VL thresholds did not result in significant changes in running sprint time ($p = 0.540$; SMD = -0.09). Improvements in sports-related physical tasks such as jump and sprint performance are of great interest to strength and conditioning coaches. Thus, it is important to identify the optimal intra-set VL threshold to induce positive changes in the relevant physical abilities in order to design more effective and less fatiguing training sessions. Pareja-Blanco et al. [28] observed an

increase in CMJ and sprint 30-m time following a 6-week RT program using a 15% VL (total number of repetitions = 251) in professional soccer players, while no statistical difference was found for the 40% VL group (total number of repetitions = 415). Of note, no difference was found in the number of repetitions at high velocities ($> 0.90 \text{ m}\cdot\text{s}^{-1}$) during the RT program. On the other hand, the 30% VL group performed more repetitions at slow velocities (0.40 to $0.90 \text{ m}\cdot\text{s}^{-1}$) than the 15% VL group. Likewise, Rodríguez-Rosell et al. [45] compared three distinct VL (10%, 30%, and 45%), and noted a greater improvement after an 8-week RT program using 10% VL (total number of repetitions = 180.8 ± 29.0) in CMJ height and 10 and 20 m sprint times compared to 30% (total number of repetitions = 347.9 ± 62.3) and 45% (total number of repetitions = 501.1 ± 106.8) VL groups. Of note, the 30% and 45% VL groups completed more slow and fatiguing repetitions (0.30 to $0.90 \text{ m}\cdot\text{s}^{-1}$) than the 10% VL group, while no differences between groups were found in the number of repetitions performed at high velocities ($> 0.90 \text{ m}\cdot\text{s}^{-1}$). In this regard, the training-related changes in the CMJ and sprint performances seemed to be mediated by the low level of fatigue incurred in each set instead of the absolute number of high velocity repetitions during RT, at least when maximum effort in each repetition with a relative intensity between 50 and 85% 1RM was used. These data might be of particular interest in sports disciplines that require jumping and sprinting actions.

In this regard, it has been reported that low and moderate VL thresholds (i.e., $< 30\%$) induce positive neuromuscular adaptations through increases in maximal neuromuscular excitation [29] and enhancements in muscle stiffness indicators [23]. In contrast, it has been shown that high VL thresholds evoke impairments in early rate of force development (RFD) and slower muscle responses to electrical stimulation [23]. These adaptations, along with the aforementioned reduction in the IIX fiber pool, may hamper improvements in high-velocity actions, which are characterized by short periods in which to apply force. Thus, to guarantee the maximum effort in each repetition and to avoid an unintentional decline in high-velocity repetitions, moderate VL thresholds ($< 30\%$) should be established as the upper limit to maximize the benefits of RT on the high-velocity actions required in many sports disciplines.

4.3 Effects of Intra-Set Velocity Loss on Muscle Hypertrophy

Changes in lower-limb muscle size yielded by different VL thresholds were assessed in only two studies [22,23], showing an overall positive, albeit small, effect derived from RT in young adults. Despite the lack of significant within-group changes in muscle hypertrophy, likely due to the limited number of studies (small sample size) found in the literature and the relatively short duration of the RT interventions (8 weeks), there was a small increase in lower limb muscle size for both moderate (SMD = 0.40) and high (SMD = 0.44) VL thresholds. In contrast, low VL thresholds ($< 15\%$) resulted

in trivial and non-significant changes in lower-limb muscle hypertrophy (SMD = 0.14). Pareja-Blanco et al. [22] used magnetic resonance imaging and noted a 4.6% increase in quadriceps femoris muscle volume after 8 weeks of RT using a 20% VL, while the increase reached 7.7% in participants using a 40% VL. Notably, these adaptations were accompanied by 8.6% and 10.2% increases, respectively, in single muscle fiber CSA obtained from the participants' vastus lateralis muscle [22]. On the other hand, Pareja-Blanco et al. [23], recorded 7.0% and 5.3% increases in ultrasound-based vastus lateralis cross-sectional area (CSA) after 8 weeks of RT using 20% and 40% of VL, respectively, while no significant changes were reported for 0% and 10% VL thresholds. Likewise, another study analyzing effects of different VL thresholds in an upper-limb exercise (bench-press) also found greater pectoralis major hypertrophy following RT with moderate and high VL thresholds (25-50%) [51]. Of note, RT volume was 60-80% greater when using high VL thresholds compared to moderate VL thresholds, while it was up to 6-fold greater when comparing high vs. low VL thresholds [22,23,51]. In this regard, the interaction of high RT volumes and the fatiguing and slow repetitions associated with high VL thresholds may explain the greater hypertrophic effects observed for higher magnitudes of VL. Likewise, RT protocols that use greater VL thresholds induce greater mechanical and metabolic stress [12]. This leads to greater muscle damage, metabolite accumulation, and release of muscle growth-promoting hormones [6,52,53], which may be mediating factors in the greater hypertrophic adaptations observed with these protocols [54,55]. In this sense, low VL thresholds (i.e., < 15%) may be insufficient to produce adequate stimuli for skeletal muscle hypertrophy. In addition, higher RT volumes promote increased ribosomal biogenesis, responsible for protein synthesis and muscle hypertrophy [56]. However, although muscle hypertrophy has been reported to be similar between moderate and high VL thresholds [23], or even greater after high VL thresholds [22], in the present meta-analysis muscle function adaptations were slightly superior under moderate and low VL thresholds when compared to high VL thresholds. The dissociation between changes in muscle size and muscle function may be related to the molecular events occurring after each RT protocol. High VL thresholds also result in increased skeletal muscle protein expression of total and phosphorylated CaMKII, a predominantly sarcoplasmic protein [32]. In contrast, moderate but not high VL thresholds led to greater elevations in IGF-1 levels [57], which play a major role in the synthesis of important muscle-specific contractile proteins [58]. These findings are compatible with the hypothesis that moderate VL thresholds favor a greater contractile protein addition, while a larger sarcoplasmic expansion would occur after high VL thresholds, allowing higher RT volumes [59]. Further studies are necessary to assess the actual mechanisms involved in the differential adaptations observed among VL thresholds in muscle hypertrophy.

**** Fig. 10 here****

5 Limitations and Considerations

To our knowledge, this is the first systematic review using meta-analysis to examine the effects of different intra-set VL thresholds on neuromuscular adaptations. While our findings provide new insights into how the within-set level of effort modulates the dose-response relationship between the training stimulus and chronic effects, some limitations must be considered. One limitation is that of eleven studies included in this systematic review, nine recruited physically active participants ($n = 282$) and only two studies included athletes ($n = 27$). Additionally, no study recruited exclusively female participants. Secondly, our findings are specific to lower-body resistance exercise (i.e. back-squat). Previous studies have suggested that training-induced changes in upper and lower limbs may differ due to the possible higher trainability of upper-limb muscles, since lower-limb muscles are more habitually activated and loaded to a higher level in daily living activities (i.e. anti-gravity) [60,61]. However, it is still unclear whether similar VL-derived results will be found for upper-limb muscles. Future studies on this topic are warranted. Third, the limited number of studies that evaluated muscle hypertrophy as an outcome led to a small number of participants being included in the meta-analyses. Finally, it was not possible to identify information about the details of randomization and allocation sequence; therefore, most of the studies were classified to be at unclear risk of selection bias.

Despite these limitations, the present study has key strengths that should be highlighted. This systematic review and meta-analysis is an original contribution to the literature, providing evidence of what seems to be an optimal dose of RT for the lower limbs, capable of modulating the magnitude of each strength and sports-related parameter gain in physically young adults. The optimal dose of stimulus ranges from low ($<15\%$) to moderate ($15\text{-}30\%$) VL thresholds depending on the type of adaptation targeted. However, moderate ($15\text{-}30\%$) to high ($\geq 30\%$) VL thresholds are likely required to induce muscle hypertrophy, at least within ~ 8 weeks of training.

Another factor that highlights the strength of the evidence provided here is the small to moderate levels of heterogeneity found in data analyses, suggesting that the results observed are consistent. The low heterogeneity observed for most outcomes can be explained by the similarity of the standardization procedures for evaluation and the characteristics of the intervention programs of the included studies (Table 1). The variability across studies concerning sample characteristics, training experience of participants, program duration, exercise, number of sets, intensity, inter-set recovery, and method of controlling the level of effort could impact the heterogeneity of results.

Future studies with athletes with different neuromuscular demands (e.g., endurance, intermittent, maximum strength) and female participants (athletes and non-athletes) are warranted to assess the dose-response of distinct VL and chronic adaptations. Additional studies analyzing the effects of distinct intra-set VL on muscle hypertrophy are also desirable to confirm our findings. Finally, testing the effects of controlling the level of effort through the VL threshold in programs with multiple exercises, different RT configurations (cluster, contrast, and complex), and in combination with other types of training (e.g., concurrent training) would also be of considerable interest. More research in ecologically valid contexts is needed, due to the large practical implications.

6 Conclusions

High VL thresholds do not elicit additional benefits in terms of muscle strength compared to low and moderate VL thresholds and could even result in lower strength gains, especially in high-velocity actions (e.g., efforts against light loads, jump performance, and sprint ability). By contrast, moderate and high VL thresholds maximize muscle hypertrophy. Accordingly, once a certain degree of fatigue within the set is attained, performing more repetitions does not elicit further strength gains and may even induce “suboptimal adaptations” in sports-related performance, although they may result in greater muscle hypertrophy. For this reason, the monitoring of intra-set VL should be implemented as a practical tool to guiding the decision-making process for strength and conditioning coaches and practitioners, in order to design and manage the optimal level of effort during RT.

7 Practical applications

Chronic adaptations to RT seem to be dependent on the VL incurred within the training set. Low and moderate VL thresholds (< 30%) should be used to optimize neuromuscular adaptations, since high VL thresholds ($\geq 30\%$) do not produce further strength gains and may even be detrimental for improving performance in sport-related actions. Therefore, low and moderate VL thresholds are of great practical relevance for strength and conditioning professionals aiming to find optimal and more efficient RT stimuli (i.e., more time-efficient and less fatiguing). Conversely, setting moderate to high intra-set VL (i.e., more volume in the set) may provide greater stimulation of hypertrophic gains compared with low VL. Therefore, a VL threshold should be chosen beforehand, depending on the specific training goal being pursued. The dose-response relationship between the VL incurred within the set and exercise-induced adaptations shows an inverted U-shaped curve (Fig. 11). This relationship is parameter-specific and indicates that a progressive increase in the VL achieved within

the set will be accompanied by an increase in exercise-induced adaptations up to a certain limit, beyond which an increase will not produce additional benefits and may even dampen gains in sports-related performance.

Setting a certain percentage of VL as a criterion to stop the exercise sets can also provide an objective tool for managing fatigue levels and the time course of recovery during RT programs. This is especially important for those strength and conditioning coaches working with athletes who often train and compete under congested fixture schedules, and those practitioners who have time constraints or aim to increase the training frequency for the same muscle group. Strength and conditioning coaches can design RT sessions with low to moderate VL thresholds to optimize the duration of training sessions, minimize fatigue (i.e., mechanical and physiological stress), and speed up recovery following RT sessions, as demonstrated in previous studies [6,25].

**** Fig. 11 here ****

Fig. 1. PRISMA flowchart for the description of the overall process

Table 1. Summary of the studies included in the review.

Study	Sample	Age (years)	RT Experience (years)	Training Program									Velocity Parameters	Outcomes
				Weeks	Total Sessions	Exercise	Sets	VL (%)	Reps per set	Total Reps	Intensity (% 1RM)	Inter-set Recovery		
Pareja-Blanco et al. [22]	22 young men	22.7 ± 1.9	1.5-4	8	16	Full-squat	3	20%	~4	~186	70-85%	4 min	LVT (MPV)	1RM, CMJ, T20, MPV (light and heavy loads), muscle hypertrophy
								40%	~7	~310				
Pareja-Blanco et al. [28]	16 male soccer athletes	23.8 ± 3.5	Yes	6	18	Full-squat	2-3	15%	~6	~251	50-70%	4 min	LVT (MPV)	1RM, CMJ, T30
								30%	~10	~414				
Galiano et al. [24]	28 physically active men	~23.0	1.5	7	14	Full-squat	3	5%	~4	~156	50%	3 min	LVT (MPV)	1RM, CMJ, T20, MPV (light and heavy loads)
								20%	~11	~480				
Rodríguez-Rosell et al. [29]	25 healthy men	~22.0	1-3	8	16	Full-squat	3	10%	~2	~109	70-85%	4 min	LVT (MPV)	1RM, CMJ, T10, T20, MPV (light and heavy loads), MNR
								30%	~5	~228				
Pareja-Blanco et al. [23]	55 physically active men	24.1 ± 4.3	1.5-4	8	16	Full-squat	3	0%	1	~48	70-85%	4 min	LVT (MPV)	1RM, CMJ, T10, T20, MPV (light and heavy loads), MNR, muscle hypertrophy
								10%	~3	~143				
								20%	~4	~168				
								40%	~6	~305				
Martinez-Canton et al. [32]	22 young men	22.7 ± 1.9	1.5-4	8	16	Full-squat	3	20%	~4	~186	70-85%	4 min	LVT (MPV)	MNR
								40%	~7	~310				
Sánchez-Moreno et al. [46]	22 young men	25.2 ± 4.9	2-5	8	16	Full-squat	3	15%	~4	~177	60-70%	3 min	LVT (MPV)	1RM, CMJ, T10, T20, MPV (light and heavy loads)
								45%	~9	~401				
Rodríguez-Rosell et al. [47]	32 healthy men	~23.0	1-3	8	16	Full-squat	3	15%	~5	~221	50-80%	4 min	LVT (MPV)	1RM, CMJ, MPV (light and heavy loads), MNR
								15%	~5	~223				
Held et al. [31]	11 male and female rowing athletes	19.8 ± 2.3	> 2	8	16	Squat and Deadlift	4	10%	~7	-	80%	2-3 min	LPT (MPV)	1RM
Riscart-López et al. [16]	43 strength-trained men	18–33	1.5-4	8	16	Full-squat	3	20%	~7	~320	50-85%	4 min	LVT (MPV)	1RM, CMJ, T20, MPV (light and heavy loads)
								20%	~5	~263				
								20%	~7	~315				
								20%	~5	~231				
Rodríguez-Rosell et al. [45]	33 healthy men	~22	1-3	8	16	Full-squat	3	10%	~4	~180	55-70%	4 min	LVT (MPV)	1RM, CMJ, T10, T20, MPV (light and heavy loads), MNR
								30%	~7	~347				
								45%	~10	~501				

VL= velocity loss; RT = resistance training; Reps = repetitions; 1RM = one-repetition maximum; LVT = linear velocity transducer; LPT = linear positional transducer; MPV = mean propulsive velocity; T10 = 10-m sprint time; T20 = 20-m sprint time; T30 = 30-m sprint time; MNR = maximum number of repetitions.

	Random Sequence Bias	Allocation Concealment Bias	Blinding of Outcome Assessment	Incomplete Data	Selective Reporting	Effort Bias	Familiarization Bias
Galiano et al. [24]	?	?	?	+	+	+	-
Held et al. [31]	?	?	?	+	+	+	+
Martinez-Canton et al. [32]	?	?	?	+	+	+	+
Pareja-Blanco et al. [22]	?	?	?	+	+	+	+
Pareja-Blanco et al. [23]	?	?	+	+	+	+	+
Pareja-Blanco et al. [28]	?	?	?	+	+	+	+
Riscart-López et al. [16]	?	?	?	+	+	+	+
Rodríguez-Rosell et al. [29]	+	?	?	+	+	+	-
Rodríguez-Rosell et al. [45]	?	?	?	+	+	+	-
Rodríguez-Rosell et al. [47]	+	?	?	+	+	+	+
Sanchez-Moreno et al. [46]	+	?	?	+	+	-	-

Fig. 2 Risk of bias assessment for all included studies. + low risk of bias; - high risk of bias; ? unclear risk of bias.

Fig. 3. Training effects of different intra-set velocity loss thresholds on 1RM strength gains. Subgroup analysis based on the magnitude of the intra-set velocity loss (VL). Low VL = < 15%; moderate VL = $\geq 15\%$ and < 30%; and high VL = $\geq 30\%$. Squares represent the Std. mean difference for each study. Diamonds represent the pooled Std. mean difference across studies. CI = confidence interval (95%); SD = standard deviation. Std. = standard.

Fig. 4. Training effects of different intra-set velocity loss thresholds on velocity against light loads. Within-groups analysis based on the magnitude of the intra-set velocity loss (VL). Low VL = $< 15\%$; moderate VL = $\geq 15\%$ and $< 30\%$; and high VL = $\geq 30\%$. SD = standard deviation. Std. = standardized; Squares represent the Std. mean difference for each study. Diamonds represent the pooled Std. mean difference across studies. CI = confidence interval (95%).

Fig. 5. Training effects of different intra-set velocity loss thresholds on velocity against heavy loads. Within-groups analysis based on the magnitude of the intra-set velocity loss (VL). Low VL = $< 15\%$; moderate VL = $\geq 15\%$ and $< 30\%$; and high VL = $\geq 30\%$. SD = standard deviation. Std. = standardized; Squares represent the Std. mean difference for each study. Diamonds represent the pooled Std. mean difference across studies. CI = confidence interval (95%).

Fig. 6. Training effects of different intra-set velocity loss thresholds on maximum number of repetitions (MNR). Within-groups analysis based on the magnitude of the intra-set velocity loss (VL). Low VL = $< 15\%$; moderate VL = $\geq 15\%$ and $< 30\%$; and high VL = $\geq 30\%$. SD = standard deviation. Std. = standardized; Squares represent the Std. mean difference for each study. Diamonds represent the pooled Std. mean difference across studies. CI = confidence interval (95%).

Fig. 7. Training effects of different intra-set velocity loss thresholds on countermovement jump (CMJ) height. Within-groups analysis based on the magnitude of the intra-set velocity loss (VL). Low VL = $< 15\%$; moderate VL = $\geq 15\%$ and $< 30\%$; and high VL = $\geq 30\%$. SD = standard deviation. Std. = standardized; Squares represent the Std. mean difference for each study. Diamonds represent the pooled Std. mean difference across studies. CI = confidence interval (95%).

Fig. 8. Training effects of different intra-set velocity loss thresholds on running sprint time. Within-groups analysis based on the magnitude of the intra-set velocity loss (VL). Low VL = < 15%; moderate VL = $\geq 15\%$ and < 30%; and high VL = $\geq 30\%$. SD = standard deviation. Std. = standardized; Squares represent the Std. mean difference for each study. Diamonds represent the pooled Std. mean difference across studies. CI = confidence interval (95%).

Fig. 9. Training effects of different intra-set velocity loss thresholds on muscle hypertrophy. Within-groups analysis based on the magnitude of the intra-set velocity loss (VL). Low VL = < 15%; moderate VL = ≥ 15% and < 30%; and high VL = ≥ 30%. SD = standard deviation. Std. = standardized; Squares represent the Std. mean difference for each study. Diamonds represent the pooled Std. mean difference across studies. CI = confidence interval (95%).

Fig. 10. Summary of the chronic adaptations to resistance training (back-squat exercise) using different intra-set velocity loss thresholds. Each length of the bar is expressed as the magnitude of standardized mean differences (SMD) across studies; S = small SMD; M = moderate SMD; and L = large SMD; The bar colors represent the magnitude of intra-set velocity loss (VL); green = low VL (< 15%); yellow = moderate VL ($\geq 15\%$ and $< 30\%$); and red = high VL ($\geq 30\%$).

Fig. 11. Relationship between distinct intra-set velocity loss thresholds and standardized mean difference (Std. Mean Difference) obtained in muscular strength (1RM), velocity outputs against submaximal loads (light and heavy loads), muscular endurance, countermovement jump height, sprint time, and muscle hypertrophy.

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