THE EFFICACY OF INDIVIDUALIZED LAST REPETITION VELOCITIES FOR
AUTOREGULATING AND MONITORING IN RESISTANCE TRAINING

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ABSTRACT

Traditional resistance training (RT) methods often involve a fixed prescription based on a pre-determined percentage of one-repetition maximum (1RM); however, a plethora of variables may impact an individual’s performance on a micro- and macro-level: fitness, fatigue, readiness, amongst several others. Autoregulated resistance training has developed as a potential framework to rectify traditional methods by systematically measuring and adjusting the programming prescription on a short-, medium-, and long-term monitoring basis according to an individual’s performance and context-specific goals. Although initial findings have provided some evidence to support the efficacy of autoregulation on muscular adaptations in college-aged resistance-trained males, the available evidence is unclear whether autoregulation indeed provides a greater advantage over traditional methods for additional neuromuscular adaptations, performance outcomes, and functional measures in varying populations and females. Therefore, the primary purpose of this PhD thesis/dissertation was four-fold. The initial purpose was to systematically review and meta-analyze the existing evidence on the effect of load and volume autoregulation on muscular strength and hypertrophy adaptations. Autoregulated compared to traditional load prescription resulted in significantly greater increases in 1RM strength. Autoregulating volume with lower and higher magnitudes of intra-set fatigue were most effective for improving 1RM strength and hypertrophy; respectively. The second purpose was to conceptualize a theoretical velocity-based training model based on the advantages and limitations of the current traditional and autoregulation methods: the Individualized Last Repetition Velocity Model (LRV Model), which is described in a narrative review. The third purpose was to compare the accuracy of subjective estimations to objective velocities (an iteration of the LRV Model) at quantifying proximity to failure for the bench press in resistance trained males and females across numerous parameters, in which objective velocities displayed significantly greater accuracy. The final purpose was to compare the efficacy of traditional methods, subjective autoregulation, and objective autoregulation (the LRV Model iteration) for load prescription on neuromuscular adaptations, performance outcomes, and functional measures in older adult males and females. Objective autoregulation elicited the best improvements in bench press strength and knee extensor hypertrophy. This thesis provides novelty regarding the efficacy of individualized average concentric last repetition velocities for autoregulating and monitoring.
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LIST OF ABBREVIATIONS

ACV: Average concentric velocity
CI: Confidence interval
CSA: Cross-sectional area
ES: Effect size
FRV: Individualized first repetition average concentric velocity
LRV: Individualized last repetition average concentric velocity
MD: Mean difference
m s⁻¹: Metres per second
PBT: Percentage-based training
PICOS: Participants, interventions, comparisons, outcomes, and study design
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PROSPERO: International Prospective Register of Systematic Reviews
RBT: Rating of perceived exertion based training
RIR: Repetitions in reserve
RIR-based RPE scale: Repetitions in reserve-based rating of perceived exertion scale
RoB 2: Revised Cochrane risk-of-bias tool for randomized trials
RPE: Rating of perceived exertion
RT: Resistance training
SD: Standard deviation
SMD: Standardized mean difference
VBT: Velocity-based training
1RM: One-repetition maximum
4RM: Four-repetition maximum
1. INTRODUCTION

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1.1 Introduction

Resistance training (RT) is the principle modality to increase strength and hypertrophy for improving athletic performance and clinical health [1]. Traditionally, RT has been prescribed based on a pre-determined percentage of one-repetition maximum (1RM), which has been referred to in the scientific literature as standardized percentage-based training (PBT) [2]. There are, however, numerous limitations evident with PBT, the primary being that daily fluctuations [3] and short-term changes [4] in 1RM have been consistently observed [5]; therefore, PBT does not match the acute performance fluctuations and chronic physiological adaptations of each individual [6]. PBT also involves prescribing load based on a single 1RM testing session; thus, if abnormal performance or improper administration were present, the training stimulus applied for the study intervention or successive training cycle may be inappropriate for the intended outcome and may impact other variables (i.e., fatigue, load, volume) in the prescription [5]. Finally, repetitions performed at given intensities are largely lift-specific [7] and highly variable between individuals [8]; therefore, PBT fails to accurately quantify proximity to failure and the degree of neuromuscular fatigue for each individual and lift.

As an alternative approach to PBT, autoregulated RT has gained considerable popularity in recent years due to its theoretical ability to account for an individual’s changes in physiological adaptations and performance parameters [6]. Autoregulation may be defined as a two-step process of measurement and adjustment based on an individual’s acute and chronic fluctuations in performance (i.e., strength), in which performance is comprised of the sum of training (fitness and fatigue) and non-training (readiness) related factors [6]. The two predominant autoregulatory methods involve the systematic manipulation of load and volume via subjective and/or objective
strategies [9]. Specifically, subjective load autoregulation involves implementing the repetitions in reserve-based rating of perceived exertion scale (RIR-based RPE scale) in attempt to quantify proximity to failure, which is commonly referred to as RPE-based training [10]. For example, a resistance trainee may be prescribed 5 sets of 3 repetitions at an 8 RPE (2 RIR), instead of at a certain percentage of 1RM. However, due to the inaccuracy in intra-set RPE ratings [11], objective velocity-based training (VBT) [12] has emerged as a novel load autoregulatory strategy to rectify the limitations of subjective RPE-based training [13] and standardized PBT [14], which involves implementing a linear position transducer velocity encoding device. VBT load autoregulation involves either prescribing an average concentric velocity (ACV) zone corresponding to the force-velocity continuum [15, 16] or an individualized first repetition average concentric velocity (FRV) corresponding to a specific percentage of 1RM via an individualized load-velocity profile [17-19], which is based on the strong inverse relationships between velocity and load [12], in addition to velocity and proximity to failure [13]. For example, rather than prescribe the load associated with 80% of a pre-determined 1RM, the load associated with an FRV corresponding to 80% of 1RM may be prescribed, such that the absolute load matches an individual’s real-time performance. In a hypothetical scenario, an individual may have an FRV of 0.40 m·s⁻¹ corresponding to 80% of 1RM; thus, an individual would utilize the load eliciting an FRV of 0.40 m·s⁻¹ during that particular training session. Despite the theoretical basis for autoregulated load prescription, the available evidence is conflicting whether it indeed provides an advantage over standardized load prescription for chronic muscular strength and hypertrophy adaptations. Although some studies have demonstrated that autoregulated load prescription may be superior to standardized load prescription for 1RM strength adaptations [15, 20] by enabling load to match the adaptation of the individual throughout a training study (i.e., enable higher relative intensities to be achieved) others have revealed no significant differences [19, 21-23].

Similar to subjective load autoregulation, subjective volume autoregulation involves implementing the RPE stop strategy, in which a particular number of sets are prescribed and each set is terminated at a pre-determined subjective RPE [24]. To date, no study has investigated the chronic effects of the RPE stop strategy on muscular strength and hypertrophy. Rather, objective velocity loss has emerged as the predominant strategy of volume autoregulation due to its inherent ability to accurately quantify acute intra-set neuromuscular fatigue [25].
neuromuscular fatigue (i.e., lower velocity loss thresholds) may be superior for optimizing neuromuscular adaptations such as power output and shifts towards velocity-oriented force-velocity profiles; whereas higher intra-set neuromuscular fatigue (i.e., higher velocity loss thresholds) may be superior for optimizing muscular endurance [26]. The available evidence remains unclear which velocity loss thresholds optimize chronic strength and hypertrophy adaptations [27-36].

Proximity to failure and neuromuscular fatigue is of paramount importance when considering the design of RT programs [37]. Although training to failure has traditionally been promoted for overload [38, 39], this practice elevates muscle damage and elongates recovery time considerably compared to not training to failure [40]. Importantly, two recent systematic reviews and meta-analyses demonstrated no difference in hypertrophy between training to failure compared to not training to failure when volume was equalized [41, 42]. Similarly, two separate systematic reviews and meta-analyses also demonstrated no difference in hypertrophy between traditional sets compared to alternative set structures (i.e., performing the same total number of repetitions in a session as traditional sets but with more frequent rest periods and fewer repetitions per set) when relative intensity and relative volume were equated, which further demonstrates that considerable magnitudes of intra-set fatigue are unnecessary to promote hypertrophy [26, 37]. Despite this, all four systematic reviews and meta-analyses demonstrated no difference in strength adaptations between comparisons [26, 37, 41, 42]; however, appropriately managing the dynamic inter-play amidst proximity to failure and neuromuscular fatigue by integrating load and volume autoregulation strategies may have important practical implications [6, 43]. To illustrate, when sets and repetitions per set are matched, autoregulating set-to-set load to match the individual’s performance by training at closer proximities to failure (i.e., at higher relative intensities) results in significantly greater 1RM strength adaptations [20]. Alternatively, when sets and percentage of 1RM are matched, autoregulating intra-set volume with velocity loss thresholds (i.e., reducing neuromuscular fatigue) also results in significantly greater 1RM strength adaptations [28]. When equated for intra-set fatigue, the time course of recovery is similar regardless of the proximity to failure and relative intensity; however, when proximity to failure is equated, training with greater intra-set fatigue results in greater elevations in indirect measures of muscle damage compared to lower intra-set fatigue [44]. Crucially, excessive acute muscle damage attenuates high-threshold motor unit recruitment and motor skill
learning; thus, impairing overall performance, training quality, and skill practice [45]. Chronic neuromuscular fatigue may reduce training frequency, an imperative variable implemented to increase volume and enhance hypertrophy to augment strength adaptations [46]. Overall, the potential practical implications but unclear efficacy of load and volume autoregulation justify the requirement to collate the existing literature and provide a comprehensive synthesis of the evidence.

Despite the aforementioned importance of autoregulating proximity to failure and neuromuscular fatigue, to date, the most common methods are subjective predictions and velocity loss; respectively. Nonetheless, both current methods contain limitations as addressed throughout the review of literature (Chapter 2); therefore, the theoretical advantages of autoregulation may potentially be further enhanced. A potential solution may be to establish the objective individualized average concentric velocity corresponding to a particular number of repetitions in reserve; however, to date, no study has directly compared the accuracy of individualized average concentric velocity to subjective predictions at quantifying proximity to failure. Moreover, to date, no study has compared the efficacy of load autoregulation with a theoretical velocity-based training model (integrating individualized average concentric velocity with proximity to failure) to the repetitions in reserve-based rating of perceived exertion scale (integrating subjective predictions with proximity to failure) on chronic adaptations and performance outcomes.

Therefore, the first objective of this thesis is to systematically review and meta-analyze the available evidence of the effects of autoregulation on muscular strength and hypertrophy adaptations. It is hypothesized that autoregulated load prescription will be superior compared to traditional load prescription for increasing 1RM strength, with no meaningful differences in muscle cross-sectional area (CSA) hypertrophy. It is also hypothesized that autoregulated volume prescription will result in significantly greater 1RM strength and CSA hypertrophy for low-moderate and moderate-high intra-set fatigue; respectively. The second objective is to identify the advantages and limitations of the present autoregulation methods and to conceptualize a potentially improved model based on the results of the systematic review and meta-analysis. The third objective is to acutely test the efficacy of the proposed model compared to subjective predictions at quantifying proximity to failure across numerous parameters (i.e., multiple sessions, sets, loads, etc.). It is hypothesized that the proposed model will be more accurate than the subjective predictions at quantifying proximity to failure in all parameters that will be
investigated. The final objective is to compare load prescription with the proposed velocity-based training model, subjective autoregulation, and traditional percentage-based training on physiological adaptations and performance outcomes in a population that has yet to be investigated (i.e., older adult males and females). It is hypothesized that the proposed model will result in significantly greater physiological adaptations and performance outcomes than subjective autoregulation and traditional percentage-based training.

1.2 References


2. THE EFFECT OF LOAD AND VOLUME AUTOREGULATION ON MUSCULAR STRENGTH AND HYPERTROPHY: A SYSTEMATIC REVIEW AND META-ANALYSIS

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Abstract

Background

Autoregulation has emerged as a potentially beneficial resistance training paradigm to individualize and optimize programming; however, compared to standardized prescription, the effects of autoregulated load and volume prescription on muscular strength and hypertrophy adaptations are unclear. Our objective was to compare the effect of autoregulated load prescription (repetitions in reserve-based rating of perceived exertion and velocity-based training) to standardized load prescription (percentage-based training) on chronic one-repetition maximum (1RM) strength and cross-sectional area (CSA) hypertrophy adaptations in resistance-trained individuals. We also aimed to investigate the effect of volume autoregulation with velocity loss thresholds ≤25% compared to >25% on 1RM strength and CSA hypertrophy.

Methods

This review was performed in accordance with the PRISMA guidelines. A systematic search of MEDLINE, Embase, Scopus, and SPORTDiscus was conducted. Mean differences (MD), 95% confidence intervals (CI), and standardized mean differences (SMD) were calculated. Sub-analyses were performed as applicable.

Results

Fifteen studies were included in the meta-analysis: six studies on load autoregulation and nine studies on volume autoregulation. No significant differences between autoregulated and
standardized load prescription were demonstrated for 1RM strength (MD = 2.07, 95% CI – 0.32 to 4.46 kg, p = 0.09, SMD = 0.21). Velocity loss thresholds ≤25% demonstrated significantly greater 1RM strength (MD = 2.32, 95% CI 0.33 to 4.31 kg, p = 0.02, SMD = 0.23) and significantly lower CSA hypertrophy (MD = 0.61, 95% CI 0.05 to 1.16 cm², p = 0.03, SMD = 0.28) than velocity loss thresholds >25%. No significant differences between velocity loss thresholds >25% and 20 – 25% were demonstrated for hypertrophy (MD = 0.36, 95% CI – 0.29 to 1.00 cm², p = 0.28, SMD = 0.13); however, velocity loss thresholds >25% demonstrated significantly greater hypertrophy compared to thresholds ≤20% (MD = 0.64, 95% CI 0.07 to 1.20 cm², p = 0.03, SMD = 0.34).

**Conclusions**
Collectively, autoregulated and standardized load prescription produced similar improvements in strength. When sets and relative intensity were equated, velocity loss thresholds ≤25% were superior for promoting strength possibly by minimizing acute neuromuscular fatigue whilst maximizing chronic neuromuscular adaptations, whereas velocity loss thresholds >20 – 25% were superior for promoting hypertrophy by accumulating greater relative volume.

**2.1 Objectives**
The primary purpose of this review was to determine the chronic effects of load and volume autoregulation on 1RM strength adaptations, with cross-sectional area (CSA) muscle hypertrophy as a secondary outcome. Specifically, systematic and meta-analytic approaches were conducted to investigate the chronic effects of autoregulated compared to standardized load prescription and to investigate the chronic effects of autoregulated volume prescription via velocity loss thresholds ≤25% compared to velocity loss thresholds >25%. It was hypothesized that autoregulated load prescription would result in significantly greater strength adaptations than standardized load prescription; however, no differences in hypertrophy would be observed. It was also hypothesized that velocity loss thresholds ≤25% would result in significantly greater strength adaptations, whereas velocity loss thresholds >25% would result in significantly greater hypertrophy. Moreover, a quality assessment of the studies and limitations of the present autoregulatory methods were identified to suggest avenues for future research. The goal is that this review will provide comprehensive evidence regarding the efficacy of load and volume autoregulation for 1RM strength and CSA hypertrophy adaptations. Ultimately, the
Dissemination of this information may assist exercise professionals in the systematic individualization of resistance training programming.

2.2 Methods

2.2.1 Research Question

A systematic review and meta-analysis were performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [47]. The original protocol was prospectively registered with the International Prospective Register of Systematic Reviews (PROSPERO) on April 8, 2021 (Registration number: CRD42021240506). A study intervention length of ≥5 weeks was selected because this corresponds to the approximate minimal amount of time required to observe significant hypertrophy with resistance training [48]. For volume autoregulation, a velocity loss threshold of ≤25% to >25% was compared as ~20 – 30% velocity loss corresponds to ~50% of the maximal number of repetitions within a set [25] and ~25% velocity loss has typically been suggested to optimize 1RM strength adaptations [25, 30-32, 36]. The research question was defined using the participants, interventions, comparisons, outcomes, and study design (PICOS) framework:

1. Participants: Apparently healthy individuals with RT experience and no injury nor health condition.

2. Interventions: RT interventions (≥5 weeks) that employed an autoregulated load prescription or volume autoregulation (≤25% velocity loss) protocol.

3. Comparator: RT interventions (≥5 weeks) that employed a standardized load prescription or volume autoregulation (>25% velocity loss) protocol.

4. Outcomes: Muscular strength and/or muscular hypertrophy.

5. Study design: Prospective randomized or non-randomized comparative studies.

2.2.2 Literature Search Strategy

A systematic search of the electronic databases MEDLINE, Embase, Scopus, and SPORTDiscus was performed to identify original research articles up to and including May 25, 2021. The searches had no language nor date restrictions. The search strategy involved the following Boolean phrase of combined MeSH terms and keywords; ‘autoregulation’ OR ‘auto-regulation’ OR ‘load autoregulation’ OR ‘volume autoregulation’ OR ‘load prescription’ OR ‘volume prescription’ OR ‘rating of perceived exertion’ OR ‘repetitions in reserve’ OR ‘velocity-based training’ OR ‘velocity based training’ OR ‘velocity loss’ OR ‘absolute velocity’
OR ‘load-velocity profile’ OR ‘load velocity profile’ AND ‘powerlifting’ OR ‘power-lifting’ OR ‘power lifting’ OR ‘weightlifting’ OR ‘weight-lifting’ OR ‘weight lifting’ OR ‘weight-training’ OR ‘weight training’ OR ‘resistance-training’ OR ‘resistance training’ OR ‘resistance-exercise’ OR ‘resistance exercise’ OR ‘strength-training’ OR ‘strength training’ AND ‘one-repetition maximum’ OR ‘one repetition maximum’ OR ‘strength’ OR ‘musc* strength’ OR ‘hypertrophy’ OR ‘musc* hypertrophy’ OR ‘musc* size’ OR ‘musc* thickness’ OR ‘musc* cross-sectional area’.

2.2.3 Study Selection

The Covidence systematic review software (Veritas Health Innovations, Melbourne, Australia) was used to screen titles and abstracts for full-text inclusion. Articles were deduplicated by Covidence and manually screened independently by LMH and KAS. Disagreements were resolved by consensus.

2.2.4 Inclusion Criteria

The inclusion criteria for this review consisted of: (1) randomized or non-randomized comparative studies; (2) training intervention group that employed load or volume autoregulation; (3) strength and/or hypertrophy assessment pre- and post-intervention; (4) apparently healthy individuals with resistance training experience and no injury nor health condition; (5) ≥5 week resistance training intervention; (6) ≥2 times per week training frequency; (7) detailed description of training intervention including training intensity and training volume; (8) a validated device to measure and monitor velocity (for studies incorporating VBT). All grey literature (i.e., conferences, theses, reports, etc.) were excluded from the review.

2.2.5 Data Extraction

The full texts of all articles that met the inclusion criteria for review were obtained for data extraction. The pre- and post-intervention data were extracted as mean differences (MD) ± standard deviations (SD). LMH extracted the relevant data of interest: (1) study information (study author and publication year); (2) participant characteristics (sample size, sex, age, height, weight, and training status); (3) training characteristics (prescription description, intervention length, training frequency, sets difference, repetitions difference, training volume, and training intensity). The authors of the selected articles were contacted to request any missing relevant information.
2.2.6 Risk of Bias Assessment

The evaluation of risk of bias was performed using the Revised Cochrane risk-of-bias tool for randomized trials (RoB 2). LMH and KAS performed the methodological quality assessment independently. Disagreements were resolved by consensus.

2.2.7 Statistical Analysis

All statistical analyses were conducted using RevMan (Version 5.3, Copenhagen, The Nordic Cochrane Centre, The Cochrane Collaboration). A fixed effects model was implemented to analyze the data. The data are reported as MD and 95% confidence intervals (CI). Standardized mean differences (SMD) were also determined to estimate effect sizes. An SMD of 0.20 – 0.49, 0.50 – 0.79, and ≥0.80 was considered a small, medium, and large effect, respectively. For load autoregulation with respect to 1RM strength outcomes, a positive and negative MD favored autoregulated and standardized load prescription, respectively. For volume autoregulation with respect to 1RM strength outcomes, a positive and negative MD favored velocity loss thresholds ≤25% and >25%, respectively. For volume autoregulation with respect to CSA hypertrophy outcomes, a positive and negative MD favored velocity loss thresholds >25% and ≤25%, respectively. Sub-analyses (i.e., intervention length, training frequency, etc.) and sub-group analyses (i.e., additional vs no additional exercise, etc.) were also performed. Results were considered statistically significant at p ≤ 0.05. The $I^2$ and Chi² statistics were used to assess heterogeneity. Funnel plots were used to assess publication bias.

2.3 Results

2.3.1 Study Selection

The PRISMA flow diagram outlining the literature search strategy is illustrated in Figure 2.1. A total of 1336 studies were identified in the search, 18 of which were included in the systematic review: eight studies on load autoregulation and 10 studies on volume autoregulation. Of those 18 studies, 15 studies were included in the meta-analysis: six studies on load autoregulation and nine studies on volume autoregulation. Specifically, two studies on load autoregulation included in the systematic review were excluded from the meta-analysis; one study compared subjective load autoregulation via RPE-based training to objective load autoregulation via ACV zones [16], whilst the other study compared objective load autoregulation via group load-velocity profiles to objective load autoregulation via individualized load-velocity profiles [18]. One study on volume autoregulation included in the
systematic review was excluded from the meta-analysis as the velocity loss threshold in the two groups compared were both below 25% velocity loss (5% and 20% velocity loss) [27]. The authors of four studies were contacted to obtain relevant data of interest required to conduct the meta-analysis that was not presented in the published manuscripts. The author of two studies was contacted to obtain the pre- and post-test mean and SD for CSA of the vastus lateralis [31] and pectoralis major [32]. One author was contacted to verify the velocity loss threshold of the training to-repetition-failure group [28]. A final author was contacted to clarify the post-test mean and SD of the bench press in the PBT group [21]. All authors responded and supplied the relevant data.
Figure 2.1 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram of literature search strategy. *n* number of studies
2.3.2 Risk of Bias Assessment and Methodological Quality

A detailed summary outlining the methodological quality of the included studies on autoregulated load and volume prescription are illustrated in Table 2.1 and Table 2.2, respectively. All studies had some risk of bias. A funnel plot for detecting publication bias of the included studies on load autoregulation for strength, volume autoregulation for strength, and volume autoregulation for hypertrophy are illustrated in Figure 2.2, Figure 2.3, and Figure 2.4, respectively. Visual inspection of the funnel plots indicated no obvious publication bias.

Table 2.1 Methodological quality of included studies on load autoregulation

<table>
<thead>
<tr>
<th>Study</th>
<th>Random sequence generation (selection bias)</th>
<th>Allocation concealment (selection bias)</th>
<th>Blinding of participants and researchers (performance bias)</th>
<th>Blinding of outcome assessment (detection bias)</th>
<th>Incomplete outcome data (attrition bias)</th>
<th>Selective reporting (reporting bias)</th>
<th>Overall bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arede et al. [23]</td>
<td>Some</td>
<td>Low</td>
<td>Some</td>
<td>Low</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
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<tr>
<td>Banyard et al. [22]</td>
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<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Some</td>
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<td>Some</td>
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<tr>
<td>Dorrell et al. [15]</td>
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<td>Low</td>
<td>Some</td>
<td>Low</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Dorrell et al. [18]</td>
<td>Some</td>
<td>Low</td>
<td>Some</td>
<td>Low</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Helms et al. [21]</td>
<td>Some</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Orange et al. [19]</td>
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<td>Low</td>
<td>Low</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Shattock and Tee [16]</td>
<td>Some</td>
<td>Low</td>
<td>Some</td>
<td>Low</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
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</table>

Table 2.2 Methodological quality of included studies on volume autoregulation

<table>
<thead>
<tr>
<th>Study</th>
<th>Random sequence generation (selection bias)</th>
<th>Allocation concealment (selection bias)</th>
<th>Blinding of participants and researchers (performance bias)</th>
<th>Blinding of outcome assessment (detection bias)</th>
<th>Incomplete outcome data (attrition bias)</th>
<th>Selective reporting (reporting bias)</th>
<th>Overall bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galiano et al. [27]</td>
<td>Some</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Held et al. [28]</td>
<td>Some</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Pareja-Blanco et al. [29]</td>
<td>Some</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Pareja-Blanco et al. [30]</td>
<td>Some</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Pareja-Blanco et al. [31]</td>
<td>Some</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Pareja-Blanco et al. [32]</td>
<td>Some</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Rodriles-Guerrero et al. [33]</td>
<td>High</td>
<td>Low</td>
<td>Some</td>
<td>Low</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
</tr>
<tr>
<td>Rodríguez-Rosell et al. [34]</td>
<td>Some</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
</tr>
</tbody>
</table>
Figure 2.2 Funnel plot for fixed effects meta-analysis of the mean differences in one-repetition maximum strength adaptations comparing autoregulated to standardized load prescription with subgroup analysis comparing subjective to objective autoregulation. MD mean difference, SE standard error
Figure 2.3 Funnel plot for fixed effects meta-analysis of the mean differences in one-repetition maximum strength adaptations comparing ≤25% to >25% velocity loss with subgroup analysis comparing additional to no additional exercise apart from the main comparator resistance training protocol. $MD$ mean difference, $SE$ standard error
2.3.3 Effect of Autoregulated versus Standardized Load Prescription on Muscular Strength

2.3.3.1 Participant Characteristics

A detailed summary outlining the participant characteristics of the included studies on load autoregulation is illustrated in Table 2.3. A total of 133 participants (autoregulated: n = 64; standardized: n = 69) and 247 comparisons (autoregulated: n = 120; standardized: n = 127) were included in the meta-analysis. Five of the six studies included in the meta-analysis involved exclusively male participants aged 17 ± 1 to 28.3 ± 5.6 years old with ≥2 years of resistance-training experience [15, 19-22], and one study involved exclusively female participants aged 15.8 ± 1.3 years old with ≥1 year of resistance-training experience [23].
### Table 2.3 Participant characteristics of included studies on load autoregulation

<table>
<thead>
<tr>
<th>Study</th>
<th>Group</th>
<th>Number of participants</th>
<th>Sex distribution</th>
<th>Age (years)*</th>
<th>Height (cm)*</th>
<th>Weight (kg)*</th>
<th>Training status (subjective description; years of resistance-training experience)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arede et al. [23]</td>
<td>PBT</td>
<td>7</td>
<td>F</td>
<td>15.8 ± 1.3</td>
<td>168.4 ± 4.5</td>
<td>60.2 ± 6.0</td>
<td>Resistance-trained female basketball players; ≥ 1 year</td>
</tr>
<tr>
<td></td>
<td>RPE</td>
<td>7</td>
<td>F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Banyard et al. [22]</td>
<td>PBT</td>
<td>12</td>
<td>M</td>
<td>26.2 ± 5.1</td>
<td>181.4 ± 7.4</td>
<td>84.2 ± 7.7</td>
<td>Resistance-trained males; ≥ 2 years</td>
</tr>
<tr>
<td></td>
<td>VBT</td>
<td>12</td>
<td>M</td>
<td>25.5 ± 5.0</td>
<td>180.7 ± 8.5</td>
<td>84.7 ± 6.8</td>
<td></td>
</tr>
<tr>
<td>Dorrell et al. [15]</td>
<td>PBT</td>
<td>8</td>
<td>M</td>
<td>22.8 ± 4.5</td>
<td>180.2 ± 6.4</td>
<td>89.3 ± 13.3</td>
<td>Resistance-trained males; ≥ 2 years</td>
</tr>
<tr>
<td></td>
<td>VBT</td>
<td>8</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dorrell et al. [18]</td>
<td>Group VBT</td>
<td>19</td>
<td>M</td>
<td>23.6 ± 3.7</td>
<td>182.7 ± 5.1</td>
<td>92.2 ± 8.7</td>
<td>Resistance-trained males; ≥ 2 years</td>
</tr>
<tr>
<td></td>
<td>Individualized VBT</td>
<td></td>
<td>M</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Graham and Cleather [20]</td>
<td>PBT</td>
<td>16</td>
<td>M</td>
<td>28.3 ± 5.6</td>
<td>177.8 ± 6.5</td>
<td>82.5 ± 8.9</td>
<td>Resistance-trained males; ≥ 2 years</td>
</tr>
<tr>
<td></td>
<td>RPE</td>
<td>15</td>
<td>M</td>
<td>27.9 ± 5.3</td>
<td>179.6 ± 6.5</td>
<td>83.2 ± 9.7</td>
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<tr>
<td>Helms et al. [21]</td>
<td>PBT</td>
<td>11</td>
<td>M</td>
<td>23.8 ± 4.2</td>
<td>175 ± 8</td>
<td>80.2 ± 12.2</td>
<td>Resistance-trained males; ≥ 2 years</td>
</tr>
<tr>
<td></td>
<td>RPE</td>
<td>10</td>
<td>M</td>
<td>20.9 ± 1.4</td>
<td>172 ± 6</td>
<td>78.8 ± 9.7</td>
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</tr>
<tr>
<td>Orange et al. [19]</td>
<td>PBT</td>
<td>15</td>
<td>M</td>
<td>17 ± 1</td>
<td>181 ± 6.3</td>
<td>84.9 ± 11.9</td>
<td>Resistance-trained male rugby players; ≥ 2 years</td>
</tr>
<tr>
<td></td>
<td>VBT</td>
<td>12</td>
<td>M</td>
<td>17 ± 1</td>
<td>178 ± 5.3</td>
<td>81.8 ± 11.9</td>
<td></td>
</tr>
<tr>
<td>Shattock and Tee [16]</td>
<td>Group 1</td>
<td>10</td>
<td>M</td>
<td>22 ± 3</td>
<td>NR</td>
<td>93.1 ± 14.5</td>
<td>Resistance-trained male rugby players; ≥ 2 years</td>
</tr>
<tr>
<td></td>
<td>Group 2</td>
<td>10</td>
<td>M</td>
<td>23 ± 3</td>
<td>NR</td>
<td>95.6 ± 16.8</td>
<td></td>
</tr>
</tbody>
</table>

*Data are presented as mean ± standard deviation

cm centimetres, F female, kg kilograms, M male, NR not reported, PBT percentage-based training, RPE repetitions in reserve-based rating of perceived exertion training, VBT velocity-based training

### 2.3.3.2 Training Characteristics

A detailed summary outlining the training characteristics of the included studies on load autoregulation is illustrated in Table 2.4. The length of the studies ranged from six to 12 weeks with a training frequency of two to three times per week. In all six studies that were included in the meta-analysis, the number of sets was matched, and in four studies, the repetitions were also matched. Outcome measures of interest for strength included 1RM of the back squat (six), bench press (three), deadlift (one), front squat (one), and overhead press (one). Outcome measures of interest for hypertrophy included muscle thickness of the vastus lateralis at 50% (one), vastus lateralis at 70% (one), and pectoralis major (one). A meta-analysis comparing the effect of autoregulated to standardized load prescription on muscular hypertrophy was unable to be conducted as only a single study measured and reported hypertrophy outcomes [21].
<table>
<thead>
<tr>
<th>Study</th>
<th>Group</th>
<th>Prescription</th>
<th>Length (weeks)</th>
<th>Frequency (days/week)</th>
<th>Sets difference</th>
<th>Repetition difference</th>
<th>Average total volume difference</th>
<th>Average relative intensity difference</th>
<th>Outcome of interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arede et al.</td>
<td>PBT</td>
<td>Exercises: back squat, bench press, hip thrust, shoulder press</td>
<td>8</td>
<td>2</td>
<td>Matched</td>
<td>PBT: 2240</td>
<td>Greater for PBT</td>
<td>No significant difference</td>
<td>1RM back squat; 1RM bench press</td>
</tr>
<tr>
<td></td>
<td>RPE</td>
<td>Week 1 – 4: 3 sets per exercise</td>
<td></td>
<td></td>
<td></td>
<td>RPE: 1568</td>
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<td>Week 5 – 8: 4 sets per exercise</td>
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<td></td>
<td></td>
<td>PBT group: 10 repetitions to failure</td>
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<td>RPE group: 7 repetitions to 7 RPE with set-to-set load adjustments of 2%</td>
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<td></td>
<td></td>
<td>increase/decrease per 0.5 RPE rating below/above RPE target</td>
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<tr>
<td>Banyard et al.</td>
<td>PBT</td>
<td>All sessions: 5 sets of 5 repetitions in back squat at loads ranging from</td>
<td>6</td>
<td>3</td>
<td>Matched</td>
<td>Matched</td>
<td>No significant difference</td>
<td>No significant difference</td>
<td>1RM back squat</td>
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<td>VBT</td>
<td>~59 – 85% of 1RM</td>
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<td></td>
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<td>PBT group: Relative load based on pre-test 1RM</td>
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<td>VBT group: Sessional target velocity from individualized load-velocity</td>
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<td>PBT group with set-to-set load adjustments of 5% increase/decrease per 0.06</td>
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<td>m s⁻¹ below/above the target velocity of all repetitions average velocity</td>
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<td></td>
<td></td>
<td>within set</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dorrell et al.</td>
<td>PBT</td>
<td>Integrated periodization structure comprised of compound exercises (back</td>
<td>6</td>
<td>2</td>
<td>Matched</td>
<td>Intended to be matched</td>
<td>Average relative volume load:</td>
<td>NR</td>
<td>1RM back squat; 1RM bench press</td>
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<tr>
<td></td>
<td>VBT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Significanty greater in</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.4 Training characteristics of included studies on load autoregulation
| Dorrell et al. [18] | Group VBT | Individualized VBT | Integrated periodization structure comprised of back squat and supplementary exercises Group VBT group: Group load-velocity profiles established from pre-test 1RM with target velocity corresponding to prescribed relative loads with the integration of velocity stops if a repetition velocity was below the target group velocity zone and set-to-set load adjustments based on group load-velocity profiles Individualized VBT group: Individualized load-velocity profiles | 6 | 2 | Matched | Intended to be matched | Average total volume load: No significant difference (p = 0.632) | NR | 1RM back squat |

squat, bench press, deadlift, and overhead press) and supplementary exercises

PBT group: Relative load based on pre-test 1RM VBT group: Group velocity zones established from published data and pre-test 1RM corresponding to identical relative loads as PBT group with the integration of velocity stops at 20% below the target group velocity zone and set-to-set load adjustments if velocity outside target group velocity zone

back squat for PBT (p = 0.033) Significantly greater in bench press for PBT (p = 0.019) No significant difference in deadlift (p = 0.398) Significantly greater in military press for PBT (p = 0.049)
established from pre-test 1RM with target velocity corresponding to prescribed relative loads with the integration of velocity stops if a repetition velocity was below the target individualized velocity zone and set-to-set load adjustments based on individualized load-velocity profiles.

| Graham and Cleathe r [20] | PBT | RPE | Day 1: Front squat | Day 2: Back squat | Week 1 – 4: 3 sets x 10 repetitions per exercise | Week 5 – 8: 4 sets x 5 repetitions per exercise | Week 9 – 12: 3 sets x 3 repetitions per exercise | PBT group: Relative load based on pre-test 1RM corresponding to 65, 67.5, 70, 72.5, 77.5, 80, 82.5, 85, 87.5, 90, 92.5, and 95% of 1RM for each single respective week from week 1 – 12 | RPE group: Relative load intended to correspond similarly to PBT group and corresponding to 6, 7, 8, 9, 6, 7, 8, 9, 8, 9, 0, max RPE each single respective week from week 1 – 12 | 12 | 2 | Matched | Matched | Average weekly volume load: No significant difference in combined back squat and front squat (p = 0.088) | No significant difference | Significantl y greater in back squat for RPE (p = 0.006) | Significantly greater in front squat for RPE (p < 0.001) | 1RM back squat; 1RM front squat |
| Helms et al. [21] | PBT | RPE | Integrated periodization structure | 8 | 3 | Matched | Matched | Average relative | No significant difference | 1RM back squat; |
comprised of back squat and bench press
Week 1 and 8: 2 sets per exercise
Week 2 – 7: 3 sets per exercise
PBT group: Relative load based on pre-test 1RM corresponding to 65 – 92.5% of 1RM
RPE group: Relative load intended to correspond similarly to PBT group and corresponding to 5 – 10 RPE with set-to-set load adjustments of 2% increase/decrease per 0.5 RPE rating below/above RPE target

<table>
<thead>
<tr>
<th>Orange et al. [19]</th>
<th>PBT</th>
<th>VBT</th>
<th>Exercises: Back squat and supplementary exercises</th>
<th>7</th>
<th>2</th>
<th>Matched</th>
<th>Matched</th>
<th>No significant difference</th>
<th>No significant difference</th>
<th>1RM back squat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Session 1: Back squat at 60% of 1RM</td>
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<td>Session 2: Back squat at 80% of 1RM</td>
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<td></td>
<td></td>
<td></td>
<td>PBT group: Relative load based on pre-test 1RM</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>VBT group: Sessional target velocity from individualized load-velocity profile corresponding to identical relative load as PBT group with set-to-set load adjustments of 5% increase/decrease per 0.06 m s(^{-1}) below/above target velocity of first repetition velocity within set</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group 1</td>
<td>12</td>
<td></td>
<td>Matched</td>
<td>Matched</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NR</td>
</tr>
<tr>
<td>Shattuck and Tee [16]</td>
<td>Group 2</td>
<td>Comprised of compound exercises and supplementary exercises Week 1 – 6: Maximal-strength block Week 7 – 12: Strength-speed block VBT prescription: Group velocity zones established from published data with target velocity corresponding to prescribed relative loads with set-to-set load adjustments if velocity outside target group velocity zone RPE prescription: Relative load intended to correspond similarly to VBT prescription with load dictated via RPE and set-to-set load adjustments if RPE outside target RPE zone</td>
<td>Week 1 – 6 = 4 Week 7 – 12 = 3</td>
<td>No significant difference</td>
<td>1RM back squat; 1RM bench press</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.3.3.3 Strength Outcomes

Five of the six studies measured muscular strength with a 1RM test [15, 19-22], while the remaining study estimated 1RM in accordance with the Brzycki [49] prediction equation using a 10RM test [23]. The overall pooled analysis revealed no significant difference for 1RM strength adaptations between autoregulated and standardized load prescription (MD = 2.07, 95% CI – 0.32 to 4.46 kg, p = 0.09, SMD = 0.21) as illustrated in Figure 2.5. Specifically, three studies employed subjective load autoregulation [20, 21, 23] and three studies employed objective load autoregulation [15, 19, 22], comprising a total of six outcome measures for each autoregulation type. The sub-analysis revealed near-significance with a small effect favoring autoregulated over standardized load prescription when subjective autoregulation was employed (MD = 3.15, 95% CI – 0.06 to 6.36 kg, p = 0.06, SMD = 0.38) as illustrated in Figure 2.6.

**MT** muscle thickness, $m s^{-1}$ metres per second, **NR** not reported, **PBT** percentage-based training, **RPE** repetitions in reserve-based rating of perceived exertion training, **VBT** velocity-based training, **1RM** one-repetition maximum
CI – 0.14 to 6.45 kg, p = 0.06, SMD = 0.30), but no meaningful difference when objective autoregulation was employed (MD = 0.88, 95% CI – 2.59 to 4.34 kg, p = 0.62, SMD = 0.10). Despite this finding, the pooled subgroup analysis comparing subjective to objective load autoregulation revealed no significant difference (p = 0.35).

Figure 2.5 Forest plot for fixed effects meta-analysis of the mean differences in one-repetition maximum strength adaptations comparing autoregulated to standardized load prescription with subgroup analysis comparing subjective to objective autoregulation. CI confidence interval, df degrees of freedom, kg kilograms, SD standard deviation

Sub-analyses are presented in Table 2.5. The sub-analysis revealed near-significance with a small effect favoring autoregulated over standardized load prescription when the training intervention was ≥8 weeks (p = 0.06, SMD = 0.30), but no significant differences for all other sub-analyses (i.e., when the training intervention was <8 weeks, when the training frequency was 3 times per week or <3 times per week, when training volume was controlled or uncontrolled, when relative intensity was greater for autoregulated or the same as standardized load prescription, when lower or upper body exercises were assessed separately, when squat or bench press were assessed separately, or when exercises additional to the resistance training were performed or not performed).
Table 2.5 Results from sub-analyses for 1RM strength between autoregulated and standardized load prescription

<table>
<thead>
<tr>
<th>Sub-analysis</th>
<th>Test of effect and variability</th>
<th>Heterogeneity</th>
<th>Test for subgroup differences</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MD (kg)</td>
<td>95% CI (kg)</td>
<td>p</td>
</tr>
<tr>
<td>≥8 weeks</td>
<td>3.15</td>
<td>-0.14 to 6.45</td>
<td>0.06</td>
</tr>
<tr>
<td>intervention length</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;8 weeks</td>
<td>0.88</td>
<td>-2.59 to 4.34</td>
<td>0.62</td>
</tr>
<tr>
<td>intervention length</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 times per week frequency</td>
<td>0.98</td>
<td>-4.70 to 6.65</td>
<td>0.74</td>
</tr>
<tr>
<td>&lt;3 times per week frequency</td>
<td>2.31</td>
<td>-0.33 to 4.94</td>
<td>0.09</td>
</tr>
<tr>
<td>Volume</td>
<td>2.12</td>
<td>-2.06 to 6.31</td>
<td>0.32</td>
</tr>
<tr>
<td>controlled</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td>2.05</td>
<td>-0.86 to 4.95</td>
<td>0.17</td>
</tr>
<tr>
<td>uncontrolled</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative intensity significantly greater for autoregulated over standardized</td>
<td>3.85</td>
<td>-2.27 to 9.97</td>
<td>0.22</td>
</tr>
<tr>
<td>Relative intensity not significantly different between subgroups</td>
<td>1.75</td>
<td>-0.84 to 4.34</td>
<td>0.19</td>
</tr>
<tr>
<td>Lower body exercises</td>
<td>2.14</td>
<td>-1.53 to 5.81</td>
<td>0.25</td>
</tr>
<tr>
<td>Upper body exercises</td>
<td>2.02</td>
<td>-1.13 to 5.16</td>
<td>0.21</td>
</tr>
<tr>
<td>Squat</td>
<td>1.92</td>
<td>-1.84 to 5.69</td>
<td>0.32</td>
</tr>
<tr>
<td>Bench press</td>
<td>2.83</td>
<td>-1.11 to 6.77</td>
<td>0.16</td>
</tr>
<tr>
<td>Exercises additional to resistance training protocol were performed</td>
<td>2.71</td>
<td>-0.61 to 6.03</td>
<td>0.11</td>
</tr>
<tr>
<td>Exercises additional to resistance training protocol were not performed</td>
<td>1.39</td>
<td>-2.04 to 4.82</td>
<td>0.43</td>
</tr>
</tbody>
</table>

*Statistically significant difference (p ≤ 0.05)

CI confidence interval, df degrees of freedom, kg kilograms, MD mean difference, SMD standardized mean difference, 1RM one-repetition maximum

2.3.4 Effect of Volume Autoregulation on Muscular Strength and Hypertrophy

2.3.4.1 Participant Characteristics

A detailed summary outlining the participant characteristics of the included studies on volume autoregulation is illustrated in Table 2.6. A total of 308 participants (≤25% velocity loss: n = 171; >25% velocity loss: n = 137) and 457 comparisons (≤25% velocity loss: n = 230; >25% velocity loss: n = 227) were included in the meta-analysis. All studies involved male participants, while one study also involved four female participants. All participants possessed resistance-training experience and the age ranged from 19.4 ± 1.7 to 26.7 ± 5.5 years old.
Table 2.6 Participant characteristics of included studies on volume autoregulation

<table>
<thead>
<tr>
<th>Study</th>
<th>Group</th>
<th>Number of participants</th>
<th>Sex distribution</th>
<th>Age (years)*</th>
<th>Height (cm)*</th>
<th>Weight (kg)*</th>
<th>Training status (subjective description; years of resistance-training experience)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galiano et al. [27]</td>
<td>VL5</td>
<td>15</td>
<td>M</td>
<td>22.1 ± 2.9</td>
<td>175.1 ± 5.3</td>
<td>72.5 ± 11.3</td>
<td>Resistance-trained males; ≥1.5 years</td>
</tr>
<tr>
<td></td>
<td>VL20</td>
<td>13</td>
<td>M</td>
<td>23.9 ± 3.0</td>
<td>176.6 ± 3.5</td>
<td>75.7 ± 9.4</td>
<td></td>
</tr>
<tr>
<td>Held et al. [28]</td>
<td>VL10</td>
<td>11</td>
<td>9 M / 2 F</td>
<td>19.8 ± 2.3</td>
<td>184 ± 5</td>
<td>75.8 ± 8.6</td>
<td>Resistance-trained male and female rowers; ≥2 years</td>
</tr>
<tr>
<td></td>
<td>TRF</td>
<td>10</td>
<td>8 M / 2 F</td>
<td>19.4 ± 1.7</td>
<td>180 ± 10</td>
<td>73.3 ± 8.9</td>
<td></td>
</tr>
<tr>
<td>Pareja-Blanco et al. [29]</td>
<td>VL15</td>
<td>8</td>
<td>M</td>
<td>23.8 ± 3.4</td>
<td>174 ± 7</td>
<td>75.5 ± 8.6</td>
<td>Resistance-trained professional male soccer players; NR</td>
</tr>
<tr>
<td></td>
<td>VL30</td>
<td>8</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pareja-Blanco et al. [30]</td>
<td>VL20</td>
<td>12</td>
<td>M</td>
<td>22.7 ± 1.9</td>
<td>176 ± 6</td>
<td>75.8 ± 7.0</td>
<td>Resistance-trained males; ≥1.5 years</td>
</tr>
<tr>
<td></td>
<td>VL40</td>
<td>10</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pareja-Blanco et al. [31]</td>
<td>VL0</td>
<td>14</td>
<td>M</td>
<td>24.1 ± 4.3</td>
<td>175 ± 5.5</td>
<td>75.5 ± 9.7</td>
<td>Resistance-trained males; ≥1.5 years</td>
</tr>
<tr>
<td></td>
<td>VL10</td>
<td>14</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>VL20</td>
<td>13</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>VL40</td>
<td>14</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pareja-Blanco et al. [32]</td>
<td>VL0</td>
<td>15</td>
<td>M</td>
<td>24.1 ± 4.3</td>
<td>175 ± 5.5</td>
<td>75.5 ± 9.7</td>
<td>Resistance-trained males; ≥1.5 years</td>
</tr>
<tr>
<td></td>
<td>VL15</td>
<td>16</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>VL25</td>
<td>15</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>VL50</td>
<td>16</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rodiles-Guerrero et al. [33]</td>
<td>VL10</td>
<td>15</td>
<td>M</td>
<td>23.0 ± 2.0</td>
<td>173 ± 5</td>
<td>73.3 ± 5.9</td>
<td>Resistance-trained males; ≥1 year</td>
</tr>
<tr>
<td></td>
<td>VL30</td>
<td>15</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>VL50</td>
<td>15</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rodriguez-Rosell et al. [34]</td>
<td>VL10</td>
<td>12</td>
<td>M</td>
<td>22.8 ± 3.1</td>
<td>177 ± 8</td>
<td>75.1 ± 10.3</td>
<td>Resistance-trained males; ≥1 year</td>
</tr>
<tr>
<td></td>
<td>VL30</td>
<td>13</td>
<td>M</td>
<td>22.2 ± 2.7</td>
<td>176 ± 7</td>
<td>74.0 ± 9.1</td>
<td></td>
</tr>
<tr>
<td>Rodriguez-Rosell et al. [35]</td>
<td>VL10</td>
<td>11</td>
<td>M</td>
<td>22.8 ± 3.9</td>
<td>176 ± 4</td>
<td>70.7 ± 5.1</td>
<td>Resistance-trained males; ≥1 year</td>
</tr>
<tr>
<td></td>
<td>VL30</td>
<td>11</td>
<td>M</td>
<td>21.9 ± 2.3</td>
<td>176 ± 7</td>
<td>73.7 ± 9.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>VL45</td>
<td>11</td>
<td>M</td>
<td>21.6 ± 2.8</td>
<td>172 ± 8</td>
<td>72.1 ± 9.6</td>
<td></td>
</tr>
<tr>
<td>Sánchez-Moreno et al. [36]</td>
<td>VL25</td>
<td>15</td>
<td>M</td>
<td>26.7 ± 5.5</td>
<td>175.8 ± 6</td>
<td>74.1 ± 4.7</td>
<td>Resistance-trained males; ≥2 years</td>
</tr>
<tr>
<td></td>
<td>VL50</td>
<td>14</td>
<td>M</td>
<td>24.8 ± 6.1</td>
<td>176.1 ± 5</td>
<td>74.3 ± 8.1</td>
<td></td>
</tr>
</tbody>
</table>

*Data are presented as mean ± standard deviation

cm centimetres, F female, kg kilograms, M male, TRF to-repetition-failure, VL percentage velocity loss

2.3.4.2 Training Characteristics

A detailed summary outlining the training characteristics of the included studies on volume autoregulation is illustrated in Table 2.7. The length of the studies ranged from five to eight weeks with a training frequency of two to three times per week. In all nine studies, the number of sets were matched; however, the total number of repetitions performed varied and increased concomitantly with an increasing velocity loss threshold employed. Outcome measures of interest for strength included 1RM of the back squat (one), bench press (one), deadlift (one), bench row (one), smith machine back squat (five), smith machine bench press (one), weight
stack bench press (one), and body mass prone-grip pullup (one). Outcome measures of interest for hypertrophy included CSA of the rectus femoris (one), vastus lateralis (one), vastus lateralis + vastus intermedius (one), vastus medialis (one), and pectoralis major (one).

<table>
<thead>
<tr>
<th>Study</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Prescription</th>
<th>Length (weeks)</th>
<th>Frequency (days/week)</th>
<th>Sets difference</th>
<th>Repetitions difference</th>
<th>Average relative volume difference</th>
<th>Average relative intensity difference</th>
<th>Outcomes of interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galiano et al. [27]</td>
<td>VL5</td>
<td>VL20</td>
<td>Smith machine back squat, 3 sets per session, each group terminated each set at respective VL threshold, 3 minutes inter-set rest, absolute loads adjusted for each session from the first repetition of the first set to ensure velocity (± 0.03 ms⁻¹) matched prescribed % of 1RM (based on 50% of 1RM corresponding to 1.14 ms⁻¹)</td>
<td>7</td>
<td>2</td>
<td>Matched</td>
<td>VL5: 156.9 ± 25.0</td>
<td>VL20: 480.5 ± 162.0</td>
<td>Significantly greater for VL20</td>
<td>No significant difference</td>
</tr>
<tr>
<td>Held et al. [28]</td>
<td>VL10</td>
<td>TRF</td>
<td>Power clean + back squat + bench row + deadlift + bench press, 4 sets per exercise per session, VL10 group terminated each set at VL10 threshold and TRF group performed each set to repetition failure, 2 – 3 minutes inter-set rest</td>
<td>8</td>
<td>2</td>
<td>Matched</td>
<td>VL10: 2145 ± 285</td>
<td>TRF: 2825 ± 100</td>
<td>Significantly greater for TRF</td>
<td>No significant difference</td>
</tr>
</tbody>
</table>
supplementary training  
Day 2: resistance training, 90 minutes of low-intensity rowing  
Day 3: 90 minutes of low-intensity rowing, 60 minutes of optional low-intensity cross-training (running and biking)  
Day 4: 120 minutes of low-intensity cross-training (running and biking)  
Day 5: resistance training, 60 minutes of low-intensity cross-training (running and biking)  
Day 6: 90 minutes of low-intensity rowing, 120 minutes of optional low-intensity cross-training (running and biking)  
Day 7: 3 x 2000 metre high-intensity rowing

| Pareja-Blanco et al. [29] | VL15 | VL30 | 6 | 3 | Matched | VL15: 251.2 ± 55.4  
VL30: 414.6 ± 124.9 | Significantly greater for VL30 | No significant difference | 1RM smith machine back squat |
| VL15: 251.2 ± 55.4  
VL30: 414.6 ± 124.9 | Significantly greater for VL30 | No significant difference | 1RM smith machine back squat |
(based on 50% of 1RM corresponding to 1.13 m s⁻¹, 55% of 1RM to 1.06 m s⁻¹, 60% of 1RM to 0.98 m s⁻¹, 65% of 1RM to 0.90 m s⁻¹, and 70% of 1RM to 0.82 m s⁻¹) Session 1 – 3: 50% of 1RM Session 4 – 6: 55% of 1RM Session 7 – 10: 60% of 1RM Session 11 – 14: 65% of 1RM Session 15 – 17: 70% of 1RM Session 18: 60% of 1RM

<p>| Pareja-Blanco et al. [30] | VL20  | VL40  | Smith machine back squat, 3 sets per session, each group terminated each set at respective VL threshold, 4 minutes inter-set rest, absolute loads adjusted for each session from the first repetition of the first set to ensure velocity (± 0.03 m s⁻¹) matched prescribed % of 1RM (based on 70% of 1RM corresponding to 0.82 m s⁻¹, 75% of 1RM to 0.75 m s⁻¹, 80% of 1RM to 0.68 m s⁻¹, and 85% of 1RM to 0.60 m s⁻¹) Session 1 – 6: 70% of 1RM Session 7 – 10: 75% of 1RM Session 11 – 13: | 8 | 2 | Matched | VL20: 185.9 ± 22.2 VL40: 310.5 ± 42.0 | Significantly greater for VL40 | No significant difference | IRM smith machine back squat; CSA rectus femoris; CSA vastus lateralis + vastus intermedius; CSA vastus medialis |</p>
<table>
<thead>
<tr>
<th>Pair of conditions</th>
<th>Smith machine back squat, 3 sets per session, each group terminated each set at respective VL threshold, 4 minutes inter-set rest, absolute loads adjusted for each session from the first repetition of the first set to ensure velocity ($\pm 0.03 \text{ m s}^{-1}$) matched prescribed % of 1RM (based on individualized load-velocity profile)</th>
</tr>
</thead>
</table>
| Session 14 – 16: 85% of 1RM | 8 | 2 | Matched | VL0: 48.0 ± 0.0  
VL10: 143.6 ± 40.2  
VL20: 168.5 ± 47.4  
VL40: 305.6 ± 81.7 | VL50 significantly greater than VL0, VL10, and VL20;  
VL10 and VL20 significantly greater than VL0; No significant difference between VL10 and VL20 | No significant difference | 1RM smith machine back squat; CSA vastus lateralis |
| Pareja-Blanco et al. [31] | VL0 | 48.0 ± 0.0 | VL10: 143.6 ± 40.2 | VL20: 168.5 ± 47.4 | VL40: 305.6 ± 81.7 | VL50 significantly greater than VL0, VL10, and VL20;  
VL10 and VL20 significantly greater than VL0; No significant difference between VL10 and VL20 | No significant difference | 1RM smith machine back squat; CSA vastus lateralis |

<table>
<thead>
<tr>
<th>Pair of conditions</th>
<th>Smith machine bench press, 3 sets per session, each group terminated each set at respective VL threshold, 4 minutes inter-set rest, absolute loads adjusted for each session from the first repetition of the first set to ensure velocity ($\pm 0.03 \text{ m s}^{-1}$) matched prescribed % of 1RM (based on individualized load-velocity profile)</th>
</tr>
</thead>
</table>
| Session 1 – 5: 70% of 1RM | 8 | 2 | Matched | VL0: 48.0 ± 0.0  
VL10: 136.6 ± 17.5  
VL25: 191.1 ± 34.1  
VL50: 316.4 ± 65.1 | VL50 significantly greater than VL0, VL10, and VL25;  
VL15 and VL25 significantly greater than VL0; No significant difference between VL15 and VL25 | No significant difference | 1RM smith machine bench press; CSA pectoralis major |
| Pareja-Blanco et al. [32] | VL0 | 48.0 ± 0.0 | VL10: 136.6 ± 17.5 | VL20: 191.1 ± 34.1 | VL50: 316.4 ± 65.1 | VL50 significantly greater than VL0, VL10, and VL25;  
VL15 and VL25 significantly greater than VL0; No significant difference between VL15 and VL25 | No significant difference | 1RM smith machine bench press; CSA pectoralis major |
| Rodiles-Guerrero et al. [33] | VL10 | Weight stack bench press, 4 sets per session, each group terminated each set at respective VL threshold, 3 minutes inter-set rest, absolute loads adjusted for each session from the first repetition of the first set to ensure velocity (± 0.03 ms\(^{-1}\)) matched prescribed % of 1RM (based on 65% of 1RM corresponding to 0.67 ms\(^{-1}\), 70% of 1RM to 0.60 ms\(^{-1}\), 75% of 1RM to 0.53 ms\(^{-1}\), 80% of 1RM to 0.46 ms\(^{-1}\), and 85% of 1RM to 0.39 ms\(^{-1}\))  | 5 | 3 | Matched | VL10: 211.1 ± 17.3  
VL30: 398.1 ± 61.4  
VL50: 444.4 ± 51.9  | No significant difference | 1RM weight stack bench press |
| | VL30 |  |  |  |  |  |  |  |  |
| | VL50 |  |  |  |  |  |  |  |  |
| | Rodriguez-Rosell et al. [34] | VL10 | Smith machine back squat, 3 sets per session, each group terminated each set at respective VL threshold, 4 minutes inter-set rest,  | 8 | 2 | Matched | VL10: 109.6 ± 2.0  
VL30: 228.0 ± 76.6  | No significant difference | 1RM smith machine back squat |
Rodriguez-Rosell et al. [35] conducted a study using a Smith machine back squat, with 3 sets per session for each group. Each session began with a VL threshold, followed by 4 minutes of rest. Absolute loads were adjusted for each session from the first repetition of the first set to ensure velocity (± 0.03 m·s⁻¹) matched prescribed % of 1RM (based on 70% of 1RM corresponding to 0.84 m·s⁻¹, 75% of 1RM to 0.75 m·s⁻¹, 80% of 1RM to 0.68 m·s⁻¹, and 85% of 1RM to 0.60 m·s⁻¹). The study included:

<table>
<thead>
<tr>
<th>Session</th>
<th>Percentage of 1RM</th>
<th>Absolute Loads</th>
<th>Velocity Matched</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – 6</td>
<td>70% of 1RM</td>
<td>55% of 1RM</td>
<td>No significant difference</td>
</tr>
<tr>
<td>7 – 10</td>
<td>75% of 1RM</td>
<td>60% of 1RM</td>
<td>1RM smith machine back squat</td>
</tr>
<tr>
<td>11 – 13</td>
<td>80% of 1RM</td>
<td>65% of 1RM</td>
<td>1RM smith machine back squat</td>
</tr>
<tr>
<td>14 – 16</td>
<td>85% of 1RM</td>
<td>70% of 1RM</td>
<td>1RM smith machine back squat</td>
</tr>
</tbody>
</table>

Matched:
- VL10: 180.8 ± 29.0
- VL30: 347.9 ± 62.3
- VL45: 501.1 ± 106.8

VL45 significantly greater than VL30 and VL10; VL30 significantly greater than VL10.
2.3.4.3 Strength Outcomes

All nine studies reported our primary outcome measure of muscular strength and employed a 1RM test [28-36]. In studies comparing ≥3 velocity loss threshold groups, the velocity loss thresholds were separated into their respective groups for comparisons (i.e., ≤25% or >25% velocity loss). Therefore, our overall meta-analysis for strength was comprised of 230 and 227 comparisons for velocity loss thresholds ≤25% and >25%, respectively. The overall pooled analysis revealed a significant difference for 1RM strength adaptations favoring velocity loss thresholds ≤25% over velocity loss thresholds >25% (Figure 2.6; p = 0.02, SMD = 0.23). The sub-analysis revealed a significant difference for 1RM strength adaptations favoring velocity loss thresholds ≤25% over velocity loss thresholds >25% when exercise in addition to the resistance training protocol was performed (p = 0.002, SMD = 0.62), but not for when no additional exercise was performed (p = 0.25, SMD = 0.13). Importantly, the pooled subgroup analysis comparing additional exercise to no additional exercise also revealed a significant difference (p = 0.02).
Figure 2.6 Forest plot for fixed effects meta-analysis of the mean differences in one-repetition maximum strength adaptations comparing ≤25% to >25% velocity loss with subgroup analysis comparing additional to no additional exercise apart from the main comparator resistance training protocol. BMPGP body mass prone-grip pullup, CI confidence interval, df degrees of freedom, kg kilograms, SD standard deviation, SMBP smith machine bench press, SMBS smith machine back squat, TRF to-repetition-failure, VL percentage velocity loss, WSBP weight stack bench press

Sub-analyses are presented in Table 2.8. The sub-analysis revealed a significant difference for 1RM strength favoring velocity loss thresholds ≤25% over velocity loss thresholds >25% when the training intervention was 8 weeks (p = 0.009), when training frequency was <3 times per week (p = 0.009), in lower body exercises (p = 0.007), in the smith machine back squat (p = 0.05), and in free-weight exercises (p = 0.0007), but no meaningful difference when the training intervention was <8 weeks, when training frequency was 3 times per week, in upper body exercises, in the smith machine / weight stack bench press, or in machine-based exercises. The results from all additional sub-analyses for 1RM strength adaptations comparing each velocity loss threshold and every range iteration from 0 – 25% compared to >25% are presented in Table 2.9. Significantly greater 1RM strength adaptations were demonstrated for velocity loss thresholds of 10%, 10 – 25%, 10 – 20%, 0 – 20%, and 10 – 15% compared to velocity loss thresholds >25%. 
2.3.4 Hypertrophy Outcomes

A total of three studies [30-32] reported our secondary outcome measure of muscular hypertrophy measured as muscle CSA. Similar to strength outcomes, in studies comparing ≥3

Table 2.8 Results from sub-analyses for 1RM strength between ≤25% velocity loss and >25% velocity loss

<table>
<thead>
<tr>
<th>Sub-analysis</th>
<th>Test of effect and variability</th>
<th>Heterogeneity</th>
<th>Test for subgroup differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>MD (kg)</td>
<td>95% CI (kg)</td>
<td>p</td>
</tr>
<tr>
<td>8 weeks intervention length</td>
<td>2.99</td>
<td>0.76 to 5.22</td>
<td>0.009</td>
</tr>
<tr>
<td>&lt;8 weeks intervention length</td>
<td>-0.33</td>
<td>-4.73 to 4.08</td>
<td>0.88</td>
</tr>
<tr>
<td>3 times per week frequency</td>
<td>-0.33</td>
<td>-4.73 to 4.08</td>
<td>0.88</td>
</tr>
<tr>
<td>&lt;3 times per week frequency</td>
<td>2.99</td>
<td>0.76 to 5.22</td>
<td>0.009</td>
</tr>
<tr>
<td>Lower body exercises</td>
<td>4.40</td>
<td>1.18 to 7.61</td>
<td>0.007</td>
</tr>
<tr>
<td>Upper body exercises</td>
<td>1.02</td>
<td>-1.51 to 3.56</td>
<td>0.43</td>
</tr>
<tr>
<td>Smith machine back squat</td>
<td>3.42</td>
<td>0.07 to 6.76</td>
<td>0.05</td>
</tr>
<tr>
<td>Smith machine/weight stack</td>
<td>-1.03</td>
<td>-4.04 to 1.97</td>
<td>0.50</td>
</tr>
<tr>
<td>Free-weight exercises</td>
<td>7.49</td>
<td>3.14 to 11.84</td>
<td>0.0007</td>
</tr>
<tr>
<td>Machine-based exercises</td>
<td>0.95</td>
<td>-1.29 to 3.19</td>
<td>0.41</td>
</tr>
</tbody>
</table>

*Statistically significant difference (p ≤ 0.05)

CI confidence interval, df degrees of freedom, kg kilograms, MD mean difference, SMD standardized mean difference, 1RM one-repetition maximum

Table 2.9 Results from sub-analyses for 1RM strength between respective velocity loss and >25% velocity loss

<table>
<thead>
<tr>
<th>Sub-analysis</th>
<th>Test of effect and variability</th>
<th>Heterogeneity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity loss</td>
<td>MD (kg)</td>
<td>95% CI (kg)</td>
</tr>
<tr>
<td>25%</td>
<td>3.38</td>
<td>-1.93 to 8.70</td>
</tr>
<tr>
<td>20%</td>
<td>3.42</td>
<td>-3.08 to 9.93</td>
</tr>
<tr>
<td>15%</td>
<td>-0.50</td>
<td>-6.89 to 5.88</td>
</tr>
<tr>
<td>10%</td>
<td>3.56</td>
<td>0.77 to 6.34</td>
</tr>
<tr>
<td>0%</td>
<td>-1.56</td>
<td>-6.56 to 3.45</td>
</tr>
<tr>
<td>20 – 25%</td>
<td>3.40</td>
<td>-0.72 to 7.52</td>
</tr>
<tr>
<td>15 – 25%</td>
<td>2.25</td>
<td>-1.21 to 5.71</td>
</tr>
<tr>
<td>10 – 25%</td>
<td>3.04</td>
<td>0.87 to 5.21</td>
</tr>
<tr>
<td>15 – 20%</td>
<td>1.42</td>
<td>-3.13 to 5.98</td>
</tr>
<tr>
<td>10 – 20%</td>
<td>2.98</td>
<td>0.60 to 5.35</td>
</tr>
<tr>
<td>0 – 20%</td>
<td>2.14</td>
<td>-0.00 to 4.29</td>
</tr>
<tr>
<td>10 – 15%</td>
<td>2.91</td>
<td>0.36 to 5.46</td>
</tr>
<tr>
<td>0 – 15%</td>
<td>1.99</td>
<td>-0.29 to 4.26</td>
</tr>
<tr>
<td>0 – 10%</td>
<td>2.35</td>
<td>-0.08 to 4.78</td>
</tr>
</tbody>
</table>

*Statistically significant difference (p ≤ 0.05)

CI confidence interval, df degrees of freedom, kg kilograms, MD mean difference, SMD standardized mean difference, 1RM one-repetition maximum

2.3.4.4 Hypertrophy Outcomes

A total of three studies [30-32] reported our secondary outcome measure of muscular hypertrophy measured as muscle CSA. Similar to strength outcomes, in studies comparing ≥3
velocity loss threshold groups, the velocity loss thresholds were separated into their respective groups for comparisons (i.e., >25% or ≤25% velocity loss). Therefore, our overall meta-analysis for hypertrophy was comprised of 120 and 123 comparisons for velocity loss thresholds >25% and ≤25%, respectively. The overall pooled analysis revealed a significant difference for CSA hypertrophy adaptations favoring velocity loss thresholds >25% over velocity loss thresholds ≤25% (MD = 0.61, 95% CI 0.05 to 1.16 cm², p = 0.03, SMD = 0.28) as illustrated in Figure 2.7. The results from all sub-analyses for CSA hypertrophy adaptations comparing velocity loss thresholds >25% to each velocity loss threshold and every range iteration from 0 – 25% are presented in Table 2.10. The sub-analysis revealed no significant difference and negligible effects for CSA hypertrophy when comparing velocity loss thresholds >25% to velocity loss thresholds of 20 – 25%; however, all additional sub-analyses revealed small-to-moderate effects in favor of >25%. Significantly greater CSA hypertrophy adaptations were demonstrated for velocity loss thresholds >25% compared to velocity loss thresholds of 0 – 20%, 0 – 15%, 0 – 10%, and 0%.

**Table 2.10** Results from sub-analyses for CSA hypertrophy between >25% velocity loss and respective velocity loss

<table>
<thead>
<tr>
<th>Sub-analysis</th>
<th>Test of effect and variability</th>
<th>Heterogeneity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity loss threshold</td>
<td>MD (cm²)</td>
<td>95% CI (cm²)</td>
</tr>
<tr>
<td>20 – 25%</td>
<td>0.36</td>
<td>-0.29 to 1.00</td>
</tr>
<tr>
<td>15 – 25%</td>
<td>0.43</td>
<td>-0.20 to 1.06</td>
</tr>
<tr>
<td>10 – 25%</td>
<td>0.46</td>
<td>-0.15 to 1.06</td>
</tr>
<tr>
<td>20%</td>
<td>0.39</td>
<td>-0.28 to 1.05</td>
</tr>
<tr>
<td>15 – 20%</td>
<td>0.46</td>
<td>-0.18 to 1.11</td>
</tr>
<tr>
<td>10 – 20%</td>
<td>0.49</td>
<td>-0.13 to 1.11</td>
</tr>
<tr>
<td>10 – 15%</td>
<td>1.19</td>
<td>-0.54 to 2.92</td>
</tr>
<tr>
<td>0 – 20%</td>
<td>0.64</td>
<td>0.07 to 1.20</td>
</tr>
<tr>
<td>0 – 15%</td>
<td>1.31</td>
<td>0.22 to 2.39</td>
</tr>
<tr>
<td>0 – 10%</td>
<td>1.21</td>
<td>0.04 to 2.38</td>
</tr>
<tr>
<td>0%</td>
<td>1.38</td>
<td>-0.01 to 2.77</td>
</tr>
</tbody>
</table>

*Statistically significant difference (p ≤ 0.05)

CI confidence interval, cm centimetres, CSA cross-sectional area, df degrees of freedom, MD mean difference, SMD standardized mean difference
2.4 Discussion

To the authors’ knowledge, this is the first systematic review and meta-analysis to directly investigate the effect of load and volume autoregulation on muscular strength and hypertrophy adaptations. There were similar improvements in 1RM strength between autoregulated and standardized load prescription. Moreover, the subgroup analysis demonstrated no difference in 1RM strength whether subjective or objective autoregulated load prescription was employed. For volume autoregulation, low–moderate velocity loss thresholds (≤25%) were optimal for 1RM strength, which was only apparent when studies included exercise outside of the main comparator training protocol. Conversely, moderate–high velocity loss thresholds (>25%) were optimal for muscle hypertrophy; however, velocity loss thresholds of 20 and 25% stimulate similar improvements in hypertrophy. Collectively, velocity loss thresholds of ~20–25% may be optimal for 1RM strength adaptations plausibly by promoting type II phenotype muscle hypertrophy [30], and potentially by maximizing chronic neuromuscular adaptations (i.e., late rate of force development) [32] whilst minimizing excessive and unnecessary acute neuromuscular fatigue [44]. Appropriate prescription of load and volume autoregulation strategies may enable the stimulus to parallel an individual’s performance and overarching goals of a resistance training program.
2.4.1 Load Autoregulation

2.4.1.1 Muscular Strength

Overall, there was no significant difference in 1RM strength adaptations between autoregulated and standardized load prescription. Although non-significant, the sub-analysis demonstrated a small effect (SMD = 0.28) for greater 1RM strength when autoregulated load prescription employed a significantly higher relative intensity compared to standardized load prescription. It has been consistently supported that 1RM strength adaptations are primarily driven by high relative intensity training [50, 51], which agrees with the well documented force-velocity relationship (strength-speed continuum) [52, 53]. To illustrate, Graham and Cleather [20] demonstrated that when volume load, sets, and repetitions per set were matched, autoregulating load using RIR-based RPE to utilize a significantly higher relative intensity (percentage of 1RM) than the standardized PBT group resulted in significantly greater 1RM strength in both the back squat and front squat. Therefore, it appears that autoregulated load prescription has the potential to be slightly superior to standardized load prescription for 1RM strength if it enables a greater load (percentage of 1RM) to be utilized while accounting for an individual’s fluctuations and changes in 1RM.

The pooled analysis revealed near-significance (p = 0.06) with a small effect (SMD = 0.30) favoring subjective autoregulated over standardized load prescription; however, objective autoregulated load prescription failed to reveal any differences (p = 0.62; SMD = 0.10). The underlying rationale for these results is plausibly due to the objective autoregulated load prescription groups training at similar relative intensities as the standardized load prescription groups in all three of the objective load autorregulation studies [15, 19, 22]. In contrast, subjective autoregulated load prescription employed a significantly higher relative intensity than standardized load prescription for 50% of the total exercises in the subjective load autoregulation studies [20, 21, 23]. Moreover, an important consideration is that the studies employing subjective load autoregulation [20, 21, 23] were notably longer in duration than the studies employing objective load autoregulation [15, 19, 22]. Therefore, the reason for the marginally greater 1RM strength adaptations observed with subjective load autoregulation is likely two-fold: (1) enabling a higher average RPE to be achieved; thus, resulting in a higher relative intensity being employed; and (2) longer training interventions; thus, providing a longer duration for strength adaptations to ensue. Interestingly, the results from this meta-analysis are conflicting
with the sole study to date to directly compare subjective versus objective load autoregulation: a
12-week randomized cross-over design by Shattock and Tee [16] revealed that the 1RM strength
improvements for objective load autoregulation (VBT) were significantly greater than subjective
load autoregulation (RPE) in both the back squat (p = 0.00001; ES: 1.37) and the bench press (p
= 0.003; ES: 0.98). As the number of sets and repetitions per set were matched between groups,
the significantly greater 1RM strength improvements following objective load autoregulation
were postulated to be due to training at a higher average RPE (higher relative intensity) than the
subjective load autoregulation protocol since it has been supported that subjective intra-set RPE
ratings tend to be underestimated [11]. Furthermore, evidence has supported that velocity
feedback improves competitiveness and motivation to train [54]; ensuring maximal intended
concentric velocity, which results in significantly greater 1RM strength compared to half-
maximal intended concentric velocity training [55].

Finally, no noteworthy differences in 1RM strength were demonstrated between
autoregulated and standardized load prescription when sub-analyses on training frequency,
volume differences, exercise type, and additional exercises were conducted. Based on the meta-
analytic findings from the present review it appears that autoregulated and standardized load
prescription are similarly effective at eliciting considerable improvements in 1RM strength
adaptations. These findings may be attributable to the limitations and lack of optimization in the
presently employed autoregulatory strategies.

2.4.1.2 Primary Limitations

RPE-based training often autoregulates load prescription by attempting to standardize the
inter-individual proximity to failure [20, 21, 23]; however, it contains a limitation: subjectivity
[7, 11]. To illustrate, when participants performed a set to failure at 70% of 1RM in the back
squat and verbally indicated when they believed that they were at a five, seven, and nine RPE,
their predicted RPE values were ~five, four, and two repetitions below the actual RPE,
respectively [11]. Despite the limitations of RPE-based training, the ability to accurately predict
RPE improves from set-to-set and when performed closer to failure [7]; therefore, it may serve as
a suitable autoregulatory strategy in certain settings (i.e., clinical).

Banyard et al. [22] and Orange et al. [19] employed individualized load-velocity profiles
to prescribe and autoregulate load from set-to-set. Average concentric velocity (ACV) is reliable
from session-to-session in the back squat at 20 – 90% of 1RM [56]; therefore, prescribing an
individualized first repetition average concentric velocity (FRV) corresponding to a particular percentage of 1RM from an individualized load-velocity profile is a feasible strategy to dictate and autoregulate relative training load. Specifically, in the study conducted by Banyard et al. [22], if the ACV of all repetitions within a set was ±0.06 metres per second (m s\(^{-1}\)) outside the target ACV corresponding to a particular percentage of 1RM, the load was adjusted by a universal ±5% of 1RM. However, ACV decreases linearly from repetition-to-repetition as one approaches failure [25]; Morán-Navarro et al. [13] reported that changes in ACV of 0.03 m s\(^{-1}\) can produce a difference of two RPE in the back squat. As a result, load was seemingly reduced prematurely as evidenced by the VBT group training at similar relative intensities as the PBT group (~69 and ~71% of 1RM, respectively) [22]. Although a universal load adjustment of ±5% of 1RM was still prescribed in Orange et al. [19], the load was appropriately adjusted from the FRV (rather than the ACV of all repetitions). Despite this, the intervention simply did not enable adequate progressive overload to observe any significant differences in 1RM strength improvements between the VBT and PBT groups [19]. In one of the most recent load autoregulation studies, individualized set-to-set load adjustments based off the actual percentage of 1RM from the previous set were performed; however, no differences in 1RM strength were reported between individualized and group load-velocity profiles following the six-week training protocol [18].

An additional velocity-based load autoregulation strategy is the use of ACV zones [15, 16]. Although ACV zones account for specific zones on the force-velocity continuum [52, 53], they can correspond to considerably large ranges of relative intensities and proximities to failure. For example, if 3 sets of 8 repetitions in an ACV zone of 0.60 – 0.40 m s\(^{-1}\) is prescribed, some individuals may commence the set at 0.60 m s\(^{-1}\) and terminate the set at 0.45 m s\(^{-1}\), while other individuals may commence the set at 0.50 m s\(^{-1}\) and terminate the set at 0.40 m s\(^{-1}\). However, Morán-Navarro et al. [13] reported group ACVs of ~0.49, 0.45, and 0.40 m s\(^{-1}\) at a four, six, and eight RPE, respectively during a single set to failure in the back squat. Therefore, terminating the set at an ACV of ~0.45 and ~0.40 m s\(^{-1}\) in the back squat is associated with approximately six and eight RPE, respectively [13]; thus, ACV zones also fail to equate for proximity to failure and intra-set neuromuscular fatigue.

Finally, 1RM prediction from individualized regression equations of submaximal ACV may be inaccurate for determining sessional 1RM to prescribe load and autoregulate volume
within a training session, or for tracking estimated 1RM to monitor chronic strength improvements across a training intervention [57-59]. In theory, the efficacy of 1RM prediction from individualized regression equations of submaximal ACV is predicated upon its ability to accurately predict 1RM, which has lacked consistent support [60-68]. These 1RM prediction methods have been purported to accurately predict the actual 1RM for most machine-based exercises [67, 68]; however, they over-predict the actual 1RM for barbell exercises in all [60-63, 65] but two [64, 66] studies. To summarize, the present load autoregulation strategies likely require further optimization encompassing individualized load adjustments and accurate quantifications of proximity to failure.

2.4.2 Volume Autoregulation

2.4.2.1 Muscular Strength

Velocity loss thresholds ≤25% were superior for increasing 1RM strength over velocity loss thresholds >25%, which is plausibly attributable to more favorable neuromuscular adaptations [31, 32] and lower neuromuscular fatigue [25, 44]. To better contextualize the overall meta-analytic findings for neuromuscular adaptations contributing to 1RM strength, a recent study conducted by Pareja-Blanco et al. [32] comparing 0, 15, 25, and 50% velocity loss demonstrated that 25% velocity loss resulted in the greatest 1RM strength improvements and was the velocity loss threshold that significantly increased late rate of force development. Crucially, maximizing late rate of force development is the paramount component of the force-time curve to optimize 1RM strength as shifting the force-time curve towards late rate of force development-oriented profiles optimizes the peak absolute force (absolute load) that can be produced [69, 70]. It is important to recognize that when percentage of 1RM and total repetitions are matched, maximizing intra-set force production with alternative set structures does not result in meaningfully different chronic strength adaptations compared to traditional sets as supported in two recent systematic reviews and meta-analyses [26, 37]. Rather, increases in the force component of the force-velocity curve for 1RM strength adaptations are largely contingent upon the load (i.e., percentage of 1RM) employed [50, 51, 71, 72]. Our meta-analytic data suggests that there may be a non-significant dose-response relationship between autoregulated velocity loss and 1RM strength adaptations from zero to ~25% velocity loss when training up to ~85% of 1RM possibly due to adaptation shifts from early to late rate of force development-oriented profiles [31, 32]. Moreover, velocity loss thresholds exceeding 25% typically result in
meaningfully lower 1RM strength adaptations caused by unfavorable neuromuscular adaptations concomitant with counterproductive neuromuscular fatigue.

Velocity loss thresholds ≤25% were superior to velocity loss thresholds >25% for increasing strength when the training intervention was 8 weeks in length, but not when it was <8 weeks. This supports the contention that the advantages of lower intra-set fatigue for strength development are predominantly a result of chronic neuromuscular adaptations. A recent investigation by Pareja-Blanco et al. [31] demonstrated that 0% and 10% velocity loss significantly decreased vastus medialis muscle displacement, which is an indication of increased muscle stiffness [73, 74]; a property that mediates the force capabilities of skeletal muscle’s contractile elements [75]. Training at 0% velocity loss significantly increased early rate of force development [32], whilst 40% velocity loss significantly decreased early rate of force development [31]. Moreover, 40% velocity loss significantly increases vastus lateralis delay time [31], which has a positive relationship with myosin heavy chain I adaptations [76]. Rate of force development is a vital component for overcoming the sticking point in compound barbell lifts [77] and the decrease in rate of force development correlates with a decrease in the percentage of type IIx fibers [78, 79]. Importantly, type IIx fibers possess greater cross-bridge cycling rates compared to type I fibers [80] and are essential for enhancing muscle fiber conduction velocity [81]. Although 15% velocity loss elicits high peak muscle excitation [32], which is related to increased neural drive, rate coding, and sarcoplasmic reticulum calcium kinetics [82-85], training with 15% velocity loss does not change early nor late rate of force development [32].

Compared to training with >25% velocity loss, training with 25%, 20%, and 10% velocity loss all revealed small effects for increasing 1RM; however, both 15% and 0% velocity loss failed to reveal greater benefits for 1RM strength adaptations. For optimizing 1RM strength, it appears that the velocity loss thresholds may be polarized at 10% and 20 – 25% up to ~85% of 1RM as a viable strategy to minimize neuromuscular fatigue and maximize late rate of force development, respectively [28, 32]. However, upon further inspection of the included studies, it must be noted that the investigation conducted by Held et al. [28] comparing velocity loss thresholds of 10% at ~8 RPE to repetition-failure training at 80% of 1RM in the barbell back squat, bench press, deadlift, bench row, and power clean also involved a high volume of additional exercises every day apart from the resistance training protocol (i.e., 90-minutes and 120-minutes of low-intensity rowing and cycling, respectively, on day six of the seven-day
microcycle). Therefore, due to the possibility that the concurrent endurance training in Held et al. [28] confounded the findings, the sub-analysis comparing a velocity loss threshold of 10% to >25% with Held et al. [28] excluded failed to reveal a small effect (MD = 1.65, p = 0.32, SMD = 0.16). As 20 – 25% velocity loss provided the greatest effect (SMD = 0.30), it may be suggested that 0 – 25% velocity loss with most training allocated at ~20 – 25% (the highest threshold compared to training at ~9.5 RPE – failure) is recommended to optimize 1RM strength.

Our pooled analysis revealed that velocity loss thresholds ≤25% resulted in significantly greater 1RM strength adaptations than velocity loss thresholds >25% when additional exercise (beyond resistance training) was performed; however, no differences were observed when no additional exercise was performed. Therefore, it appears that the utility of velocity loss thresholds ≤25% for increasing 1RM strength may be most apparent when additional exercise beyond the resistance training protocol is performed (i.e., in-season) to minimize neuromuscular fatigue [28, 44]. Although relative intensity- and relative volume-equated failure training elevates muscle damage and elongates recovery time considerably compared to non-failure training [40], high volume and high velocity loss training results in greater neuromuscular fatigue and delayed recovery compared to high intensity and high RPE training [44, 86, 87]. For example, the counter-movement jump required 48 hours to recover following 3 sets at 60% of 1RM with 40% velocity loss (~5.5 RPE) in the smith machine back squat; however, it was recovered within 6 hours following 3 sets at 80% of 1RM with 20% velocity loss (~7 RPE) [86]. Pareja-Blanco et al. [44] also revealed that when set volume and velocity loss was equated (~17 – 23% velocity loss), the counter-movement jump was recovered at 24-hours post-intervention regardless of training at a four, five, six, seven, or eight RPE at 70, 75, 80, 85, and 90% of 1RM in the smith machine back squat, respectively. Notably, Watkins and colleagues [88] investigated the counter-movement jump as an indicator of neuromuscular fatigue and readiness [89]; demonstrating that ~8% decrease in counter-movement jump height resulted in a ~28% decrease in the number of repetitions performed at 80% of 1RM in the back squat. Upon synthesis of the available evidence, it appears that training at velocity loss thresholds of 0 – 25% may limit undesirable neuromuscular fatigue; thereby, enabling the utilization of higher percentages of 1RM more frequently to train the high-force component of the force-velocity profile for 1RM strength adaptations.
2.4.2.2 Muscular Hypertrophy

Training with velocity loss thresholds >25% resulted in significantly greater muscle hypertrophy than velocity loss thresholds ≤25%. This finding is consistent with the literature corroborating that there is a malleable inverted U-curve of optimal training volume for strength [90] and hypertrophy [91-93] that is individual-specific [94]. It is important to recognize that although the velocity loss threshold groups within each study were equated for set volume, velocity loss thresholds >25% were associated with substantially greater total relative volume [30-32]. However, two recent systematic reviews and meta-analyses reported no difference in hypertrophy between traditional sets (higher intra-set fatigue) and alternative set structures (lower intra-set fatigue) when total relative volume was equated [26, 37]. Therefore, it appears that the significantly greater hypertrophy observed at >25% velocity loss in our meta-analysis could be attributable to the greater total relative volume accumulated rather than due to the magnitude of intra-set fatigue (velocity loss threshold) achieved.

Although considerable intra-set fatigue and metabolic stress is unnecessary to stimulate hypertrophy [95], our meta-analysis suggests that a minimal velocity loss threshold of ~20 – 25% may be required to optimize hypertrophy as exemplified by small-to-moderate effects in favor of >25% velocity loss arising in all sub-analyses including velocity loss thresholds at or below 20%. Despite this, future studies equated for relative volume that report intra-set fatigue with velocity loss and proximity to failure with a precise strategy are required to support or refute this finding and to establish the specific inter-dependent training status, velocity loss, and proximity to failure thresholds to optimize hypertrophy. Upon further inspection of the individual studies included in this meta-analysis, Pareja-Blanco et al. [31] demonstrated that despite no significant difference between 10% and 20% velocity loss in relative volume, number of sets, number of repetitions performed within the set, and percentage of 1RM, and despite training at nearly identical proximities to failure for the entire 8-week intervention (10% velocity loss: ~4 – 7.5 RPE; 20% velocity loss: ~4.5 – 8 RPE), 20% velocity loss elicited more than three-fold greater hypertrophy compared to 10% velocity loss. Higher velocity loss thresholds result in elevated metabolite accumulation [25, 96], which has been postulated to amplify the hypertrophic response that is primarily induced from mechanical tension [97]. Consequently, it may be hypothesized that velocity loss thresholds < ~20% are inadequate at accumulating sufficient metabolites (i.e., lactate) to assist in augmenting optimal hypertrophic responses [97-
99]; however, the evidence that lactate modulates anabolic signaling during resistance training in humans is conflicting [100, 101]. It is not entirely clear whether the results of this meta-analysis are due to differences between velocity loss threshold groups for relative volume, intra-set fatigue, or a combination of both.

Velocity loss thresholds of ≤~25% and >~35% are associated with the preservation and reduction, respectively, of muscle fiber phenotypic characteristics that are favorable for enhancing 1RM strength adaptations [30, 102]. For example, when training at 70 – 85% of 1RM, 20% velocity loss at ~5 – 8 RPE preserved myosin heavy chain IIX muscle fiber percentage, whereas 40% velocity loss at ~9.5 RPE – failure reduced the type IIX fiber pool (i.e., with a conversion to slower fiber types) [30]. This is consistent with the electromyography literature and implies that high-threshold motor units of prime movers are activated initially within a set at ≥~70% of 1RM in trained individuals [30, 103-105]. However, 40% velocity loss increased vastus lateralis and vastus intermedius muscle volume to a significantly greater magnitude, suggesting that motor unit activation of synergists increases as velocity loss increases above ~25 – 35% [30]. It may be argued that hypertrophy should be related to increases in strength as muscle size accounts for ≥70% of the variance in strength in trained individuals [106-111]. Collectively, it may be suggested that if the primary goal is to increase strength, the majority of training should be performed at ~20 – 25% velocity loss to ensure and optimize hypertrophy whilst preserving type II muscle fiber phenotypic characteristics. Conversely, if the goal is to increase strength along with hypertrophy, velocity loss thresholds exceeding 25% may be employed; however, performing training at ~20 – 25% velocity loss for compound exercises with accessory exercises that target the synergist musculature may also accomplish this goal.

Nonetheless, if increasing strength is of minimal importance, allocating the majority of training at a minimum of ~20 – 25% velocity loss may be recommended to optimize hypertrophy. A periodized approach integrating higher velocity loss initially within a macrocycle and decreasing towards lower velocity loss prior to competition may be employed in athletic programming settings to promote the spectrum of hypertrophy and strength velocity loss-specific adaptations in a sequential order for maximal performance.

2.4.2.3 Primary Limitations

Although velocity loss can accurately quantify acute intra-set neuromuscular and metabolic fatigue [25], it cannot precisely quantify proximity to failure [112, 113]. For example,
in one of the preliminary longitudinal velocity loss studies by Pareja-Blanco et al. [31], a
prescription would have been 3 sets at 70% of 1RM with a 20% velocity loss; stipulating that the
FRV on each set corresponded to 70% of the individual’s 1RM. However, for example, one
individual may have had an FRV of 0.60 m s\(^{-1}\) at 70% of 1RM; thus, a 20% velocity loss would
have terminated the set at an ACV of 0.48 m s\(^{-1}\), which is associated with ~4 RPE [13].
Conversely, another individual may have had an FRV of 0.50 m s\(^{-1}\) at 70% of 1RM; thus, a 20%
velocity loss would have terminated the set at an ACV of 0.40 m s\(^{-1}\), which is associated with ~8
RPE [13]. To further illustrate, a separate investigation by the same researchers reported that the
40% velocity loss group performed ~56% of the sets to failure, indicating that 40% velocity loss
corresponded to differing intra- and inter-individual proximities to failure [30].

Most importantly, velocity loss is primarily influenced by the number of repetitions
performed within the set rather than the proximity to failure (i.e., low velocity loss is not
necessarily indicative of low RPE) [25]. For example, if an individual has an ACV
corresponding to an 8 RPE of 0.30 m s\(^{-1}\) and a velocity decay (change in velocity per change in
RPE) of 0.04 m s\(^{-1}\), the velocity loss for 3 and 7 repetitions at an 8 RPE would equate to 21% and
44%, respectively. Moreover, each velocity loss threshold is load- and lift-specific;
corresponding to a different proximity to failure depending on the percentage of 1RM and
exercise employed [112-114]. Furthermore, the inter-individual range in repetitions reported in
the back squat at 10, 20, and 30% velocity loss with an FRV of 0.70 m s\(^{-1}\) was 2 – 11, 4 – 19, and
4 – 24 repetitions, respectively [115]. Therefore, due to the extensive range in repetitions that can
be performed at each percentage of 1RM [7, 8] and at each velocity loss threshold [115], as well
as the FRV [116], the ACV corresponding to a specific RPE [13], and the individualized velocity
decay, each individual will experience varying degrees of fatigue, terminate each set at a
different proximity to failure, and perform a different number of repetitions and magnitude of
relative volume. Conclusively, an autoregulatory model conceptualizing the overarching results
from this meta-analysis may be required to suggest avenues for future research and potential
practical applications.

2.4.3 Future Directions and Practical Applications

Although the results from this meta-analysis demonstrated significant differences
between velocity loss thresholds ≤25% and >25% for both strength and hypertrophy adaptations,
several limitations require further investigation. Future studies should compare different velocity
loss thresholds and equate for total relative volume and relative intensity to detect whether the specific adaptations are due to differences in the amount of volume performed, magnitude of intra-set fatigue, or a combination of both. Additionally, future research is also warranted to investigate the chronic effects of load and volume autoregulation in clinical settings when standardized resistance training strategies may be contraindicated [117]. Due to the limitations in which velocity-based load and volume autoregulation strategies have been employed and considering the conflicting findings between this meta-analysis and the sole study to date to directly compare objective to subjective load autoregulation [16], a separate autoregulatory model potentially warrants conceptualization and investigation within autoregulatory contexts. Accordingly, a model integrating individualized last repetition average concentric velocity (LRV) may be a potential autoregulatory model to conceptualize the individual- and lift-specific relationship between LRV, repetitions performed, percentage of 1RM, proximity to failure (RPE), and intra-set fatigue (velocity loss) based on emerging evidence [13, 118, 119].

In practical settings, velocity loss zones from our meta-analysis may be conceptualized contingent upon the primary goal of the individual or training phase within a theoretical model; however, LRVs may be utilized as a prescription strategy within the velocity loss zones to quantify proximity to failure and potentially aid to rectify the limitations of the present mutually exclusive autoregulatory prescription strategies. From a more holistic programming perspective, a periodized approach whereby higher velocity loss with higher relative volume and lower RPE change over time towards lower velocity loss with higher relative intensity and higher RPE may be recommended. An integrated approach may be a plausible advantageous strategy for optimizing total hypertrophy to potentiate neuromuscular adaptations and limit neuromuscular fatigue for peak performance at the time of primary importance [120]. Perhaps most noteworthy, the efficacy of LRVs and potential model warrants future investigation in: (1) a longitudinal volume autoregulation study comparing LRV stops to RPE stops and velocity loss thresholds; and (2) a longitudinal load autoregulation study comparing LRV-based training to RPE-based training and individualized PBT.

2.5 Conclusion

The results of this systematic review and meta-analysis provide novel evidence regarding the effect of autoregulated load and volume prescription on muscular strength and hypertrophy adaptations. Specifically, autoregulated and standardized load prescription demonstrated similar
improvements in 1RM strength. Low-moderate velocity loss thresholds of 0 – 25% (i.e., lower intra-set fatigue) and moderate-high velocity loss thresholds of >20 – 25% (i.e., higher intra-set fatigue) produce the greatest improvements in 1RM strength and muscle hypertrophy, respectively. Velocity loss thresholds of ~20 – 25% may optimize 1RM strength adaptations by maximizing favorable chronic hypertrophy adaptations (i.e., type II phenotypic characteristics), chronic neuromuscular adaptations (i.e., late rate of force development), whilst minimizing unnecessary acute neuromuscular fatigue. Collectively, integrating load and volume autoregulation is a plausible strategy to aid in the systematic individualization of resistance training programming prescriptions, acute responses, chronic adaptations, and performance outcomes.

2.6 References


The key takeaways from the systematic review and meta-analysis (Chapter 2) are three-fold: (1) autoregulated is superior to traditional load prescription for one-repetition maximum (1RM) strength improvements; (2) autoregulating with low-moderate intra-set fatigue is ideal for 1RM strength; and (3) autoregulating with moderate-high intra-set fatigue is ideal for hypertrophy [1]. Although these preliminary meta-analytic findings suggest that autoregulation is beneficial for augmenting numerous muscular adaptations, the main current methods of autoregulation are generally investigated as separate strategies in research settings, despite autoregulation existing as a conceptual framework in applied settings [2]. Due to this limited lens by which autoregulation has been viewed, the main current methods are typically sub-optimal in their ability to accurately measure the intended variable (i.e., proximity to failure), which may consequently generate sub-optimal adjustments of the prescription (i.e., manipulation of load). A primary objective of the narrative review (Chapter 3) is to highlight the advantages and limitations of the main current methods of autoregulation: repetitions in reserve (RIR)-based rating of perceived exertion (RPE)-based training (RBT), velocity zones, load-velocity profiles, RPE stops, and velocity loss thresholds. Another primary objective of the narrative review (Chapter 3) is to theorize how autoregulation may be potentially improved through the conceptual integration of the main current methods by proposing a theoretical model for suggesting future directions and practical applications: the Individualized Last Repetition Velocity Model (LRV Model).

References:
Abstract

Resistance training (RT) load and volume are considered crucial variables to appropriately prescribe for eliciting the intended muscular adaptation(s): strength, power, hypertrophy, among others. In traditional RT contexts, the magnitude of load and dosage of volume are generally fixed (i.e., pre-prescribed and non-adjusting); thereby, potentially yielding sub-optimal adaptations. A concept of RT that adjusts to align with an individual’s goals is autoregulation, which is a systematic two-step feedback process of: (1) monitoring performance and its constituents across multiple time-frames; and (2) adjusting programming (i.e., load and volume) to elicit the desired goals (i.e., responses and adaptations). A growing body of autoregulation research has accelerated in the past few years, with evidence suggesting that autoregulation may provide a small advantage over traditional RT; albeit some studies have demonstrated no differences. Nonetheless, the existing literature has conceptualized the current methods of autoregulation as standalone practices, which has limited its extensive utility in research and applied settings. The primary purpose of this review was three-fold. Initially, we synthesized the current methods of load and volume autoregulation, while disseminating each method’s main advantages and limitations. Second, we proposed a theoretical model that integrates the current methods for a more holistic perspective of autoregulation. Lastly, we illustrated how the theoretical model may be compared to the current methods for future directions and how it may be implemented for practical applications. We hope that this review assists to contextualize an overarching autoregulation framework to help inform future investigations for researchers and practices for RT professionals.

3.1 Introduction

A fundamental component of resistance training (RT) is to ensure that the prescription of variables aligns with the needs and goals of the individual whilst simultaneously adjusting according to their responses and performance to the program [1]. Two key variables within the
prescription of RT programs are load and volume: the intensity of load is largely indicative of adaptations to specific portions of the force-velocity curve (i.e., strength and power) [2, 3]; whereas the appropriate dosage of volume is essential for promoting hypertrophy [4, 5]. Despite the importance of said variables, traditional RT typically prescribes fixed pre-determined loads and volumes that do not adjust according to an individual’s evolving performance [6]. Autoregulated RT systematically measures performance feedback and its constituents (fitness, fatigue, and readiness) over various time-scales (short-, moderate-, and long-term) and subsequently adjusts the prescription of variables, such as load and volume to ensure that the relevant acute responses and chronic adaptations are achieved [1]. Indeed, a systematic review and meta-analysis by Hickmott et al. [7] demonstrated a small estimate of effect for one-repetition maximum (1RM) strength favoring autoregulated over traditional load prescription. Moreover, Hickmott et al. [7] demonstrated that autoregulating volume with different magnitudes of intra-set neuromuscular fatigue yielded divergent adaptations: low-moderate intra-set fatigue produced significantly greater 1RM strength, whereas moderate-high intra-set fatigue produced significantly greater hypertrophy. A separate systematic review and meta-analysis by Hernández-Belmonte and Pallarés [8] also found that low-moderate intra-set fatigue generated greater efficacy for improving velocity performance at low loads and moderate-high loads.

Although preliminary meta-analyses [7, 8] have supported that the appropriate implementation of autoregulation strategies may yield slightly greater adaptations than traditional RT, the current methods of autoregulation are generally researched as mutually exclusive practices despite autoregulation existing as a conceptual framework [1, 7]. Therefore, autoregulation may potentially provide increasingly beneficial outcomes if the current methods are improved through their integration within a holistic theoretical model. Our initial objective was to provide a balanced and critical review of the literature addressing the current methods of load and volume autoregulation. As a potential solution to highlight the advantages whilst rectifying the limitations of the current methods, we propose a theoretical model that encompasses their beneficial subtleties. We exemplify how researchers in future investigations may compare our proposed theoretical model to each of the current standalone methods with specific examples. Moreover, we also depict how RT professionals may implement our proposed theoretical model in broader RT contexts. Our aim is that this article provides an authoritative review of the current load and volume autoregulation methods, and contextualizes a theoretical
model that may suggest possible avenues for further research and applicable strategies for RT professionals.

3.2 Traditional Prescription Methods

3.2.1 Percentage-Based Training

Percentage-based training (PBT) is the prominent method of traditional load prescription, which involves prescribing load as a percentage of an individual’s 1RM that has been pre-established from a baseline 1RM test [6]. For example, 4 sets of 8 repetitions at 75% of 1RM may be a universal prescription administered in a group setting across various exercises.

3.2.1.1 Advantages

There are three evident main advantages of PBT. Firstly, with respect to traditional load prescription methods, an individual using PBT methods with sets performed not to failure has exhibited superior maximal strength outcomes than sets performed with load prescribed to repetition maximums [6]. Secondly, PBT provides a quantification of percentage of 1RM: an essential RT variable due to the load-dependent nature of strength adaptations [2, 3]. Thirdly, it is a simple and effective load prescription method to implement, serving as desirable and feasible in large-scale randomized controlled trials than more sophisticated methods. Although autoregulated load prescription may potentially be ideal for maximizing strength [7, 9], fixed PBT evokes significant improvements in numerous adaptations [10, 11]; thus, its advantages should not be neglected.

3.2.1.2 Limitations

Perhaps the most apparent limitation of PBT is that it fails to tailor the prescription to an individual’s performance fluctuations from session-to-session and changes from week-to-week, despite data illustrating that daily 1RM may oscillate up to 10.8% over 37-days [12]. A basic tenet of RT programming is a needs analysis; however, atypical performance in the 1RM test may cause an undesirable prescription for the ensuing RT protocol with respect to the overarching goals and needs of the individual; thereby, manifesting sub-optimal results. Furthermore, a considerable growing body of evidence has demonstrated that the repetitions performed-percentage of 1RM relationship is specific to each individual [13, 14] and exercise [15, 16]; thus, individual- and exercise-specific repetitions performed-percentage of 1RM relationships should ideally be established. Despite preliminary meta-analytic evidence only demonstrating a small estimate of effect favoring autoregulated over traditional load prescription
for improving 1RM strength [7], it may be suggested that the current autoregulation practices can potentially be further improved as addressed herein this review.

3.3 Load Autoregulation Methods

3.3.1 RPE-Based Training

The repetitions in reserve-based rating of perceived exertion scale (RIR-based RPE scale) was published in 2016 [17], integrating and expanding upon the original work of Hackett et al. [18] and Tuchscherer [19]. In RT-specific contexts, subjective RIR and RPE values are generally used interchangeably, whereby RPE values range from 0 to 10 and are equivalent to 10 minus the number of subjective RIR: a 10 RPE is equivalent to maximum effort and 0 RIR, a 9 RPE is equivalent to 1 RIR, and an 8 RPE is equivalent to 2 RIR, etc. Moreover, RPE values in half increments indicate that the individual perceives that they definitely have a certain number of RIR, and maybe 1 additional RIR: an 8.5 RPE is equivalent to definitely 1 maybe 2 RIR, and a 7.5 RPE is equivalent to definitely 2 maybe 3 RIR, etc. RPE-based training (RBT) is the primary subjective load autoregulation method in RT that encompasses the RIR-based RPE scale and is commonly comprised of stipulating a targeted RPE (or RIR) to be achieved for a specified number of repetitions per set [20]. For example, an individual may be prescribed 6 sets of 3 repetitions at an 8 RPE (or 2 RIR) in place of a traditional approach, such as a pre-specified percentage of 1RM (i.e., 6 sets of 3 repetitions at 85% of 1RM).

3.3.1.1 Advantages

The primary advantages of RBT for load prescription are three-fold: (1) RBT appears to produce a small benefit over PBT for strength adaptations [7, 9]; (2) RBT adjusts load from set-to-set according to one’s real-time performance (i.e., based on subjective RIR/RPE value) [21, 22]; and (3) RBT provides an inherent individualization of one’s subjective perception of their proximity to failure (i.e., their number of RIR) [20, 23]. Indeed, subgroup analyses from Hickmott et al. [7] indicated a small estimate of effect for 1RM strength favoring RBT over PBT load prescription (Standardized Mean Difference or SMD = 0.30). The greater strength gains from RBT are mainly attributable to its facilitation of considerably greater average RT loads (i.e., greater percentages of 1RM relative to baseline 1RM) [7].

3.3.1.2 Limitations

RBT’s primary limitations with respect to load autoregulation are also three-fold: (1) different individuals have varying ability to accurately gauge proximity to failure [23]; (2)
conventional RBT approaches implement universally standardized, rather than individualized
(i.e., individual- and exercise-specific) load adjustments from set-to-set [21, 22]; and (3) most
contemporary RBT paradigms do not provide a quantification for percentage of 1RM nor
neuromuscular fatigue, although, quantifying load and fatigue are important in RT contexts [2,
24, 25].

Granted Halperin et al. [23] uncovered that individuals were reasonably accurate at
predicting proximity to failure (~0.95 repetitions below the actual number of RIR on average),
two main limitations of nearly all studies in the meta-analysis are apparent. First, predicting
proximity to failure manifests an anchoring bias that some individuals may aim to achieve.
Indeed, when Armes et al. [26] implemented deception as to the primary purpose of their
investigation, participants were approximately two repetitions below the actual number of RIR,
which is considerably worse and approximately two-times greater than the current meta-analysis
indicates [23]. Second, individuals appear more accurate during later sets than initial sets [23];
however, this is plausibly attributable to obtaining the ability to more accurately predict
proximity to failure simply because the first set within the session is performed to failure.
Nonetheless, in practical settings, training to failure is unnecessary to optimize adaptations [27,
28]; therefore, it is typically avoided, particularly early within a RT session to avoid
accumulating counterproductive fatigue [29]. Indeed, when an initial set is not performed to
failure, individuals are markedly less accurate at predicting proximity to failure: during a single
set to failure at 70% of 1RM in the back squat, the number of repetitions below the actual RPE
was 5.15 ± 2.92, 3.65 ± 2.46, and 2.05 ± 1.73 at a predicted 5, 7 and 9 RPE (5, 3, and 1 RIR);
respectively [30]. In this study, there were considerable interindividual differences within the
group of 25 males: at the predicted 7 RPE (3 RIR), 5 individuals were 7 repetitions below the
actual RPE, whereas only 1 individual precisely predicted the actual RPE [30].

A foundational principle of autoregulation is individualizing all components of the
measurement and adjustment process; however, the universally prescribed 2% load increase and
decrease per RPE rating below and above the RPE target; respectively [21, 22], fails to
individually adjust load from set-to-set. Furthermore, if multiple individuals are prescribed – for
instance – 6 sets of 3 repetitions with a self-selected load that they believe will achieve an 8 RPE
(i.e., a load they believe they will have 2 RIR after 3 repetitions are performed), this will likely
result in a different percentage of 1RM employed for nearly everyone [20]. However, achieving a
specific percentage of 1RM whilst avoiding failure (i.e., autoregulating by maintaining the relative volume while reducing the number of repetitions per set) [31-33] may in fact be more desirable for strength adaptations than lowering the load simply to achieve a specified RPE as a plethora of evidence has demonstrated no difference between training to failure and not training to failure for improving strength and hypertrophy [27, 28]; albeit, ample data has revealed the benefit of heavier load RT for strength [2, 3].

3.3.2 Velocity Zones

The current velocity-based training (VBT) load autoregulation methods involve implementing: (1) velocity zones; and (2) load-velocity profiles (addressed in section 3.3) [34]. Velocity zones prescribe and manipulate load to coincide with specific portions of the force-velocity continuum [35]. For example, a prescription for strength-speed (i.e., ~70 – 80% of 1RM) may be 6 sets of 4 repetitions with a load that is appropriately adjusted to ensure that all repetitions elicit a velocity that is within the prescribed strength-speed velocity zone on each set.

3.3.2.1 Advantages

The existing longitudinal studies investigating velocity zones have resulted in greater benefits compared to PBT and RBT, despite using group-based velocity zones for only 6-week protocols: (1) Dorrell et al. [36] reported significantly greater and two-fold percentage gains in 1RM bench press compared to PBT; and (2) Shattock and Tee [37] demonstrated significantly greater 1RM back squat, 1RM bench press, and countermovement jump height changes relative to RBT. The primary advantage of velocity zones is that it enables for distinct zones on the force-velocity curve to be targeted to promote the desired training effect (i.e., force- or velocity-oriented individualized force-velocity profiles) [38, 39]. Specifically, an individual’s force-velocity profile will adapt depending on the location along the force-velocity curve that is mainly trained (i.e., according to the principle of specificity): the locations where the majority of training is allocated provide the largest adaptations whilst adaptations diminish further from that location on the curve [40]. Indeed, the alternative set structure (i.e., whereby the total repetitions are equated with the traditional sets protocol; however, rest periods are re-distributed to allow for shorter yet more frequent rest periods and fewer repetitions per set) literature supports this concept: a systematic review and meta-analysis by Jukic et al. [32] demonstrated no difference in strength adaptations between alternative set structures and traditional sets (SMD = 0.06) as load was matched between protocols; however, adaptations towards velocity-oriented force-velocity
profiles were more prevalent for alternative set structures (SMD = 0.28) due to a greater accumulation of total repetitions at faster velocities. Therefore, a strength athlete may perform the greatest distribution of training with autoregulated loads corresponding to the velocity zone associated with absolute-strength (i.e., slow velocities and high loads), whereas a power athlete may primarily train with autoregulated velocities matching the speed-strength velocity zone (i.e., faster velocities and moderate loads); albeit, some evidence has suggested that devoting similar attention to all components of the force-velocity curve may be ideal for certain sports and athlete positions that include an array of force-velocity demands [41]. An additional advantage of implementing, monitoring, and recording velocity zones is that concentric velocity data is provided which assists to drive maximal intent [42] and the corresponding magnitude of adaptation [43] (i.e., an individual is aiming to match or beat objective velocity outputs).

3.3.2.2 Limitations

The primary limitations of velocity zones are: (1) they require individualization for every person [44] and exercise [45]; and (2) they typically fail to specify the percentage of 1RM, proximity to failure, and magnitude of neuromuscular fatigue. Although Dorrell et al. [36] and Shattock and Tee [37] appeared to utilize group-based velocity zones based on a combination of published and participant data for feasibility, a plethora of evidence has supported that velocity is individual- [44] and exercise-specific [45]. Therefore, despite a basic tenet of autoregulation stipulating to individualize the prescription to the desired goal [1], some individuals may not be training within the intended velocity zone; thus, potentially resulting in sub-optimal adaptations and perhaps in particular instances, unintended outcomes.

The velocity zones prescribed are generally excessively large (i.e., a range of ≥0.25 m·s⁻¹) [37]; therefore, if the actual loads, and actual velocities of the first and last repetitions are not recorded it is difficult to determine the actual percentage of 1RM, proximity to failure, and neuromuscular fatigue to monitor training and detect whether improvements or maladaptation has occurred. For example, if 8 sets of 3 repetitions in a velocity zone of <0.40 m·s⁻¹ is prescribed in the bench press, during an initial session an individual may utilize a load with a fastest (i.e., typically first or second) repetition velocity (FRV) near 0.40 m·s⁻¹, while several subsequent microcycles (i.e., weeks) later the FRV may be ~0.20 m·s⁻¹. However, the trend in estimated 1RM could be unintentionally regressing across the mesocycle (i.e., block) if an individual is not recording the load and cross-referencing an estimated 1RM in accordance with the individualized
load-velocity relationship (addressed in section 3.3) to identify progression or regression. Furthermore, if the velocity of the last repetition is not recorded (addressed in section 5), the proximity to failure cannot be established [24, 46] and the magnitude of neuromuscular fatigue (i.e., percentage decrease in velocity from the first to the last repetition; addressed in section 4.2) [47] cannot be calculated to aid at informing future training decisions (i.e., autoregulating in the moderate-term).

3.3.3 Load-Velocity Profiles

Individual- and exercise-specific load-velocity profiles are commonly created from a 1RM test: FRV is plotted against percentage of 1RM from the sets that were performed to work up to the 1RM, and a trendline of best fit is applied (i.e., a linear or second order polynomial regression equation, whereby x is equal to FRV, and y is equal to percentage of 1RM) [35]. Load-velocity profiles autoregulate load to ensure the elicitation of an FRV that corresponds with the prescribed percentage of 1RM [35]. For example, if 5 sets of 5 repetitions were prescribed at 80% of 1RM from the load-velocity profile, and an individual has an FRV of 0.40 m s\(^{-1}\) corresponding to 80% of 1RM, the absolute load that elicits an FRV of 0.40 m s\(^{-1}\) (±0.03 m s\(^{-1}\)) would be utilized during that particular session.

3.3.3.1 Advantages

The primary advantage of load-velocity profiles is that it indicates the percentage of 1RM for a given absolute load according to real-time performance fluctuations (i.e., according to the FRV at the absolute load) [48, 49]. Moreover, the load-velocity relationship is reliable (as outlined below) in the following 3 scenarios: (1) across a large range of percentages of 1RM [50]; (2) over several sessions [51]; and (3) in longitudinal study time frames [52]. Sánchez-Moreno et al. [50] reported a mean \(R^2\) value of 0.993 for smith machine bench press individualized load-velocity profiles of mean propulsive velocity plotted against relative load with second order polynomial regression equations. In this study, from the first to the second measurement the mean difference in mean propulsive velocity did not differ by >0.01 m s\(^{-1}\) for each percentage of 1RM between 40 and 90% of 1RM in 10% incremental loads [50]. For instance, at 80% of 1RM the recorded mean propulsive velocities were 0.40 ± 0.03 and 0.39 ± 0.03 m s\(^{-1}\) during measures one and two; respectively [50]. Furthermore, Banyard et al. [51] demonstrated no significant difference in the relationship between load and velocity of the barbell back squat across 3 trials for mean propulsive velocity and average concentric velocity (ACV) whether linear or
polynomial regression equations were employed. González-Badillo and Sánchez-Medina [52] also revealed that the bench press load-velocity profiles of 56 participants in 5% increments from 30 – 100% of 1RM did not significantly change from initial- to re-test following 6 weeks of resistance training, in spite of average 1RM increasing by 9.3%.

3.3.3.2 Limitations

The primary limitations of load-velocity profiles (as outlined below) are three-fold: (1) every individual [44] and exercise [45] have a unique load-velocity relationship; and (2) they fail to quantify proximity to failure and neuromuscular fatigue; and 3) they have a propensity to over-estimate 1RM regardless of the 1RM prediction strategy (i.e., model) performed [49]. Evidence has supported that individualized load-velocity relationships are more accurate than group relationships at quantifying load (i.e., percentage of 1RM) for a given velocity [48], primarily because individualized equations consider interindividual differences. Fahs et al. [53] revealed that relative strength appears to be the most influential factor associated with differences in ACV of those under investigation: relative strength, height, RT age, RT frequency, and limb lengths. However, even if individualized load-velocity profiles are established, prescribing the same number of repetitions to all individuals is prone to resulting in differing proximities to failure and magnitudes of neuromuscular fatigue further owing to the necessity for individualized proximity to failure-velocity (addressed in section 5), percentage of repetitions performed-velocity loss (addressed in section 4.2), and repetitions performed-percentage of 1RM relationships. In the event that load-velocity relationships are utilized to forecast 1RM with regression equations of submaximal FRVs, a recent systematic review and meta-analysis by Greig et al. [49] discovered that these models over-predict the actual 1RM by ~4.5 kg or 3.7% on average; thus, although this strategy may be logistical to evaluate general trends in estimated 1RM, caution is warranted when seeking to precisely determine actual 1RM.

3.4 Volume Autoregulation Methods

3.4.1 RPE Stop

The RPE stop method involves prescribing a particular number of repetitions at a certain load and terminating the session when a pre-specified RPE has been reached (or exceeded) on a set [54]. For example, an individual may be prescribed to perform sets of 4 repetitions at 80% of 1RM in the back squat until a set elicits an RPE ≥8 (≤2 RIR). The primary advantages and limitations of the RPE stop method coincide with RBT load prescription as outlined in section
3.1; however, it poses an additional clear limitation. Specifically, the total number of sets within the session should be capped (i.e., a maximum number of sets should be stipulated if the prescribed RPE is never achieved on a set) to prevent an excessive amount of volume from being performed in a single session and to more appropriately disperse volume throughout sessions.

3.4.2 Velocity Loss Thresholds

A velocity loss threshold involves terminating a set when the velocity (ACV or mean propulsive velocity) of a repetition has decreased by a pre-prescribed percentage from the set’s fastest repetition [47], which is typically the first repetition within a set because of the strong relationship between the percentage of repetitions performed and decreases in velocity ($R^2 = 0.93$ for smith machine back squat; $R^2 = 0.97$ for smith machine bench press) independent of the absolute total number of repetitions performed [16]. For example, if a 20% velocity loss threshold was prescribed in the back squat at 80% of 1RM and an individual had a first (i.e., fastest) repetition velocity of 0.50 m s$^{-1}$ at 80% of 1RM in the back squat, the set would be terminated once a repetition elicited a velocity of $\leq 0.40$ m s$^{-1}$.

3.4.2.1 Advantages

The primary advantages of velocity loss comprise of the following: (1) objectively quantifies, standardizes, and individualizes the magnitude of intra-set neuromuscular fatigue and level of metabolic stress for a given exercise [16, 47]; (2) dictates the spectrum of strength and hypertrophy adaptations [7]; (3) promotes various neuromuscular adaptations (i.e., force-velocity and force-time profile shifts) [8, 25, 55, 56]; (4) influences muscle fiber phenotypic adaptations (i.e., type II interconversion) [56, 57]; (5) indicative of the time course of recovery from an acute bout of RT [25, 58, 59]; and (6) possesses a relatively stable proximity to failure from set-to-set across multiple sessions at a given load due to the reliability of the load-velocity relationship [50-52] and RIR-velocity relationship [24, 46] for an individual and exercise.

Sánchez-Medina and González-Badillo [47] provided preliminary evidence supporting velocity loss as a valid objective measurement of RT-induced neuromuscular fatigue and metabolite accumulation over 10 years ago. Specifically, there was a strong correlation between velocity loss in the back squat and bench press from 15 different 3-set acute RT protocols, the decrease in velocity from pre-post RT with the load eliciting a velocity of 1.00 m s$^{-1}$, and decline in countermovement jump height ($r = 0.91 – 0.97$) [47]. With respect to fatigue quantification, velocity loss also demonstrated a strong linear relationship with lactate ($r = 0.93 – 0.97$), and a
strong curvilinear relationship with ammonia ($R^2 = 0.85 – 0.95$) [47]. To summarize, the magnitude of neuromuscular fatigue achieved for a specific velocity loss threshold was nearly identical regardless of the total number of repetitions required to reach the velocity loss threshold [47].

The initial longitudinal studies investigating the effect of velocity loss thresholds on chronic muscular adaptations were conducted 5 years later [57, 60]; with a plethora of studies conducted in recent years aimed to determine the optimal thresholds to maximize strength, hypertrophy, endurance, and neuromuscular performance outcomes (i.e., sprinting capacity, jumping ability, power production at sub-maximal loads, etc.) [7, 8, 25]. Indeed, meta-analytic data by Hickmott et al. [7] established that significantly greater 1RM strength resulted from $\leq 25\%$ compared to $>25\%$ velocity loss RT when both RT and concurrent exercise was performed; oppositely, $>25\%$ velocity loss RT resulted in significantly greater muscle cross-sectional area (CSA) hypertrophy. It appears that there is a certain magnitude of fatigue (i.e., velocity loss threshold) rather than a specific proximity to failure (i.e., RIR threshold) that has been supported for hypertrophy. From Schoenfeld’s three-factor model of hypertrophy [61], mechanical tension remains supported, muscle damage has lacked support [62], and meta-analytic data from Hickmott et al. [7] and Jukic et al. [32] has emerged to aid at suggesting the possible metabolic fatigue thresholds that have been challenged over the years. Specifically, Hickmott et al. [7] demonstrated that when set volume is equated between protocols and loads are $\sim 70 – 85\%$ of 1RM, a minimal velocity loss threshold $\geq 20 – 25\%$ is required to optimize muscle hypertrophy. Similarly, Jukic et al. [32] revealed in relative volume-equated interventions that $\geq 50\%$ of the maximal possible total repetitions for a given load – which typically corresponds to $\sim 20\%$ velocity loss [63] – is needed to maximize hypertrophy, considering the sub-group analyses indicating no meaningful difference between traditional sets compared to intra-set rest (SMD = 0.06), yet a large effect favoring traditional sets over cluster sets (SMD = 0.98). As a given velocity loss threshold and intra-set rest protocol corresponds to a different RIR contingent on the load [16, 64], it appears that the minimal intra-set fatigue threshold required to optimize hypertrophy may be $\sim 20 – 25\%$ velocity loss, instead of a universal RIR for all loads, since an individual may achieve a low RIR (i.e., reasonably close proximity to failure) with a heavy load, yet accumulate limited intra-set fatigue and remain below $\sim 20 – 25\%$ velocity loss if a low number of repetitions are performed in the set.
Although no significant differences were observed for 1RM strength in the present existing systematic reviews and meta-analyses on velocity loss thresholds [7, 8, 25], Hernández-Belmonte and Pallarés [8] indicated that ≤25% velocity loss also resulted in similar local endurance, despite completing significantly fewer total repetitions on average (212.0 ± 102.3 vs 384.0 ± 95.0); yielding its potential time efficiency at eliciting said adaptations. Most notable and interestingly, further sub-analyses from Hickmott et al. [7] uncovered that ~20 – 25% velocity loss was optimal for improving 1RM strength (SMD = 0.30) and that thresholds exceeding 25% did not result in significantly greater hypertrophy; supporting that ~20 – 25% velocity loss may be ideal for those seeking to concomitantly prioritize maximal strength with hypertrophy secondarily. To elaborate, ~20 – 25% velocity loss optimizes the force-generating capacity at 1RM plausibly due to neuromuscular adaptations that are characteristic of stimulating late rate of force development-oriented individualized force-time profiles [65], which has been further supported in individual studies conducted by Pareja-Blanco and colleagues [55, 56]. Hernández-Belmonte and Pallarés [8] identified that ≤25% velocity loss promoted significantly greater (SMD = 0.31) pre- to post-test increases in velocity for sub-maximal loads of ≤60% of 1RM (i.e., absolute loads corresponding to ≥1.00 and 0.80 m s⁻¹ at pre-test in the back squat and bench press; respectively). This data agrees with the force-velocity specificity principle [40]; suggesting that a larger upward shift can be obtained at the component of the force-velocity curve that is principally trained, which provides practical recommendations for high velocity- and early rate of force development-dominant sports (i.e., track sprinters and most field athletes). The summarized results contextualizing the effect of velocity loss thresholds on chronic muscular adaptations from the systematic reviews and meta-analyses conducted by Hernández-Belmonte and Pallarés [8] for power, in addition to Hickmott et al. [7] for 1RM strength and hypertrophy is illustrated in Figure 3.1.
### Figure 3.1

Summary of results from the systematic reviews and meta-analyses for the effect of velocity loss thresholds on power [8], 1RM strength [7], and hypertrophy [7]. Statistical significance is \( p \leq 0.05 \). The MD units for strength is kg; the MD units for hypertrophy is cm\(^2\). An SMD of 0.20 – 0.49, 0.50 – 0.79, and ≥0.80 is considered a small, medium, and large effect, respectively. \( cm \) centimetres, \( kg \) kilograms, \( MD \) mean difference, \( NA \) not available, \( SMD \) standardized mean difference, \( VL \) percentage velocity loss, \( IRM \) one-repetition maximum.

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<th>10</th>
<th>15</th>
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In accordance with the supposition that type IIx fibers possess a higher force-generating capability; the aforementioned neuromuscular adaptations are also associated with skeletal muscle fiber phenotype transitions: Pareja-Blanco et al. [57] reported that 40% velocity loss RT significantly decreased myosin heavy chain IIx percentage approximately two-fold (pre: 14.6 ±
8.9 vs post: 7.2 ± 7.6); conversely, it remained unchanged from 20% velocity loss RT. Therefore, moderate-high velocity loss thresholds incur unnecessarily fatiguing repetitions that may be detrimental for promoting favorable neuromuscular adaptations (i.e., early and late rate of force development, increased and synchronous motor unit firing, etc.) [57].

With respect to inter-session neuromuscular fatigue (i.e., beyond the intra-set level), Pareja-Blanco et al. [58] demonstrated no significant difference in countermovement jump height before and 24-hours following several ~20% velocity loss conditions: 3 sets with 50% of the total possible repetitions at either 4, 6, 8, 10, and 12RM in the smith machine back squat, which elicited velocity losses of 17.1, 18.1, 22.7, 17.0, and 20.4%; respectively. Most noteworthy, this data suggests that the time course of recovery is similar for a given magnitude of intra-set fatigue (~20% velocity loss), despite the wide range in RIR (~2 – 6 RIR), even if the relative intensity is moderate-high (~75 – 90% of 1RM) [58]. These acute findings agree with the chronic implications demonstrating that the optimal proximity to failure for strength and hypertrophy has been supported to be a velocity loss zone of ~20 – 25% [7] and that 1RM strength adaptations have been well supported to be primarily driven by training at heavy loads (i.e., high relative intensities) [2, 3].

The majority of recent longitudinal velocity loss studies have employed individualized load-velocity profiles in conjunction with velocity loss thresholds [7, 8, 25]; thus, for a participant, exercise, and percentage of 1RM, the proximity to failure plausibly remains reasonably consistent during the multi-set sessions throughout the interventions primarily because of three reasons: (1) the individualized load-velocity relationship is reliable from set-to-set and session-to-session [51]; (2) the individualized RIR-velocity relationship is reliable from set-to-set [24] and session-to-session [46]; and (3) velocity is reliable across the duration of longitudinal studies [52]. Indeed, Hackett [66] illustrated that the ACV of the first two repetitions remained stable during the initial 4 sets performed to failure at 70% of 1RM in the barbell back squat: set 1, 2, 3, and 4 corresponded to ACVs of 0.59, 0.58, 0.55, and 0.57 m s\(^{-1}\); respectively. In accordance with the largest differences in FRVs from Hackett [66], an FRV of 0.59 and 0.55 m s\(^{-1}\) with a 20% velocity loss would terminate the set at an ACV ≤0.47 and 0.44 m s\(^{-1}\); respectively, which corresponds to ~5 and 4 RIR on average; respectively [24]. Furthermore, considering Hickmott [24] reported a 95% CI of 0.44 – 0.50 and 0.42 – 0.48 m s\(^{-1}\) at a 5 and 4 RIR; respectively, and that the smallest detectable change in velocity is ±0.03 m s\(^{-1}\), it is unlikely that
the proximity to failure varied drastically from set-to-set in the longitudinal velocity loss studies, even in the thresholds that performed some sets to failure (i.e., plausibly no greater than ~1 RIR difference for a given individual, exercise, and percentage of 1RM from set-to-set).

A velocity loss threshold prescription does not necessarily guarantee achieving the precise set termination ACV (i.e., 0.47 m s\(^{-1}\) for a 20% velocity loss with an FRV of 0.59 m s\(^{-1}\)) since, for example, a repetition may elicit an ACV of 0.48 m s\(^{-1}\); therefore, an additional repetition would be required to reach \textless0.47 m s\(^{-1}\); however, considering the simple slope of 0.025 m s\(^{-1}\) in the back squat [24], the set termination ACV would likely be at ~0.45 – 0.44 m s\(^{-1}\), which corresponds to ~4 RIR. Although certain studies have reported that only some sets were performed to failure: Pareja-Blanco et al. [57] noted that ~56.3% of sets were performed to failure for the 40% velocity loss group (i.e., a velocity loss <40% was achieved on the repetition at a 0 RIR prior to the repetition resulting in failure) in one of the seminal longitudinal velocity loss studies, many of these studies involved a range of percentages of 1RM within a single intervention (i.e., 70 – 85% of 1RM) [55-57, 67]. Thus, considering that a given velocity loss threshold corresponds to a closer proximity to failure with respect to RIR as the percentage of 1RM increases [16], it appears that the sets performed to failure were primarily at the higher percentages of 1RM in the latter sessions. Despite the available aforementioned evidence supporting this contention, there was plausibly a degree of inter-individual variability because of the individualized load-velocity [51] and RIR-velocity relationships [24, 46]: some participants may have potentially failed on later sets within a session; conversely, others may have never reached failure during the entire intervention.

### 3.4.2.2 Limitations

The main limitations of velocity loss involve the following: (1) the velocity loss-percentage of repetitions performed relationship (i.e., percentage of completed repetitions out of the maximum possible) must be individualized for each participant [50] and exercise [16]; (2) the velocity loss-percentage of repetitions performed relationship requires individualization across multiple loads for certain exercises [16]; (3) velocity loss does not quantify proximity to failure with respect to RIR [16, 55, 57]; (4) the number of RIR for a given velocity loss threshold is different contingent upon the load-velocity relationship (i.e., the load and associated FRV) [16]; (5) the degree of optimal intra-set fatigue (i.e., velocity loss value) for strength, hypertrophy, and performance outcomes may be exercise-specific [7]; (6) its advantages have yet to be
conceptualized for autoregulatory application beyond volume autoregulation protocols (i.e., in load autoregulation protocols).

In a similar regard that the load-velocity relationship requires individualization, Sánchez-Moreno et al. [50] demonstrated stronger coefficients of determination for the velocity loss-percentage of repetitions performed relationships with individualized ($R^2 = 0.97 – 0.99$) compared to generalized ($R^2 = 0.80 – 0.94$) equations at 50 – 90% of 1RM in the smith machine bench press. Indeed, Weakley et al. [68] demonstrated that a 20% velocity loss elicited a considerably large range of repetitions (4 – 19) in the barbell back squat at 70% of 1RM. Despite this, a limitation of this study by Weakley et al. [68] is that generalized load-velocity relationships were employed for the prescribed percentage of 1RM (i.e., all participants were prescribed an FRV of 0.70 m·s⁻¹); thus, it is plausible that some individuals were using varying percentages of 1RM as smaller standard deviations for repetitions performed at 70% of 1RM with a 20% velocity loss have been reported when individualized load-velocity profiles are involved (repetitions performed: 4.2 ± 1.2) [55].

Hickmott [24] reported a significant difference in the simple slope (absolute decrease in ACV per 1 unit decrease in RIR) for the three powerlifts: barbell back squat (0.025 m·s⁻¹), bench press (0.031 m·s⁻¹), and deadlift (0.015 m·s⁻¹); illustrating that the velocity decay is unique to each exercise. Indeed, Rodriguez-Rossell et al. [16] illustrated that a significantly greater velocity loss was achieved in the smith machine bench press relative to the smith machine back squat at all four loading conditions investigated to failure (50, 60, 70, and 80% of 1RM); providing further evidence that velocity loss threshold prescriptions should be individualized to the participant and exercise. Although there was no significant difference in the percentage of repetitions completed for 20 – 25% velocity loss at 70 and 80% of 1RM in the smith machine back squat, there was a significant difference in the smith machine bench press; demonstrating that the velocity loss-percentage of repetitions relationship can also be load-dependent in certain exercises [16].

It is also important to highlight that although velocity loss standardizes the magnitude of acute neuromuscular fatigue [47] and stipulates the percentage of repetitions completed across groups [50], it does not necessarily provide an accurate RIR quantification, which is important for appropriately monitoring RT for systematic autoregulatory prescription [1, 20]. To contextualize, given that a 20% velocity loss corresponds to ~50% of the total possible number of repetitions at 70% of 1RM in the squat [16, 55, 57] and considering the large inter-individual
range of repetitions that can be performed at 70% of 1RM in the barbell back squat (6–26) [13], the two extreme individuals would plausibly perform 3 repetitions at a 3 RIR and 13 repetitions at a 13 RIR; respectively.

For each velocity loss threshold, the number of RIR varies depending primarily on the FRV, which is subsequently based on the load. Rodriguez-Rosell et al. [16] reported that a 20% velocity loss at 70 and 80% of 1RM corresponded to 49.3 and 51.3% of repetitions completed out of the maximum in the smith machine back squat; however, 50% of the maximum repetitions corresponds to a different RIR for 70 and 80% of 1RM due to the different number of repetitions performed at varying loads. For example, if an individual was able to perform 12 and 8 repetitions at 70 and 80% of 1RM; respectively, 50% of the maximum repetitions would correspond to 6 repetitions at a 6 RIR and 4 repetitions at a 4 RIR; respectively.

The sub-analyses from Hickmott et al. [7] suggest that the ideal velocity loss thresholds for improving 1RM strength and thus possibly other adaptations may also be unique to the exercise employed. Specifically, ≤25% velocity loss compared to >25% velocity loss resulted in significantly greater improvement in 1RM strength in lower body exercises (MD = 4.40 kg, 95% CI = 1.18 to 7.61 kg, p = 0.007, SMD = 0.36) and free-weight exercises (MD = 7.49 kg, 95% CI = 3.14 to 11.84 kg, p = 0.0007, SMD = 0.65) [7]. This data indicates that lower intra-set fatigue may be most advantageous for exercises such as the barbell back squat, potentially because a given velocity loss threshold corresponds to a greater percentage of the total possible repetitions relative to their counterparts such as the smith machine bench press due to a faster velocity at 1RM [45], smaller simple slope (absolute decrease in ACV per 1 unit decrease in RIR) [24] and lower total velocity decline [16]. Nonetheless, the velocity loss zones established in the sub-analyses by Hickmott et al. [7] may provide a theoretical guideline for most exercises that may require small adjustments to specific exercises based on the collation of the velocity loss literature [7, 8, 25]. For example, the recommendation that the greatest allocation of RT with respect to the velocity loss thresholds is at ~20 – 25% velocity loss in squat movements may correspond to ~25 – 30% velocity loss in bench press movements, and ~15 – 20% velocity loss in deadlift movements as a potential theoretical reference due to the associated exercise-specific simple slopes [24] and velocity loss-percentage of repetitions completed relationships [16, 50]. These values also correspond to ~5% velocity loss below the level that initiates significant elevations in blood ammonia [47], and thereby may prevent excessive breakdown of purine
nucleotides that can impair performance for prolonged periods following RT (i.e., ~48 – 72 hours) [69].

Although the utility of low-moderate intra-set fatigue has been extrapolated to other RT paradigms (i.e., alternative set structures) [63], the overarching concept of velocity loss (i.e., quantifying neuromuscular fatigue) and aforementioned benefits have not been incorporated into other autoregulation practices (i.e., load autoregulation) and investigated in a longitudinal study. In autoregulation contexts, velocity loss has solely been utilized with magnitude-based thresholds to stipulate the termination of a set for autoregulating total relative volume [8, 24, 25]. However, if a fixed dosage of relative volume was desired (i.e., total repetitions at a given load), it may be valuable to know the number of repetitions that elicit a velocity loss zone (i.e., ~20 – 25%) at a given load for autoregulating load from set-to-set to not only maintain the intended load and proximity to failure as typically prescribed, but to also remain within the desired velocity loss zone. To the best of our knowledge, none of the current autoregulation methods have integrated such a concept in longitudinal study designs, albeit some acute study designs have employed similar concepts: Banyard et al. [70] compared the acute kinetic and kinematic variables of VBT and PBT in the back squat, whereby 25 total repetitions were completed at 80% of 1RM with a 20% velocity loss threshold determining the number of repetitions performed per set.

3.5 Individualized Last Repetition Velocities

A recent meta-analysis demonstrated a small effect for RBT over PBT (SMD = 0.30); however, the effect was negligible between VBT compared to PBT (SMD = 0.10) [7], which was primarily attributable to: (1) all RBT studies were comprised of RT interventions ranging from 8 – 12 weeks in length [21, 22, 71], whereas all VBT studies were <8 weeks [36, 72, 73]; and (2) half of the RBT studies employed significantly greater relative loads compared to PBT; however, all VBT studies failed to, plausibly as a result of the sub-optimal VBT methods previously described in this review. Nonetheless, RIR-based RPE is typically over-predicted (i.e., individuals tend to believe they have less RIR than actual RIR), yet training at a significantly higher RPE (lower RIR) produces significantly greater 1RM strength adaptations when sets and repetitions per set are equated between interventions [71] due to a higher relative load employed [2, 3]. Therefore, it appears that a method that more accurately quantifies RIR-based RPE and sessional relative load may be potentially justifiable of development and investigation.
In disagreement with the meta-analysis, when RBT and VBT were directly compared, VBT provided significantly greater 1RM strength adaptations in the barbell back squat (effect size: 1.37) and bench press (effect size: 0.98) after 12-weeks of RT [37]. Specifically, VBT yielded approximately two-fold greater increases for both the 6-week max-strength block (back squat: 8.8% vs 3.9%; bench press: 9.8% vs 4.7%), and the 6-week strength-speed block (back squat: 5.5% vs 2.9%; bench press: 4.9% vs 2.7%), in which the max-strength and strength-speed blocks were intended to be at group-based velocity zones corresponding to ~85 – 90% of 1RM (~1 – 2 RIR), and ~70 – 80% of 1RM (~2 – 3 RIR); respectively [37]. For the VBT protocol, all participants trained with the same velocity zones categorized into lower body, upper-body push, and upper-body pull, which comprised of considerably wide-ranging velocities for the intended percentage of 1RM and RIR, despite a plethora of evidence supporting that velocity should ideally be individualized for each participant [50], exercise [45], percentage of 1RM [51], and RIR [24, 46]. According to these collective findings, it appears that VBT may theoretically be ideal if VBT was individualized for each participant and exercise, whilst also integrated with the primary tenet of RPE (i.e., provide a value based on the number of RIR) to rectify the inherent subjectivity of traditional RBT and enable for greater relative loads to be achieved, whilst also accounting for performance changes. Within longitudinal load and volume autoregulation studies, VBT has been utilized to autoregulate: (1) relative load with load-velocity profiles [7]; and (2) neuromuscular fatigue with velocity loss thresholds [7, 8, 25]; however, VBT has yet to be employed to autoregulate proximity to failure in an objectively individualized fashion with the RIR-velocity relationship.

Indeed, pioneering data from Morán-Navarro et al. [46] and Hickmott [24] (addressed in section 5.1) has suggested that establishing RIR-velocity relationships may be a slight improvement upon prior RBT and VBT methods. An individualized last repetition average concentric velocity (LRV) corresponds to an individual’s ACV on the last repetition of a set for a specific exercise, serving as the fundamental velocity metric for the RIR-velocity relationship. For example, if an individual performed 3 repetitions at 80% of 1RM in the back squat, and the ACV on the third repetition was 0.30 m·s⁻¹, the LRV would be 0.30 m·s⁻¹. To further explain, if an individual performed 1 repetition at 90% of 1RM in the back squat, and the ACV on the single repetition was 0.20 m·s⁻¹, both the FRV and the LRV would be the same: 0.20 m·s⁻¹.
3.5.1 Advantages

The primary advantages of employing LRVs as an autoregulatory strategy are that velocities are reliable (i.e., consistently stable) at each individual RIR in the following three contexts: (1) regardless of the percentage of 1RM [46]; (2) across multiple sets [24, 66]; and (3) across multiple sessions [46]. The preliminary study supporting the efficacy of LRVs was conducted by Morán-Navarro et al. [46], in which it was established that the mean propulsive velocity corresponding to a specific RIR (2, 4, 6, and 8 RIR) was not significantly different during a set to failure at multiple percentages of 1RM (65, 75, and 85% of 1RM) across three sessions among separate exercises (smith machine back squat, bench press, shoulder press, and prone bench pull) and exhibited good reliability (coefficient of variation: 4.4 – 8.0%). Nonetheless, individuals typically perform multiple sets within a single RT session with free-weight exercises; indeed, Hickmott [24] demonstrated that in a sample of well-trained males, the ACV corresponding to particular RIRs ranging from 0 – 15 did not exceed the smallest detectable change for ACV across four sets at 80% of 1RM in a single session for each individual powerlift: barbell back squat, bench press, and deadlift. Upon visual inspection of the figures, Hickmott [24] indicated that ACVs of ~0.39, 0.40, 0.40, and 0.40 m s\(^{-1}\) corresponded to a 2 RIR at 80% of 1RM in the barbell back squat during sets one, two, three, and four; respectively. Similarly, Moran-Navarro et al. [46] reported that at 65, 75, and 85% of 1RM, respective mean propulsive velocities of 0.40 ± 0.03, 0.42 ± 0.04, and 0.39 ± 0.04 m s\(^{-1}\) corresponded to a 2 RIR in the smith machine back squat, which collectively with Hickmott [24] supports that for a given RIR, the velocity is reliable across multiple sets and regardless of the percentage of 1RM employed.

In further support, similar results indicating the reliability of the RIR-velocity relationship have been obtained in studies reporting the ACV achieved at a 0 RIR. Specifically, Hackett [66] revealed that for a given exercise, there was no significant difference in the ACV corresponding to a 0 RIR when 5 sets were performed to failure at 70% of 1RM in the barbell back squat and bench press. Recently, Sánchez-Moreno et al. [50] determined that when a single set to failure was performed per session for 5 sessions at 50, 60, 70, 80, and 90% of 1RM in a randomized order among participants, there was also no significant difference in the ACV at a 0 RIR (mean: 0.12 – 0.14 m s\(^{-1}\)). The results of these studies agree with the initial findings from Izquierdo et al. [74], demonstrating that the ACV at a 0 RIR was not significantly different at 60, 65, 70, and 75% of 1RM in the bench press (mean: 0.17 – 0.18 m s\(^{-1}\)) and in the parallel squat (mean: 0.31 –
0.33 m·s⁻¹). Moreover, Izquierdo et al. [74] exhibited that independent of load, the pattern of ACV decline for a given repetition was similar when a given magnitude of velocity loss was reached, further supporting the stability of the relationship between RIR and ACV at varying percentages of 1RM.

3.5.2 Limitations

The primary limitations of LRVs are: (1) as with all velocity metrics, they require individualization [24, 46, 66, 74]; (2) LRVs do not quantify the load employed; and (3) LRVs do not quantify the magnitude of intra-set fatigue accrued. Despite similar group averages reported for an ACV corresponding to a specific RIR within a particular exercise in the formerly described studies [24, 46, 66, 74], it must be highlighted that similar to the load-velocity and velocity loss-repetitions performed relationships, the RIR-velocity relationship should also be individualized for each participant and exercise. For instance, Hickmott [24] reported an ACV mean ± standard error (95% confidence interval) corresponding to a 4 RIR at 80% of 1RM of 0.447 ± 0.014 (0.417 – 0.476), 0.291 ± 0.015 (0.261 – 0.321), and 0.397 ± 0.015 (0.366 – 0.427) m·s⁻¹ in the barbell back squat, bench press, and deadlift; respectively [24]. Sánchez-Moreno et al. [50] reported an ACV range at 0 RIR with 80% of 1RM two-fold that of the smallest detectable change for ACV (0.06 – 0.18 m·s⁻¹) with considerable inter-individual variability (coefficient of variation = 30.5%) in the smith machine bench press. Similarly, Hackett [66] reported an ACV interquartile range of 0.25 – 0.44 m·s⁻¹ and 0.17 – 0.26 m·s⁻¹ corresponding to a 0 RIR at 70% of 1RM in the barbell back squat and bench press, respectively; further illustrating that the RIR-velocity relationship must be unique to both the lift and individual.
### Table A

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**Legend:**
- **Maximal Allocation:** ≤25 VL
- **Moderate Allocation:** >25 – 35 VL
- **Minimal Allocation:** >35 VL
- **Warmup Allocation:** VL > RIR

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**Figure 3.2** Individualized Last Repetition Velocity Model (LRV Model): a blank LRV Model; b example LRV Model of an elite powerlifter in the squat for 1RM strength development. The top left cell represents the L1RM; the top right cell represents the V1RM. The LRV corresponds to the respective RIR and individualized percentage of 1RM. Under each repetition, the left column represents individualized percentage of 1RM; the right column represents individualized percentage velocity loss. The velocity loss zones are adapted from the systematic reviews and meta-analyses on velocity loss thresholds [7, 8] and illustrate the recommended training allocation with respect to the primary goals of the individual. LRV individualized last repetition average concentric velocity in meters per second, L1RM load at one-repetition maximum in kilograms, RIR repetitions in reserve, VL percentage velocity loss, V1RM average concentric velocity at one-repetition maximum in meters per second, 1RM one-repetition maximum

### 3.6 Proposing A Theoretical Model

Although the establishment of the RIR-velocity relationship may enhance the efficacious properties of RBT (addressed in section 5), it does not account for the remaining essential variables and relationships highlighted and comprehensively explained throughout this review, such as sessional variances in 1RM load accomplished via load-velocity profiles and magnitudes of intra-set fatigue accomplished via velocity loss-repetitions performed profiles [7, 34]. Therefore, a conceptual model integrating all of these profiles may be a potential avenue to explore in future research and to contextualize for practical applications. To propose a theoretical model, the emerging concept of LRV may be utilized as the foundational velocity variable for the establishment of the aforementioned velocity-based relationships due to its widespread versatility.

The Individualized Last Repetition Velocity Model (LRV Model) may be proposed as a novel model that is unique to each individual and lift, yet also universally adaptive for numerous autoregulating and monitoring strategies. The blank LRV Model is illustrated in Figure 3.2a, and an example LRV Model for an elite-trained powerlifter in the squat with the primary goal of 1RM strength development is illustrated in Figure 3.2b. The conceptual velocity loss zones within the LRV Model may be established from the summarized systematic reviews and meta-analyses [7, 8] illustrated in Figure 3.1, contingent upon the primary goal of RT (i.e., strength, hypertrophy, velocity at submaximal loads, etc.). It is important to note that the LRV for a single...
repetition set at 0 RIR (the velocity at 1RM; V1RM) is different than the LRV for a multiple repetition set at a 0 RIR [75]; hence, our LRV Model also contains the V1RM. Likewise, the load at 1RM (L1RM) will fluctuate in the short-term and adapt in the long-term [12]; thus, the dynamic L1RM (rather than a pre-determined L1RM) must be incorporated for autoregulating and monitoring purposes, which may be determined from our proposed single strategies (addressed in section 6.3). For the LRV Model’s formulation, the overarching flow-diagram is illustrated in Figure 3.3, and the comprehensive step-by-step explanation of the example LRV Model in Figure 3.2b is included below.

**Figure 3.3** Formulation flow-diagram of the Individualized Last Repetition Velocity Model (LRV Model). *ACV* average concentric velocity, *LRV* individualized last repetition average concentric velocity, *L1RM* load at one-repetition maximum, *RIR* repetitions in reserve, *RM* repetition maximum, *RTF* repetition-to-failure, *VL* velocity loss, *V1RM* velocity at one-repetition maximum, *1RM* one-repetition maximum

The systematic formulation of the individual- and exercise-specific Individualized Last Repetition Velocity Model (LRV Model) is comprised of one testing session; the testing session is comprised of a one-repetition maximum (1RM) test and a repetition-to-failure (RTF) test. Upon completion of the testing session, individualized last repetition average concentric velocity (LRV), individualized velocity loss, and individualized percentage of 1RM values are
retroactively determined and inputted into the blank LRV Model (Figure 3.2a) to create the individual- and exercise-specific LRV Model (example in Figure 3.2b). The testing session must be performed with maximal intended concentric velocity on all repetitions, and a rest period of ~10 minutes is provided between the 1RM test and RTF test to ensure maximal performance during the testing session. The 1RM test should involve ~10, 5, 3, 2, 1, 1, 1, 1, and 1 repetition sets at ~0, 20, 40, 60, 70, 80, 85, 90, 95, and 100% of 1RM; respectively, with autoregulated rest periods from ~0 – 70% of 1RM, and ~5 – 10-minute rest periods from ~70 – 100% of 1RM. The RTF test should generate ~10 repetitions in order to provide the LRVs corresponding to 0 – 9 repetitions in reserve (RIR); therefore, for the majority of individuals on most lifts, the relative intensity will be ~80% of 1RM. Nonetheless, in the event that 10 repetitions are not achieved on the RTF test, the remaining LRVs corresponding to the remaining RIR values may be determined by establishing the second order polynomial regression equation between LRV and RIR from the existing repetitions to forecast the remaining LRVs.

The initial step to formulate the LRV Model is to determine and input the LRV corresponding to each whole RIR (i.e., 0, 1, 2, etc. RIR). Specifically, to determine the LRV, the average concentric velocity (ACV) at each whole RIR value from the RTF test is retroactively determined. For example, if the second final repetition prior to failure elicited an ACV of 0.16 metres per second (m·s⁻¹), the LRV at 1 RIR is 0.16 m·s⁻¹. The subsequent step is to determine and input the LRV corresponding to each half RIR (i.e., 0 – 1, 1 – 2, 2 – 3, etc. RIR), indicating definitely a certain RIR and maybe 1 additional RIR. The LRV corresponding to each half RIR is the average between the LRV at the whole RIR above, and the LRV at the whole RIR below. For example, if the LRV at 1 RIR is 0.16 m·s⁻¹, and the LRV at 2 RIR is 0.20 m·s⁻¹; then, the LRV at 1 – 2 RIR is 0.18 m·s⁻¹.

The subsequent step is to determine and input the typical individualized velocity loss for each repetition and RIR combination. For example, the velocity loss for 3 repetitions at 3 RIR is 25%, if the first (fastest) repetition corresponds to 5 RIR, eliciting an LRV of 0.32 m·s⁻¹, and the last (slowest) repetition corresponds to 3 RIR, eliciting an LRV of 0.24 m·s⁻¹ (i.e., velocity loss = [0.32 – 0.24] / 0.32 x 100%). The subsequent step is to determine and input the typical individualized velocity loss into each remaining repetition and RIR combination by evaluating the LRV decay (increase in velocity per increase in RIR). For example, if the LRV decay at ≥5
RIR is 0.02 m s\(^{-1}\); then, the LRV for 11 RIR is 0.44 m s\(^{-1}\); therefore, for example, the velocity loss for 7 repetitions at 5 RIR is 27% (i.e., velocity loss = \([0.44 - 0.32] / 0.44 \times 100\%\)).

The subsequent step is to provide the individualized velocity loss for each repetition and RIR combination a specific color; illustrative of optimal training allocation based on the overall meta-analytic findings for velocity loss (Figure 3.1) with respect to the goal (i.e., strength, power, hypertrophy, etc.) of the individual. For example, the primary goal of a powerlifter is to optimize 1RM strength; therefore, it may be recommended that most of the training should be allocated to 0 – 25% velocity loss at a high percentage of 1RM. Specifically, in this context (i.e., powerlifting for 1RM strength), velocity loss values ≤25% are colored green, >25 – 35% are colored yellow, and >35% are colored red, while all velocity loss values >5 RIR are colored blue. The green, yellow, and red zones are termed maximal, moderate, and minimal, respectively; illustrating how the most, some, and least amount of training should be allocated; respectively, with respect to the athlete’s context and goals. Additionally, the blue zone is termed warmup in this context to highlight that performing most training at ≤5 RIR within the green zone ensures that percentage of 1RM is maintained moderate-high for 1RM strength. Nonetheless, the blue zone is still included in the LRV Model to provide a valuable assessment of readiness and performance, to serve as a suitable prescription for power and recovery sessions, and if the goal is to promote neuromuscular adaptations for neuromuscular performance tasks (i.e., jumping, sprinting, etc.). Finally, it is important to note that based on the available evidence from the meta-analyses on velocity loss, the majority of training within the green zone may be performed at a velocity loss ≥20% to maximize strength and hypertrophy adaptations; however, at a velocity loss ≤25% to prevent negative neuromuscular adaptations and excessive neuromuscular fatigue in order to optimize 1RM strength.

The subsequent step is to determine and input the individualized percentage of 1RM for each 1 repetition and RIR combination from the 1RM test. From the sets of the 1RM test, each percentage of 1RM is inputted into its respective cell at the appropriate 1 repetition column and RIR combination based on the ACV of repetition 1. For example, if during the 1RM test, the ACV on repetition 1 at 85% of 1RM was 0.28 m s\(^{-1}\), and an ACV of 0.28 m s\(^{-1}\) corresponds to 4 RIR based on the RTF test, then 85% of 1RM is inputted into the cell corresponding to 1 repetition at 4 RIR. Furthermore, from the 1RM test, 1 repetition at 0 RIR is 100% of 1RM for
every individual; thus, 100% is inputted into the cell corresponding to 1 repetition at 0 RIR for every individual.

The subsequent step is to determine and input the individualized percentage of 1RM into each remaining 1 repetition and RIR combination. The percentage of 1RM for each remaining 1 repetition and RIR combination is determined by subtracting the most immediate cell below with a percentage of 1RM value from the most immediate cell above with a percentage of 1RM value and dividing this value by one more than the number of blank cells between the most immediate cell above and below with a percentage of 1RM value. This value is subtracted from the most immediate cell above with a percentage of 1RM value to provide the final resultant percentage of 1RM value for that particular cell. For example, if the percentage of 1RM for 1 repetition at 3 RIR is to be determined, the most immediate cell below with a percentage of 1RM value may be 85% of 1RM (1 repetition at 4 RIR (LRV of 0.28 m/s)), and the most immediate cell above with a percentage of 1RM value may be 89.38% of 1RM (1 repetition at “2.25 RIR” (LRV of 0.21 m/s)). Therefore, 85% of 1RM is subtracted from 89.38% of 1RM to provide 4.38%, which is divided by 3.5 to provide 1.25%. Subsequently, half of 1.25% (0.625%) is subtracted from 89.38% of 1RM to provide a final resultant 88.75% of 1RM for the cell representative of 1 repetition at 2 – 3 RIR. Moreover, 1.25% is subtracted from 88.75% of 1RM to provide a final resultant 87.5% of 1RM for the cell representative of 1 repetition at 3 RIR. Similarly, 1.25% is subtracted from 87.5% of 1RM to provide a final resultant 86.25% of 1RM for the cell representative of 1 repetition at 3 – 4 RIR.

The subsequent step is to retroactively determine and input the individualized percentage of 1RM into each remaining repetition and RIR combination. For example, 1 repetition at 2 – 3 RIR is 88.75% of 1RM; thus, by definition, 2 repetitions at 1 – 2 RIR is 88.75% of 1RM, and 3 repetitions at 0 – 1 RIR is 88.75% of 1RM. The subsequent step is to determine and input the percentage of 1RM into each remaining repetition and RIR combination by evaluating the average decrease in percentage of 1RM per increase in repetition for each RIR value. For example, if the average decrease in percentage of 1RM per increase in repetition for 5 RIR is 2.5%; then, 6, 7, 8, 9, and 10 repetitions at 5 RIR is 70, 67.5, 65, 62.5, and 60% of 1RM; respectively.

The final step to formulate the LRV Model is to determine the load at 1RM (L1RM) and velocity at 1RM (V1RM.) The L1RM is specific to the session; however, the pre-determined
L1RM is the heaviest load attained from the 1RM testing session. Furthermore, the typical sessional V1RM is the ACV attained at the heaviest load from the 1RM testing session. For example, if during the 1RM testing session, the load and ACV was 302.5 kilograms (kg) and 0.10 m\text{s}^{-1}; respectively, the pre-determined L1RM is 302.5 kg and the typical sessional V1RM is 0.10 m\text{s}^{-1}. After formulating the LRV Model, it may be investigated in research and applied in practice.

### 3.6.1 Advantages

A notable advantage of individualized RIR-velocity relationships is that it involves velocity; thereby, the individualized load-velocity, velocity loss-repetitions performed, and load-repetitions performed relationships may also be established to formulate a more holistic theoretical autoregulatory model by which the conceptual integration of multiple methods provides advantages that seemingly mitigates the limitations of the current standalone methods that have been thoroughly synthesized throughout this review (sections 2 – 5). The load-velocity relationship is imperative as relative load is a principal variable influencing strength adaptations [2, 3]; however, since the load at 1RM may fluctuate on a sessional basis [12], the velocity enables for the measurement and adjustment component of autoregulation to be applied: load is systematically monitored and manipulated [48]. Moreover, the velocity loss-repetitions performed relationship has been supported to be indicative of muscular adaptations: low-moderate and moderate-high intra-set fatigue during RT produces significantly greater gains in 1RM strength and CSA hypertrophy; respectively [7]. Specifically, \(~20 – 25\%\) velocity loss was optimal for 1RM strength; further, \(~20 – 25\%\) velocity loss was the threshold in which larger increases in velocity loss did not promote significantly greater hypertrophy [7]. The load-repetitions performed relationship enables for the individualized prescription element of autoregulation to be enforced: load is adjusted conforming to the individualized percentage of 1RM rather than an arbitrary percentage or absolute value as has typically been imposed in the current investigations [21, 22].

### 3.6.2 Limitations

Although we believe that the proposed LRV Model may potentially be a slight improvement upon prior methods and provides a theoretical framework for a more holistic conceptualization of autoregulatory practices it is certainly not without limitations. The main evident limitation is that the LRV Model (or sub-variations of the LRV Model) should be
investigated and compared to other autoregulation methods to discern whether it will indeed provide an advantage across longitudinal study clinical trials on muscular adaptations (i.e., strength, hypertrophy, power, etc.) and performance (i.e., sprinting, jumping, velocity attained at submaximal loads, etc.).

It is imperative to highlight that it is improbable that the LRVs elicited in a RT session will always precisely match the LRVs of the individual’s LRV model; thus, to account for this, there are two viable solutions. First, the LRV elicited may be rounded to the nearest LRV and corresponding RIR within the individual’s LRV Model. For example, if a LRV of 0.31 m s\(^{-1}\) is elicited in a session, but the individual’s LRV Model does not contain a value of 0.31 m s\(^{-1}\) (i.e., the individual’s LRV Model contains values of 0.30 and 0.34 m s\(^{-1}\) corresponding to 5 and 6 RIR; respectively), then the LRV would be rounded to correspond to 5 RIR. Second, an LRV range (an LRV value ± 0.03 m s\(^{-1}\)) and/or RIR range (i.e., an RIR value ± 0 – 1 RIR) may be prescribed. In a similar regard, the individualized velocity loss values for each repetition-RIR combination represent the typical velocity loss values; thus, the actual velocity loss values attained during a session may deviate slightly based on the exact FRV and LRV achieved during the set.

Nonetheless, it is noteworthy to recognize that precision is unnecessary with respect to velocity loss values, since the available meta-analytic evidence [7, 8, 25] suggests that conceptual velocity loss zones rather than precise velocity loss values dictate specific RT-induced adaptations; hence, the establishment of velocity loss zones and allocation distributions with respect to the primary goals of the individual in our LRV Model. Furthermore, it remains to be elucidated whether repetitions performed at given relative intensities (i.e., individualized percentages of 1RM) change on a short- and/or long-term basis. Despite the possibility that an individual may have subtle intra-individual variability in the number of repetitions that they can perform at a given percentage of their 1RM, we consider our LRV Model an improvement owing to the substantial inter-individual variability in this phenomenon (i.e., a range of 6 – 26 repetitions at 70% of 1RM) [13].

Since the relationship between velocity and percentage of 1RM remains consistently stable (i.e., is reliable) in longitudinal studies [52, 72], we believe that the LRV Model can be tested in future studies; however, the LRVs in the LRV Model plausibly require updating in longer-term practical settings, as an individual’s velocity for a given RIR and percentage of 1RM tends to decrease slightly (i.e., becomes slower) with RT experience [17, 76]. A limitation of
VBT as an entirety is that it does not account for technical errors in performance execution (i.e., if an individual’s barbell path deviates considerably on a repetition compared to their normal barbell path). Therefore, if velocity alone is used for autoregulatory purposes, the measured velocity may cause inappropriate ensuing prescription (i.e., an unworthy load adjustment or set termination); thus, it may be wise to also incorporate a subjective RPE value, in addition to other tools (i.e., video feedback) [77] in practical settings.

It is necessary to acknowledge the complexity of the LRV Model compared to simpler programming methods previously mentioned. In practice, applying our LRV Model to participants or athletes would likely require supervision by an experienced researcher and strength and conditioning practitioner in VBT autoregulating and monitoring. Furthermore, its utility for training large groups of participants or a large team of athletes that perform numerous multi-joint compound exercises may be problematic.

3.6.3 Future Directions

Notwithstanding the limitations, we would like to highlight that our proposed theoretical LRV Model may simply serve as a potential conceptual foundation that may be compared to the current autoregulation methods in future studies. The current methods that have been addressed in this review for load, volume, and single strategies are presented in Table 3.1, Table 3.2, and Table 3.3; respectively. For each of the current methods, potential solutions from the example LRV Model are also presented exhibiting the advantages of LRVs as explained herein this review.
<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
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<th>Overview</th>
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<th>Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PBT</td>
<td>Current method</td>
<td>Description\Prescribe a sub-optimal dosage of volume via a generalized set and repetition scheme at a generic percentage of 1RM from a generalized repetitions allowed table</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Example</td>
<td>3 sets of 4 repetitions at 82.5% of typical 1RM</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>LRV load maintenance strategy</td>
<td>Proposed method</td>
<td>Description\Prescribe an optimal dosage of relative volume via a total number of repetitions at a specific percentage of 1RM with an individualized repetition number within Green Zone of LRV Model (i.e., at ~20 – 25% VL) for set 1 and RIR target based on the LRV for all sets</td>
<td>Measure the LRV upon completion of each set to determine the RIR based on the LRV</td>
<td>Set 2: LRV of 0.20 m s$^{-1}$ corresponding to 2 RIR (38% VL / Red Zone)</td>
<td>Set 3: Prescribe 2 repetitions at 250 kg (since, on set 2, the RIR based on the LRV was 1 less than the RIR target of 3)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Example</td>
<td>12 total repetitions at 82.5% of typical 1RM (250 kg) with 3 repetitions for set 1 and 3 RIR target based on the LRV for all sets</td>
<td>Set 2: Subjectively estimate 1 RIR / 9 RPE</td>
<td>Set 3: Prescribe 3 repetitions at 250 kg (since, on set 2, the RIR was 1 less than the RIR target range of 2 – 4)</td>
</tr>
<tr>
<td>2</td>
<td>RBT</td>
<td>Current method</td>
<td>Description\Prescribe a sub-optimal dosage of volume via a generalized set and repetition scheme at a subjectively estimated RIR target range</td>
<td>Subjectively estimate RIR upon completion of each set</td>
<td>For each subsequent set, perform a universal 4% load increase/decrease per subjectively estimated RIR higher/lower than the RIR target range</td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td>Example</td>
<td>3 sets of 4 repetitions at 2 – 4 RIR / 6 – 8 RPE (typically ~82.5% of 1RM / ~250 kg)</td>
<td>Set 2: Subjectively estimate 1 RIR / 9 RPE</td>
<td>Set 3: Prescribe 3 repetitions at a 4% load decrease (240 kg; since, on set 2, the RIR was 1 lower than the RIR target range of 2 – 4)</td>
</tr>
<tr>
<td>LRV load adjustment strategy</td>
<td>Proposed method</td>
<td>Description\Prescribe an optimal dosage of relative volume via an individualized set and repetition scheme within Green Zone of LRV Model (i.e., at ~20 – 25% VL)</td>
<td>Measure LRV upon completion of each set to determine the actual percentage of 1RM and estimated 1RM of set based on the LRV</td>
<td>For each subsequent set, prescribe same repetition number at same percentage of 1RM based on estimated 1RM from prior set</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Example</td>
<td>4 sets of 3 repetitions at 82.5% of typical 1RM (250 kg)</td>
<td>Set 2: LRV of 0.20 m s$^{-1}$ (2 RIR / 38% VL / Red Zone) corresponding to 85% of 1RM and estimated 1RM of 294 kg</td>
<td>Set 3: Prescribe 3 repetitions at 82.5% of 294 kg (242.5 kg; since, on set 2, the actual percentage of 1RM for 250 kg was 85% and estimated 1RM was 294 kg based on the LRV)</td>
</tr>
</tbody>
</table>

$k$ kilograms, $LRV$ individualized last repetition average concentric velocity, $m s^{-1}$ meters per second, $PBT$ percentage-based training, $RBT$ rating of perceived exertion-based training, $RIR$ repetitions in reserve, $RPE$ rating of perceived exertion based on subjective estimation of repetitions in reserve, $VL$ velocity loss, $1RM$ one-repetition maximum
<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
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<th>Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RPE stop</td>
<td>Current</td>
<td>Description</td>
<td>Prescribe a given percentage of 1RM with a generalized number of repetitions per set and terminate session once a specific subjectively estimated RIR for a set is achieved</td>
<td>Subjectively estimate RIR upon completion of each set</td>
<td>Terminate session once a specific subjectively estimated RIR for a set is achieved</td>
</tr>
<tr>
<td></td>
<td></td>
<td>method</td>
<td>Example</td>
<td>Perform sets of 3 repetitions at 82.5% of typical 1RM (250 kg) until a subjectively estimated 2 RIR / 8 RPE for a set is achieved</td>
<td>Set 4: Subjectively estimate 2 RIR / 8 RPE</td>
<td>Set 4: Terminate session after set 4 (since, on set 4, the subjectively estimated 2 RIR / 8 RPE was achieved)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LRV volume cap strategy Proposed method</td>
<td>Description</td>
<td>Measure the LRV upon completion of each set to determine the RIR based on the LRV</td>
<td>Terminate session once a specific RIR based on the LRV for a set is achieved or a total number of sets are achieved</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Example</td>
<td>Perform sets of 3 repetitions at 82.5% of typical 1RM (250 kg) until 2 RIR based on the LRV for a set is achieved or 5 total sets are achieved</td>
<td>Set 4: LRV of 0.20 m s⁻¹ corresponding to 2 RIR (38% VL / Red Zone) achieved</td>
<td>Set 4: Terminate session after set 4 (since, on set 4, the 2 RIR based on the LRV was achieved)</td>
</tr>
<tr>
<td>2</td>
<td>VL threshold</td>
<td>Current</td>
<td>Description</td>
<td>Prescribe a sub-optimal dosage of set volume at a given percentage of 1RM with a generalized VL threshold for each set</td>
<td>Measure VL upon completion of each repetition</td>
<td>Terminate the set when the prescribed VL threshold is achieved</td>
</tr>
<tr>
<td></td>
<td></td>
<td>method</td>
<td>Example</td>
<td>3 total sets at 82.5% of typical 1RM (250 kg) with a 20% VL threshold for each set</td>
<td>Set 1: 20% VL achieved on repetition 4</td>
<td>Set 1: Terminate set after repetition 4 (since, on repetition 4, the 20% VL threshold was achieved)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LRV volume stop strategy Proposed method</td>
<td>Description</td>
<td>Measure LRV upon completion of each repetition to determine the RIR based on the LRV</td>
<td>Terminate the set when the prescribed RIR based on the LRV is achieved</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>Example</td>
<td>4 total sets at 82.5% of typical 1RM (250 kg) with 3 RIR based on the LRV stop for each set</td>
<td>Set 1: LRV of 0.24 m s⁻¹ corresponding to 3 RIR (25% VL / Green Zone) achieved on repetition 3</td>
<td>Set 1: Terminate set after repetition 3 (since, on repetition 3, the 3 RIR based on the LRV was achieved)</td>
</tr>
</tbody>
</table>

kg kilograms, LRV individualized last repetition average concentric velocity, m s⁻¹ meters per second, RIR repetitions in reserve, RPE rating of perceived exertion based on subjective estimation of repetitions in reserve, VL velocity loss, 1RM one-repetition maximum
<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
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<th>Prescription</th>
<th>Measurement</th>
<th>Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Individualized regression equation(s) of submaximal velocity</td>
<td>Current method</td>
<td>Description</td>
<td>Prescribe generalized ramp-up and forecast estimated 1RM from individualized regression equation(s) of submaximal velocity</td>
<td>Measure velocity of initial repetition upon completion of each set and perform individualized regression equation(s) of submaximal velocity to forecast estimated 1RM</td>
<td>Prescribe ensuing sessional prescription from estimated 1RM and/or monitor estimated 1RM across training cycle</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LRV top single strategy</td>
<td>Proposed method</td>
<td>Description</td>
<td>Prescribe a top single repetition at a specific RIR based on the LRV to commence the session with individualized set-to-set load adjustments commencing at ( \approx 70% ) of 1RM</td>
<td>Measure LRV upon completion of each set at ( \geq 70% ) of 1RM (performing single repetition sets) to determine the actual percentage of 1RM and estimated 1RM of each set based on the LRV</td>
<td>For each subsequent set, prescribe percentage of 1RM based on estimated 1RM from prior set; determine sessional estimated 1RM from LRV corresponding to a specific percentage of 1RM on top set; autoregulate and monitor from sessional estimated 1RM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Example</td>
<td></td>
<td></td>
<td>Prescribe ramp-up of ~20, 40, 60, 80, 90% of 1RM</td>
<td>Perform 5-point 20, 40, 60, 80, 90% of 1RM individualized regression equation of submaximal velocity to forecast estimated 1RM of 325 kg</td>
<td>Prescribe ensuing sessional prescription from estimated 1RM of 325 kg and/or monitor estimated 1RM of 325 kg across training cycle</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Generalized load-velocity profile</td>
<td>Current method</td>
<td>Description</td>
<td>Prescribe generalized velocity values for given percentages of 1RM from generalized load-velocity profile to commence each set or session</td>
<td>Measure velocity upon completion of repetition to determine actual percentage of 1RM and estimated 1RM of each set or session</td>
<td>Prescribe ensuing set or sessional prescription from estimated 1RM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Example</td>
<td></td>
<td></td>
<td>Perform top single repetition at 2 RIR based on the LRV (~90% of 1RM)</td>
<td>Performance ‘normal’ until final ramp-up set at 85% of typical 1RM (257.5 kg); LRV of 0.24 m s(^{-1}) (3 RIR) corresponding to 87.5% of 1RM and estimated 1RM of 294 kg</td>
<td>For top set, prescribe 90% of 294 kg (265 kg); if top set of 265 kg elicits an LRV of 0.20 m s(^{-1}) (2 RIR) corresponding to 90% of 1RM and estimated 1RM of 294 kg, the sessional estimated 1RM is 294 kg; autoregulate and monitor from sessional estimated 1RM of 294 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LRV base single strategy</td>
<td>Proposed method</td>
<td>Description</td>
<td>Prescribe a base single repetition at a given percentage of 1RM to commence each set or session</td>
<td>Measure LRV upon completion of repetition to determine actual percentage of 1RM and estimated 1RM of each set or session</td>
<td>Prescribe ensuing set or sessional prescription from estimated 1RM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Example</td>
<td></td>
<td></td>
<td>Perform base single repetition at 82.5% of typical 1RM (250 kg)</td>
<td>LRV of 0.34 m s(^{-1}) (6 RIR) corresponding to 80% of 1RM and estimated 1RM of 312.5 kg</td>
<td>Prescribe ensuing set or sessional prescription from estimated 1RM of 312.5 kg</td>
<td></td>
</tr>
</tbody>
</table>

kg kilograms, \( LRV \) individualized last repetition average concentric velocity, \( m s^{-1} \) meters per second, \( RIR \) repetitions in reserve, \( 1RM \) one-repetition maximum
3.6.4 Practical Applications

The proposed theoretical LRV Model may be integrated into top-down periodized and bottom-up framework approaches within practical application contexts to assist RT professionals. Figure 3.4 illustrates an example of a top-down periodized approach for a strength athlete (i.e., a powerlifter), exemplifying three key points: (1) relative volume decreases throughout the macrocycle to counteract the corresponding increase in relative intensity as force-velocity specificity [2, 3, 78, 79] of a 1RM escalates to peak strength performance at competition; (2) LRV decreases (and thus the RIR decreases / RPE increases) throughout the macrocycle to optimize force-time specificity [55, 56, 65] of a 1RM as an athlete progresses towards competition; and (3) velocity loss values decline across the macrocycle to amalgamate the velocity loss-specific spectrum of acute responses and chronic adaptations in a methodological order for diminished fatigue and maximal performance [7, 8, 25]. Figure 3.5 illustrates an example of a bottom-up framework approach for a strength athlete (i.e., a powerlifter), demonstrating three essential factors: (1) the top set involves ramping up to a high percentage of 1RM, which provides a more accurate assessment of sessional 1RM [80, 81] with the identical prescription from session-to-session enabling for consistent monitoring of estimated 1RM; (2) the base sets involve maintaining a constant load, which manifests a self-competition by encouraging the athlete to perform the load at faster LRVs (i.e., at greater RIRs); forcing maximal intended concentric velocity, which attenuates velocity loss [42] and has several associated neuromuscular benefits [43, 82, 83]; and (3) overall, fatigue is balanced as the load of the top set increases towards an automated test, whilst the velocity loss of the base sets decreases towards an automated taper. The proposed methods presented in Table 3.1, Table 3.2, and Table 3.3 may be appropriately applied within the two aforementioned approaches.
Figure 3.4 Example top-down periodized approach integrated block strategy. Metrics for each session type (hypertrophy, power, strength) across the mesocycles/blocks (1: hypertrophy; 2: strength; 3: peaking): a average relative intensity (percentage of 1RM); b average RIR (based on LRV); c average VL (based on relative intensity and RIR/LRV). LRV individualized last repetition average concentric velocity, RIR repetitions in reserve, VL percentage velocity loss, 1RM one-repetition maximum
Figure 3.5 Example bottom-up framework approach hybrid block strategy. a example top set peak static RIR based on the LRV strategy illustrating a top set single repetition at 2 RIR based on the LRV (0.20 m·s⁻¹); b example base sets average static load strategy illustrating 5 sets of 3 repetitions with a load typically corresponding to 2 RIR based on the LRV (250 kg). kg kilograms, LRV individualized last repetition average concentric velocity, m·s⁻¹ meters per second, RIR repetitions in reserve, 1RM one-repetition maximum

3.7 Conclusion

In this review, we critically evaluated the current methods of load and volume autoregulation to provide a balanced and authoritative overview of their advantages and limitations, in addition to propose a novel theoretical model. Specifically, we comprehensively reviewed the following: (1) PBT (percentage-based training) for traditional RT; (2) RBT (RPE-based training), load-velocity profiles, and velocity zones for load autoregulation; and (3) RPE stops and velocity loss thresholds for volume autoregulation. Our review has highlighted that the limitations of particular autoregulation methods are seemingly rectified through the advantages of other autoregulation methods. Therefore, we have proposed a theoretical model based on the emerging concept of LRVs (individualized last repetition average concentric velocities) that conceptually integrates the advantages and ameliorates the limitations of the current mutually
exclusive autoregulation methods. Moreover, we have exemplified how LRVs serve as a foundation for our proposed theoretical model to establish individualized load-velocity, proximity to failure-velocity, and velocity loss-repetitions performed relationships for considerable versatility within autoregulation practices. It is hoped that our review provides an overarching autoregulation framework for exploration as RT professionals and in future research to consistently progress the area of autoregulation.

3.8 References


68. Weakley J, Ramirez-Lopez C, McLaren S, Dalton-Barron N, Weaving D, Jones B et al. The effects of 10%, 20%, and 30% velocity loss thresholds on kinetic, kinematic, and repetition


The two most common methods for autoregulating proximity to failure and neuromuscular fatigue outlined in the narrative review (Chapter 3) involve applying the repetitions in reserve (RIR)-based rating of perceived exertion (RPE) scale and velocity loss thresholds; respectively; however, both methods possess considerable limitations [1]. A potential improved method that enables autoregulation of both proximity to failure and neuromuscular fatigue involves establishing individualized average concentric last repetition velocities (LRVs) corresponding to a particular number of RIR (for autoregulating proximity to failure) and corresponding to velocity loss values (for autoregulating neuromuscular fatigue) [2]. Therefore, the primary purpose of the acute study (Chapter 4) is to investigate whether a typical variable that autoregulation monitors as a proxy of performance (proximity to failure) can be more accurately measured with a simplified integrated iteration (LRV-RIR profiles) of the Individualized Last Repetition Velocity Model (LRV Model) proposed in Chapter 3 compared to the current primary method (subjective estimations). It was hypothesized that objective velocities would demonstrate significantly greater accuracy than subjective predictions at quantifying proximity to failure from an acute standpoint under numerous conditions prevalent in resistance training contexts (Chapter 4); thus if our hypothesis was supported, the subsequent step is to compare the potential efficacy of prescribing load with autoregulated objective velocities (LRV-RIR profiles) to autoregulated subjective estimations (RIR-based scales) and fixed percentage-based training from a chronic standpoint in a longitudinal study (Chapter 5).

References:
4. A COMPARISON OF SUBJECTIVE ESTIMATIONS AND OBJECTIVE VELOCITIES AT QUANTIFYING PROXIMITY TO FAILURE FOR THE BENCH PRESS IN RESISTANCE TRAINED MALES AND FEMALES

Abstract
The purpose of this study was to compare the accuracy of quantifying repetitions in reserve (RIR) in the bench press among 18 males and 18 females between two conditions: 1) subjective estimations; and 2) objective velocities. Participants performed four sessions over ten days: 1) one-repetition maximum (1RM) test; 2) repetition-to-failure test at 80% of 1RM; 3) 3 sets to failure at 80% of 1RM; and 4) 3 sets to failure at 75, 80, and 85% of 1RM. During sessions 2, 3, and 4, participants were blinded to the loads and verbally stated when they believed they had 4 and 2 RIR, while average concentric velocity was recorded on all repetitions. The dependent variable was difference between RIR estimated either subjectively or objectively and actual RIR with significance at $p \leq 0.05$. Session 3 and 4 had significant ($p < 0.001$) condition x set and condition x load interactions; respectively, at both 4 and 2 RIR. Objective velocities were significantly more accurate than subjective estimations on set 1 and 2 at both RIRs during session 3, and for 75 and 80% of 1RM at both RIRs during session 4. During session 3, set 3 was significantly more accurate than set 2, which was significantly more accurate than set 1 for subjective estimations at both RIRs. Furthermore, 85% of 1RM was significantly more accurate than 80 and 75% of 1RM for subjective estimations at both RIRs. Objective velocities exhibit greater accuracy than subjective estimations during initial sets and lower loads, particularly at greater RIR.

4.1 Introduction
Proximity to failure (i.e., the number of repetitions remaining prior to momentary muscular failure) is a crucial resistance training (RT) program design variable, as recent evidence has supported that RT with lower intra-set fatigue appears to be optimal for muscular strength and power, whereas RT with greater intra-set fatigue appears to be optimal for muscular hypertrophy and endurance [1-4]. The magnitude of intra-set fatigue induced from a bout of RT
dictates the time course of recovery [5, 6], which has implications for prescribing RT load, volume, and frequency, in addition to appropriately structuring RT within sport competition schedules [7-9]. Although subjective estimations that utilize repetitions in reserve (RIR)-based scales [10, 11] are arguably the primary method to quantify proximity to failure in RT contexts, individuals have varying accuracy in their ability to estimate proximity to failure [12]. Consequently, those that are prone to inaccurate estimations of proximity to failure or during instances when subjective estimations are generally less accurate (i.e., at lower loads and greater RIR) [12], individuals may train with an unintended proximity to failure, magnitude of intra-set fatigue, load, and/or volume; thereby, potentially leading to sub-optimal physiological adaptations and performance outcomes [1].

Emerging research has suggested that objective velocities may be an improved method worthy of further elucidation [1, 13, 14]; however, to our knowledge, no study has directly compared the accuracy of the two methods (subjective estimations vs objective velocities) at quantifying proximity to failure. Preliminary data from Morán-Navarro et al. [14] demonstrated that the mean propulsive velocity (MPV) corresponding to a specific RIR (2, 4, 6, and 8) was reliable (coefficient of variation: 4.4 – 8.0%) regardless of the load employed (65, 75, and 85% of one-repetition maximum (1RM)) for each individual smith machine exercise examined (squat, bench press, shoulder press, and prone bench pull) across multiple sessions (6 sessions) amongst differing training statuses of male participants. Moreover, Hackett [15] found that there was no significant difference in the average concentric velocity (ACV) associated with 0 RIR across 5 sets at 70% of 1RM in the squat as well as the bench press in resistance-trained males. Several factors warrant greater investigation prior to implementing objective velocities as a method to quantify proximity to failure as an autoregulatory strategy in future longitudinal studies. Perhaps most noteworthy involves evaluating the accuracy of objective velocities when load fluctuates across sets within a single RT session as the investigation conducted by Morán-Navarro et al. [14] performed a single set per session for each exercise.

Indeed, a fundamental tenet of autoregulation constitutes measuring performance and adjusting prescription [16], which is commonly accomplished by measuring proximity to failure and adjusting load from set-to-set for ensuring that the intended load and proximity to failure is accurately achieved to elicit the desired acute responses and chronic adaptations [1, 17-19]. It remains to be determined whether objective velocities via individualized last repetition average
concentric velocities (LRVs) corresponding to a given RIR has differing accuracy than subjective estimations of RIR for quantifying proximity to failure across multiple sets in a given session when the load fluctuates on each set. Albeit comprehensive RT programs may integrate both subjective estimations and objective velocities for quantifying proximity to failure, autoregulation strategies, and monitoring purposes, in the instance that one method (subjective estimations or objective velocities) exhibits significantly greater accuracy, it may be justified to further compare the two methods in a longitudinal autoregulation study to discern if greater accuracy indeed produces superior outcomes.

Therefore, the primary purpose of this study was to compare the accuracy of subjective estimations to objective velocities for quantifying proximity to failure at 4 and 2 RIR in the barbell bench press in males and females under numerous situations: 1) across 3 sets when the load is fixed (80% of 1RM for all sets); 2) across 3 sets when the load is adjusted (75, 80, and 85% of 1RM in a randomized order among participants); and 3) across 2 sessions. The main hypothesis was that objective velocities would result in considerably greater accuracy than subjective estimations for quantifying proximity to failure at both 4 and 2 RIR across the 2 sessions, and on all 3 sets when the load was fixed at 80% of 1RM, but that there would be no significant difference between conditions at 2 RIR for 85% of 1RM according to the findings of a meta-analysis [12] suggesting that subjective estimations are most accurate at close proximities to failure and heavy loads. The secondary hypothesis was that objective velocities would not be significantly different across all situations (i.e., objective velocities would remain consistently stable) in their ability to accurately quantify proximity to failure; however, it was also hypothesized that subjective estimations would be more accurate as sets ensued in the third session when load was fixed, and as loads increased in the fourth session when load was adjusted.

4.2 Methods
4.2.1 Experimental Approach to the Problem

The experimental design was a 10-day intervention that consisted of 36 total participants (18 males and 18 females) comparing the accuracy of two methods (subjective estimations vs objective velocities) for quantifying proximity to failure at 4 and 2 RIR in the barbell bench press under 3 circumstances: 1) across 3 sets to failure at the same load (80% of 1RM); 2) across 3 sets
to failure at differing loads in a randomized order among participants (75, 80, and 85% of 1RM); and (3) across 2 sessions (set 1 of session 3 and the 80% of 1RM set of session 4).

4.2.2 Subjects

This study was approved by the University of Saskatchewan Research Ethics Board. The benefits and risks of the study were explained to all of the participants before they were required to sign an informed consent form prior to participation. Participants were required to refrain from engaging in upper-body RT sessions and vigorous physical demands throughout the duration of the study. The inclusion criteria for participation encompassed the following: 1) ≥18 years old; 2) ≥2 years of resistance training experience; and 3) free of injury and/or illness that may contraindicate participation. The age, height, weight, and 1RM of the sample was 28.1 ± 9.6 y, 171.5 ± 9.4 cm, 77.1 ± 15.2 kg, and 72.4 ± 28.5 kg; respectively.

4.2.3 Procedures

The study consisted of 4 total sessions, with each session separated by 2 days. Session 1 involved preliminary screening, assessing height and weight, in addition to performing a 1RM strength test in the barbell bench press. Prior to all sessions, participants were instructed to perform each repetition of the barbell bench press with maximal intended velocity during the concentric phase, and with a comfortable velocity (that they were to replicate as best as possible for all repetitions) during the eccentric phase. A repetition was deemed successful according to the International Powerlifting Federation rulebook for the bench press. Research spotters and spotter arms were used to ensure that the participants performed all sets to concentric failure for the sets that were intended to be to muscular failure. For the 1RM test, participants performed a warm-up set of 10 repetitions with the unloaded barbell weighing 6.8 or 20 kg that was selected from the participant’s predicted 1RM, which was collaboratively estimated by the researcher and participant based on the participant’s most recent RT data. Afterwards, 40, 60, 80, and 85% of the predicted 1RM were performed as ramp-up sets for 5, 3, 2, and 1 repetitions; respectively. In accordance with published attempt selections for strength assessments [20], ~90% of the predicted 1RM was loaded for the initial 1RM attempt, whereas loads for the following attempts were selected according to a combination of five factors: 1) the published attempt selection data for strength assessments (i.e., increasing load by ~5% from attempt 1 to 2, and by ~3% from attempt 2 to 3) [20]; 2) the discretion of the researcher; 2) the feedback from the participant; 4) the participant’s subjective estimation of their RIR; and 5) the objective barbell ACV that was
provided from the Vitruve encoder (a validated linear position transducer; Madri, Spain) [21] positioned at the end of the shaft of the barbell. Rest periods of 5 – 7 minutes were administered between each 1RM attempt. The 1RM was the highest load that the participant was able to successfully complete with appropriate technique before failing the concentric phase on the following smallest incremental change attempt (i.e., an increase of ~1 kg). The loads and corresponding fastest repetition velocities were used for establishing a second order polynomial regression equation of the relationship between percentage of 1RM and ACV to create each participant’s individualized load-velocity profile that was subsequently implemented in session 2, 3, and 4.

Session 2, 3, and 4 involved performing a 10-repetition warm-up set with the unloaded barbell, followed by 5, 3, and 1-repetition ramp-up sets at 40, 60, and 80% of the participant’s 1RM that was established during session 1. The ACV of the repetition on the final ramp-up set at 80% of 1RM was used to determine the session’s estimated 1RM from the participant’s individualized load-velocity profile. The loads for the following sets within a session were calculated from the session’s estimated 1RM; therefore, the appropriate percentages of 1RM were autoregulated depending on the participant’s strength level for the given session. Following the warm-up set and 3 ramp-up sets, session 2 involved performing a repetition-to-failure test at 80% of 1RM in the barbell bench press (Table 4.1). The ACV on every repetition was recorded for establishing a second order polynomial regression equation of the relationship between RIR and ACV to create each participant’s individualized LRV-RIR profile for the ensuing statistical analyses (Figure 4.1). Table 4.1 presents a theoretical example of the repetition-to-failure test from session 2, and Figure 4.1 illustrates the associated LRV-RIR profile and polynomial regression equation.

Session 3 and 4 both involved performing 3 sets to muscular failure; however, the load on all 3 sets for session 3 were at 80% of 1RM, whereas the loads for session 4 were at 75, 80, and 85% of 1RM, in which the order of the percentages of 1RM on each individual set was randomized for each participant. During all sessions, the ACV was recorded on each repetition of every set with the Vitruve encoder. During sessions 2, 3, and 4 the participants verbally indicated when they believe that they had 4 and 2 RIR prior to momentary muscular failure on every set with the exclusion of the warm-up set and the 3 ramp-up sets. During sessions 2, 3, and 4 the
participants were also blinded to the load on the barbell with opaque bags covering the weight plates on every set to muscular failure and on the final ramp-up set at 80% of 1RM.

**Table 4.1** Theoretical example of session 2 repetition-to-failure test at 80% of 1RM with corresponding repetitions in reserve and associated average concentric velocities

<table>
<thead>
<tr>
<th>Repetition Number</th>
<th>Repetitions in Reserve</th>
<th>Average Concentric Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>0.29</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>0.26</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>0.23</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>0.22</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>0.20</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>0.18</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>0.15</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
</tbody>
</table>

**Figure 4.1** Theoretical example of a participant’s individualized LRV-RIR profile and second order polynomial regression equation established from the theoretical example data presented in Table 4.1
4.2.4 Dependent Variables

The dependent variable for the subjective estimations condition was the subjective RIR difference at the verbally stated 4 and 2 RIR: the difference between the actual number of RIR and the participant’s subjective estimated number of RIR. For example, if a participant verbally stated “4” (indicating they believed they had 4 RIR) on the third repetition of a set, but successfully completed a total of 9 repetitions prior to muscular failure, the subjective RIR difference would be +2, since the actual number of RIR on the verbally stated repetition (the third repetition) was 6 and the participant’s subjective estimated number of RIR on this repetition was 4 (i.e., the participant performed 2 more repetitions than subjectively estimated).

The dependent variable for the objective velocities condition was the objective RIR difference at the actual 4 and 2 RIR: the difference between the actual number of RIR and the number of RIR (rounded to the nearest whole number) as dictated by the ACV according to the participant’s baseline individualized LRV-RIR profile. For example, if a participant had a baseline individualized LRV-RIR profile (obtained in session 2) of: \( y = -32.68x^2 + 55.407x - 6.4786 \) (Figure 4.1), and the ACV of the fifth repetition was 0.20 m s\(^{-1}\) during a set in which a total of 9 repetitions were successfully completed prior to muscular failure, the objective RIR difference would be +1, since the actual number of RIR was 4 and the participant’s objective number of RIR when solving the equation for RIR (y) when the ACV is 0.20 (x) yields a value of 3 (i.e., the participant performed 1 more repetition than objectively estimated).

4.2.5 Statistical Analyses

IBM SPSS Statistics was used to conduct the statistical analyses with an a priori significance level of \( \alpha = 0.05 \) (\( p \leq 0.05 \)). A 2-sex (male vs female) x 2-condition (subjective estimations vs objective velocities) x 3-sets repeated measures ANOVA was performed to assess proximity to failure accuracy at 4 and 2 RIR across the 3 sets of session 3. A 2-sex (male vs female) x 2-condition (subjective estimations vs objective velocities) x 3-loads repeated measures ANOVA was performed to assess proximity to failure accuracy at 4 and 2 RIR across the 3 loads of session 4. A 2-sex (male vs female) x 2-condition (subjective estimations vs objective velocities) x 2-sessions repeated measures ANOVA was performed on set 1 of session 3 and on the 80% of 1RM set of session 4 to assess proximity to failure accuracy at 4 and 2 RIR across the 2 sessions. In the event of a significant condition x time (set, load, or session) interaction, Bonferroni post-hoc testing was performed.
4.3 Results

The study had no participant dropouts; therefore, the final sample was comprised of 36 total participants that were equally distributed by biological sex (18 males and 18 females). The only significant effect of sex was for a sex main effect in the 4 RIR load analysis ($p = 0.050$; males RIR difference: $0.49 \pm 0.70$; females RIR difference: $1.02 \pm 0.70$). There were no other significant sex main effects or sex interactions with condition and/or time (set, load, nor session) indicating that there were no differences in proximity to failure accuracy between males and females.

As presented in Table 4.2, there was a significant condition x set interaction ($p < 0.001$) for the accuracy comparison between subjective estimations and objective velocities across 3 sets at the same load (80% of 1RM) at both 4 and 2 RIR. Objective velocities were significantly more accurate than subjective estimations on set 1 ($p \leq 0.001$) and set 2 ($p \leq 0.01$) at 4 RIR, as well as on set 1 ($p \leq 0.001$) and set 2 at 2 RIR ($p \leq 0.01$) For subjective estimations, set 1 was significantly less accurate than set 2 and set 3, while set 2 was significantly less accurate than set 3 at 4 RIR and at 2 RIR.

Table 4.2 Differences in subjective and objective estimations of repetitions in reserve across 3 sets at 80% of 1RM

<table>
<thead>
<tr>
<th>RIR</th>
<th>Subjective</th>
<th></th>
<th></th>
<th>Objective</th>
<th></th>
<th></th>
<th>Condition x set p-value</th>
<th>Condition set p-value</th>
<th>Condition x set p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2.40 ± 2.33**^</td>
<td>0.97 ± 1.99**^</td>
<td>0.33 ± 1.87</td>
<td>-0.12 ± 1.37</td>
<td>-0.27 ± 1.57</td>
<td>-0.07 ± 1.26</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>2</td>
<td>1.42 ± 1.76**^</td>
<td>0.56 ± 1.38**^</td>
<td>0.00 ± 1.15</td>
<td>-0.36 ± 0.80</td>
<td>-0.25 ± 1.02</td>
<td>-0.17 ± 1.00</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Data are presented as mean ± standard deviation

**Significantly different than objective ($p \leq 0.001$)
**Significantly different than objective ($p \leq 0.01$)
\^Significantly different than set 2 and 3 ($p \leq 0.001$)
\#Significantly different than set 3 ($p \leq 0.01$)
\&Significantly different than set 3 ($p \leq 0.05$)

For the accuracy comparison between subjective estimations and objective velocities across 3 differing loads (75, 80, and 85% of 1RM) on each set, there was a significant condition x load interaction ($p < 0.001$) at both 4 and 2 RIR (Table 4.3). Objective velocities were significantly more accurate than subjective estimations for 75% of 1RM ($p \leq 0.001$) and 80% of
1RM ($p \leq 0.001$) at 4 RIR, as well as for 75% of 1RM ($p \leq 0.001$) and 80% of 1RM ($p \leq 0.001$) at 2 RIR. For subjective estimations, 85% of 1RM was significantly more accurate than 80% and 75% of 1RM at 4 RIR and at 2 RIR.

**Table 4.3** Differences in subjective and objective estimations of repetitions in reserve across 3 sets at 75, 80, and 85% of 1RM

<table>
<thead>
<tr>
<th>RIR</th>
<th>75% of 1RM</th>
<th>85% of 1RM</th>
<th>80% of 1RM</th>
<th>75% of 1RM</th>
<th>80% of 1RM</th>
<th>85% of 1RM</th>
<th>Condition effect $p$-value</th>
<th>Load effect $p$-value</th>
<th>Condition x load $p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2.19 ± 1.85**</td>
<td>1.86 ± 2.00**</td>
<td>0.11 ± 1.68^</td>
<td>-0.28 ± 1.11</td>
<td>-0.54 ± 1.56</td>
<td>0.10 ± 1.08</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>2</td>
<td>1.06 ± 1.33**</td>
<td>0.94 ± 1.47**</td>
<td>-0.06 ± 1.28^</td>
<td>-0.42 ± 1.16</td>
<td>-0.67 ± 1.26</td>
<td>-0.22 ± 1.12</td>
<td>&lt;0.001</td>
<td>0.05</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Data are presented as mean ± standard deviation.
**Significantly different than objective ($p \leq 0.001$)
^Significantly different than 75 and 80% of 1RM ($p \leq 0.001$)
RIR repetitions in reserve, 1RM one-repetition maximum

There was no significant condition x session interaction for the accuracy comparison between subjective estimations and objective velocities across 2 sessions (set 1 of session 3 and the 80% of 1RM set of session 4) at both 4 and 2 RIR (Table 4.4). There was a significant session main effect for 4 RIR ($p = 0.024$), in which session 4 was significantly more accurate than session 3.

**Table 4.4** Differences in subjective and objective estimations of repetitions in reserve across 2 sessions

<table>
<thead>
<tr>
<th>RIR</th>
<th>Session 3</th>
<th>Session 4</th>
<th>Session 3</th>
<th>Session 4</th>
<th>Condition effect $p$-value</th>
<th>Session effect $p$-value</th>
<th>Condition x session $p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2.40 ± 2.33</td>
<td>1.86 ± 2.00</td>
<td>-0.12 ± 1.37</td>
<td>-0.54 ± 1.56</td>
<td>&lt;0.001</td>
<td>0.024</td>
<td>0.790</td>
</tr>
<tr>
<td>2</td>
<td>1.42 ± 1.76</td>
<td>0.94 ± 1.47</td>
<td>-0.36 ± 0.80</td>
<td>-0.67 ± 1.26</td>
<td>&lt;0.001</td>
<td>0.084</td>
<td>0.709</td>
</tr>
</tbody>
</table>

Data are presented as mean ± standard deviation.
RIR repetitions in reserve

**4.4 Discussion**

To the authors’ knowledge, this is the first study that directly compares the accuracy between subjective estimations and objective velocities at quantifying proximity to failure. The
overall result was that objective velocities via LRVs yielded significantly greater accuracy than subjective estimations via intra-set predictions at determining RIR across numerous circumstances, albeit some circumstances resulted in no significant differences between conditions. According to these main findings, it may be potentially advantageous to incorporate individualized LRV-RIR profiles as an objective means of rectifying subjective RIR-based scales, particularly in certain scenarios (i.e., at loads ≤80% of 1RM). Nonetheless, it must be recognized that significantly greater accuracy in an acute context may not necessarily elicit significantly greater outcomes in the long-term; therefore, a longitudinal study comparing individualized LRV-RIR profiles to RIR-based scales for autoregulation on muscular adaptations and performance measures is required to evaluate any differences in their efficacy in a chronic context.

Similar to our study, previous investigations have examined the accuracy of subjective estimations at determining the actual number of RIR across varying proximities to failure, differing loads, and multiple sets, among other parameters (i.e., exercises, training statuses, etc.) [12]. A recent meta-analysis by Halperin et al. [12] indicated that the accuracy of subjective estimations slightly improved towards later sets (i.e., as set number increased). Likewise, our results demonstrated that at both the verbally stated 4 and 2 RIR, the accuracy of subjective estimations increased concomitantly as sets increased: the third set was significantly more accurate than the second set, which was significantly more accurate than the first set of 3 sets to failure at 80% of 1RM. Furthermore, there was no significant difference between subjective estimations and objective velocities on the last set at 4 RIR and at 2 RIR, while the difference between the two conditions decreased as sets ensued at 4 RIR (set 1: 2.52; set 2: 1.24; set 3: 0.40) and at 2 RIR (set 1: 1.78; set 2: 0.81; set 3: 0.17).

It may be plausible that individuals tend to display improved subjective estimation accuracy in the latter sets, simply because they may have a superior gauge of their proximity to failure after performing multiple initial sets to failure. In a practical sense, the majority of current evidence suggests that training to failure and/or with high intra-set fatigue (i.e., >25% velocity loss) is unnecessary and sub-optimal from both an acute (i.e., recovery) [7-9] and chronic (i.e., adaptation) [1, 3, 4] context, even when muscular endurance [2] or hypertrophy [13] are the intended goals; therefore, performing multiple initial sets within a RT session to failure simply to obtain a superior gauge of RIR in latter sets is impractical and counterproductive. Our data
supports that objective velocities quantify proximity to failure with significantly greater accuracy than subjective estimations on the first 2 sets at 4 RIR and at 2 RIR when performing 3 sets to failure at 80% of 1RM. Considering recent meta-analytic evidence [1] has supported that a magnitude of intra-set fatigue equivalent to ~20 – 25% velocity loss may be optimal for strength adaptations and that higher velocity losses do not evoke significantly greater hypertrophy, it may be wise to prioritize LRV-RIR profiles over RIR-based scales since ~20 – 25% velocity loss corresponds to ~50% of the total maximum possible repetitions in a set [22], which will be associated with ~2 – 5 RIR (i.e., a similar range of RIRs used in our study) for most loads between ~70 – 90% of 1RM [23].

It is unsurprising that there was no significant difference in the accuracy of objective velocities to quantify proximity to failure across 3 sets at 80% of 1RM for both 4 and 2 RIR and that the greatest objective RIR difference was only -0.36, as prior data has illustrated the reliability of the relationship between ACV and RIR from set-to-set at a constant load [13, 15]. Indeed, from visual inspection of the figures, Hickmott [13] revealed that across 4 sets at 80% of 1RM in the barbell bench press, the ACV was consistently stable: 0.23, 0.22, 0.23, and 0.24 m/s at 2 RIR, and 0.28, 0.28, 0.29, and 0.31 m/s at 4 RIR. Furthermore, Hackett [15] also found that there was no significant difference in the ACV at 0 RIR across 5 sets to failure at 70% of 1RM in the barbell bench press. Collectively from this data, it appears that establishing an individualized LRV-RIR profile will allow for precise quantification of proximity to failure when performing multiple sets at a fixed load (i.e., the load does not change from set-to-set).

Similar to the fixed load analysis from session 3, our results indicate significantly greater accuracy for objective velocities over subjective estimations at 4 RIR and at 2 RIR for 75 and 80% of 1RM in the adjusted load analysis from session 4. The difference in the accuracy between objective velocities and subjective estimations improved considerably at 85% of 1RM for both 4 RIR (75% of 1RM: 2.47; 80% of 1RM: 2.40; 85% of 1RM: 0.01) and 2 RIR (75% of 1RM: 1.48; 80% of 1RM: 1.61; 85% of 1RM: 0.16). In agreement with our study, meta-analytic data has shown that subjective estimations are slightly more accurate when lower repetitions (i.e., higher loads) are employed [12]. The present investigation demonstrated that subjective estimations were significantly more accurate at 85% of 1RM compared to 80 and 75% of 1RM for 4 and 2 RIR; however, there was no significant difference in the objective velocities between 75, 80, and 85% of 1RM at 4 and 2 RIR, which aligns with previous findings. Morán-Navarro et
al. [14] reported MPVs associated with 2 RIR in the smith machine bench press of 0.28, 0.26, and 0.27 m s⁻¹, along with MPVs associated with 4 RIR of 0.36, 0.35, and 0.35 m s⁻¹ at 65, 75, and 85% of 1RM, respectively. Moreover, there was no significant difference in the ACV associated with 0 RIR at 50, 60, 70, 80, and 90% of 1RM in the smith machine bench press from Sánchez-Moreno et al. [24] and at 60, 65, 70, and 75% of 1RM from Izquierdo et al. [25] for the individual exercises assessed (smith machine bench press and back squat). Ultimately, the LRV corresponding to a given RIR is consistent even when sets are performed at different loads and at low loads, which further exemplifies an additional advantage of LRV-RIR profiles over subjective estimations, since RIR-based scales tend to be less accurate at lower loads [12].

Load-velocity profiles have been demonstrated to be reliable in the short-term (3 sessions) by Banyard et al. [26] and in the moderate-term (6 weeks) by González-Badillo and Sánchez-Medina [27]; however, limited evidence is available regarding the reliability of LRV-RIR profiles. As previously elucidated, Morán-Navarro et al. [14] reported that the MPVs associated with 2 RIR and 4 RIR were reliable across 3 different loads performed on 3 separate sessions. Our data adds to these findings by revealing that the accuracy of objective velocities to quantify 2 RIR and 4 RIR was non-significantly different across 2 sessions (from session 3 to 4) across the same load (80% of 1RM).

Finally, it is imperative to highlight that greater accuracy can also be beneficial in practical settings for monitoring purposes. A key element of RT programs is to systematically monitor the athlete’s response so that the RT program can be continually adapted for optimal progress; however, this element is limited if the method utilized is flawed. For example, if an athlete performs a single repetition at 90% of their pre-determined 1RM on the first and final day of a 4-week RT block and subjectively estimates the RIR to be considerably different despite the objective RIR (i.e., the RIR based on the LRV) being identical on both days, it may result in inaccurate evaluations of progress; thereby, leading to improper prescriptions. Lastly, although the bench press was utilized for feasibility in our study, future research should determine whether similar findings can be obtained in additional exercises, such as the squat and deadlift. Overall, our study provides novel data and a novel method (individualized LRV-RIR profiles) as an objective solution to subjective RIR-based scales for an improved quantification of proximity to failure moving forward in both research and applied settings.
4.5 Practical Applications

The results of this study support that LRVs quantify proximity to failure with considerably greater accuracy than subjective estimations: LRVs quantify RIR with near precision in three situations: 1) across multiple sets when the load is fixed; 2) across multiple sets when the load is adjusted; and 3) across multiple sessions. Our collective data implies that RT professionals (coaches and athletes) can establish LRV-RIR profiles as an objective solution that rectifies subjective RIR scales for measuring performance via proximity to failure. Specifically, LRV-RIR profiles may improve the initial step (measurement of performance) in the continuous two-step feedback loop of autoregulation, which may therefore improve the latter step (adjustment of prescription) and potentially elicit favored acute responses and thus generate augmented chronic adaptations.

In the context of load autoregulation, rather than a coach prescribe – for example – 6 sets of 3 repetitions at a load corresponding to 2 RIR based on the athlete’s subjective RIR estimation, the coach may prescribe the load at a 2 RIR based on the athlete’s LRV-RIR profile. For volume autoregulation, a coach may stipulate – as a replacement (or adjunct) to the athlete’s subjective RIR estimation – that an athlete perform a specified number of repetitions at a particular load and terminate the session when one of the following two criteria are achieved: 1) a repetition elicits a certain RIR according to the athlete’s LRV-RIR profile; or 2) a certain total number of sets have been reached (i.e., if the first criteria is not achieved within a certain number of sets, one may terminate the session according to the appropriately intended volume).

Individualized load-velocity profiles for dictating percentage of 1RM and LRV-RIR profiles for determining RIR may be implemented in conjunction to integrate the advantages of multiple autoregulation methods. Similarly, a coach may stipulate the termination of a set depending on what the athlete reaches first within the set: 1) a certain RIR from the LRV-RIR profile; or 2) a velocity loss threshold. Overall, LRV-RIR profiles will provide RT professionals with a more precise assessment of RIR, which may enhance the efficacious measurement component of autoregulation and downstream processes.

4.6 References


Objective individualized average concentric last repetition velocities (LRVs) are superior to subjective intra-set estimations at quantifying proximity to failure for 4 and 2 repetitions in reserve (RIR) in the bench press of resistance-trained males and females under the three primary conditions assessed: (1) across 3 fixed loads (80% of 1RM); (2) across 3 changing loads (75, 80, and 85% of 1RM); and (3) across 2 sessions. From the findings of the acute study (Chapter 4) it would be premature to conclude that individualized LRV-RIR profiles are also superior to RIR-based scales at eliciting muscular adaptations simply due to the considerable differences in their accuracy at quantifying proximity to failure. Therefore, a longitudinal study (Chapter 5) was required to elucidate whether enhancing the first step (measurement of performance) will also enhance the final step (adjustment of prescription) within the two-step feedback autoregulation process [1] to elicit superior results. In addition to examining the efficacy of individualized LRV-RIR profiles, the longitudinal study aimed to address the limitations of the present literature outlined in the systematic review and meta-analysis (Chapter 2) [2] and narrative review (Chapter 3): (1) an older adults sample was employed to elucidate whether the benefits of autoregulation are also found beyond college-aged males in individuals prone to sarcopenia; (2) the inclusion of females (and males) to elucidate if autoregulation is also advantageous in females and to identify potential sex differences; and (3) a comparison of traditional (percentage-based training) and both autoregulated load prescription methods (subjective and objective) for an unambiguous comparison of the three main load prescription modalities.

References


5. A COMPARISON OF FIXED-, RPE-, AND VELOCITY-BASED TRAINING LOAD PRESCRIPTION ON MUSCULAR ADAPTATIONS IN OLDER ADULTS

Abstract

Introduction/Purpose
The purpose of this study was to compare fixed (percentage-based training; PBT), subjective autoregulated (rating of perceived exertion-based training via repetitions in reserve; RBT), and objective autoregulated (velocity-based training via individualized last repetition average concentric velocities; VBT) resistance training (RT) load prescription on muscular strength, hypertrophy, power, and functional measures in older (i.e., ≥50 years old) adults.

Methods
A total of 18 males and 18 females were randomized into one of the three RT groups with matching for baseline strength and were administered a 12-week RT intervention that was matched for sets and repetitions (solely differing in the load prescription method).

Results
There was a significant group x time interaction for four-repetition maximum (4RM) bench press ($p = 0.042$). Change in 4RM bench press was greater in VBT (12.2 ± 4.9 kg) compared to PBT (6.8 ± 4.5 kg), while change for RBT (8.5 ± 4.4 kg) did not differ from the other groups. There was no significant group x time interaction for 4RM back squat ($p = 0.106$); however, all groups significantly increased 4RM back squat relative to baseline ($p <0.001$; PBT: 17.9 ± 10.6 kg; RBT: 22.3 ± 10.4 kg; VBT: 28.5 ± 10.9 kg). Change in knee extensor muscle thickness was significantly greater ($p = 0.020$) in VBT (0.71 ± 0.43 cm) compared to RBT (0.21 ± 0.42 cm). There were no significant group x time interactions for power and functional measures; however, there were significant time main effects for stair climb power and all functional assessments ($p <0.05$).

Conclusion
Objective autoregulation may be superior for increasing bench press, but not back squat strength, power, and functional performance in older adults.
5.1 Introduction

Resistance training (RT) has been supported to be one of the most valuable strategies for improving health and wellbeing in older adults (i.e., individuals \( \geq 50 \)) by managing and potentially preventing sarcopenia: the age-related progressive decline in skeletal muscle mass, strength, and function [1]. Although a plethora of factors constitute a comprehensive RT program (i.e., needs analysis, periodized structure, acute variables, etc.), autoregulation (i.e., the systematic measurement of performance and subsequent adjustment of prescription) has developed as a framework integrated within RT programs to augment muscular adaptations [2]. Recent meta-analytic data from Hickmott et al. [2] has indicated that load prescription integrating autoregulation methods provides a small advantage over traditional methods on muscular strength adaptations in resistance-trained males; however, it is unclear whether similar findings are observed in other populations, such as older adults, females, and/or when longer interventions are employed. Older adults are particularly prone to daily fluctuations in performance, fitness, fatigue, and readiness due to a greater prevalence of health-related conditions compared to their younger counterparts [3]; thus, autoregulation methods may be more advantageous to evoke positive outcomes whilst controlling for performance and stressors than traditional methods in said populations. Moreover, the efficacy of load autoregulation on additional muscular adaptations beyond strength requires further elucidation: power measures for coordination and balance, functional assessments for activities of daily living, and muscle hypertrophy.

Although autoregulation may be conceptualized as an overarching RT framework upon which multiple methods (i.e., subjective and objective autoregulation) and variables (i.e., load and volume autoregulation) may be incorporated within a holistic RT program, when the two primary methods of autoregulated RT are compared directly, further evidence is required to determine which method is superior at eliciting a multitude of adaptations in different populations [2]. Despite an initial investigation resulting in significantly greater one-repetition maximum (1RM) back squat, 1RM bench press, and countermovement jump height improvements for objective relative to subjective load autoregulation in resistance-trained males [4], there has yet to be a direct comparison of the two primary methods of load autoregulation to traditional fixed load prescription in a single investigation that also examines older adult females. Proximity to failure (i.e., the number of repetitions in reserve (RIR) prior to muscular failure)
appears to be an important variable to consider for eliciting the desired acute responses [5, 6] and chronic adaptations [7, 8] from RT. Accordingly, subjective autoregulation has commonly employed RIR-based rating of perceived exertion (RPE) scales [9, 10] to autoregulate load [11-13]. It may be argued that to ensure an unambiguous comparison of the two autoregulation methods, objective load autoregulation should also incorporate an RIR-based model with similar load adjustment strategies to subjective load autoregulation, as present studies have neglected to do so [2, 4]. Indeed, it has been suggested that the emerging concept of individualized last repetition average concentric velocities (i.e., LRVs) [2] may be such a strategy to develop an objective RIR-based model [14] worthy of investigation owing to its strong individual- and exercise-specific reliability with a given RIR across multiple sessions [15], sets [16], and loads [17].

Therefore, the primary purpose of this study was to compare traditional fixed (i.e., percentage-based training; PBT), subjective autoregulated (i.e., RPE-based training; RBT) and objective autoregulated (i.e., velocity-based training; VBT) load prescription on strength, hypertrophy, power, and functional measures in older adult males and females across 14-weeks. Specifically, the PBT group established loads from a percentage of an individual’s 1RM with no set-to-set load adjustments (i.e., load was fixed), while the RBT group incorporated subjective estimations of RIR with set-to-set load adjustments (i.e., load was subjectively autoregulated) and the VBT group incorporated objective values of LRV corresponding to RIR with set-to-set load adjustments (i.e., load was objectively autoregulated). It was hypothesized that both autoregulation groups would result in significantly greater strength, power, and functional outcomes than the traditional fixed (PBT) group, and that these outcomes would be significantly greater for the objective autoregulation (VBT) group compared to the subjective autoregulation (RBT) group. It was also hypothesized that there would be no significant differences between all three groups in muscle hypertrophy.

5.2 Methods

5.2.1 Experimental Design

This study was approved by the University of Saskatchewan Research Ethics Board and all participants were required to sign an informed consent form prior to participation. The study was registered at clinicaltrials.gov (NCT05580913). The participant inclusion criteria involved the following: 1) \( \geq 50 \) years old; 2) ability to perform the barbell back squat and barbell bench
press with appropriate technique; and 3) free of injury and/or illness that may contraindicate participation. The experimental design was a 14-week prospective randomized trial comprised of 36 total participants (18 males and 18 females) comparing three RT protocols: 1) percentage-based training (PBT); 2) RPE-based training (RBT); and 3) velocity-based training (VBT) on muscular adaptations. The participants were randomized into one of the three groups after matching for sex and baseline four-repetition maximum (4RM) strength in the barbell back squat and barbell bench press.

5.2.2 Dependent Variables

Session one was comprised of preliminary screening, demographic variables (sex, age, height, and weight), baseline muscle thickness assessment (knee extensors, elbow extensors, and pectoralis major (for males) using ultrasonography), baseline isokinetic dynamometry of the knee extensors (maximal isometric force and maximal rate of force development), and baseline functional performance testing (5-times chair sit-to-stand test, timed up-and-go test, 6-meter fast gait speed test, and stair-climb power test). The muscle thickness assessment was performed in accordance with previously validated procedures from our lab using ultrasound (Aloka-SSD 500, Tokyo, Japan) [18]. The isokinetic dynamometry (Chronojump-Boscosystem Force Sensor Kit, Barcelona, Spain) of the knee extensors was performed with the participant in an adjustable back- and leg-supported exercise bench holding onto side handles, the knee joint positioned at a 90-degree angle with a goniometer, and the ankle strap of the dynamometer placed directly above the malleoli. The participant performed five 5-second trials: the first trial was at 50% of maximal effort, the second trial was at 80% of maximal effort, and the final three trials were performed at maximal effort. There was 30-seconds of rest provided between the first and second trial, whereas one-minute of rest was provided prior to each of the final three trials. The values from the final three trials were averaged to generate the participant’s final score.

The researchers explained and demonstrated each of the four functional performance tests to the participants. There was 1-minute of rest between every trial of each test. The participants performed two trials (one familiarization trial and one trial that was recorded as their score) for the 5-times chair sit-to-stand test and the timed up-and-go test. The participants performed two trials (the values from both trials were averaged to produce their final recorded score) for the 6-meter fast gait speed test. The participants performed one recorded trial for the stair-climb power test. For all of the tests (with the exception of the 6-meter fast gait speed test), the researcher
counted down, “three, two, one, go”, in which on “go”, the researcher started the stopwatch, and the participant initiated the test. For the 5-times chair sit-to-stand test, participants sat with their arms folded across their chest in a chair against a wall. The participants were instructed to stand up and sit down in the chair 5-times as fast as they could. For the stand portion participants were required to stand fully erect and for the sit portion they were required to contact the chair. The researcher stopped the stopwatch when the participants contacted the chair on the sit portion of the fifth repetition. For the timed up-and-go test, the participants sat with their arms at their sides in a chair against a wall. The participants were instructed to stand up and walk around the cone (positioned three meters from the chair by the researcher) and sit down in the chair. The researcher stopped the stopwatch when the participants returned to a fully seated position with their back resting on the backrest of the chair. For the six-meter fast gait speed test, tape line floor markers were placed at zero, two, eight, and ten meters. The participants were instructed to walk as fast as they could from the first (located at zero meters) to the final (located at ten meters) tape line. The researcher started and stopped the stopwatch when any part of the participant’s foot crossed the two-meter and eight-meter tape line; respectively. For the stair-climb power test, participants stood with both feet behind a tape line at the bottom of a flight of ten stairs. The participants were instructed to climb the stairs with one foot per step as fast as they could. The researcher stopped the stopwatch when both of the participant’s feet landed on the top (tenth) step.

Session two was comprised of 4RM strength testing of the barbell back squat followed by the barbell bench press. The criteria for a successful lift were in accordance with the International Powerlifting Federation rulebook. All participants were instructed to perform both lifts with maximal intended concentric velocity and a comfortable repeatable eccentric velocity on every repetition during all testing and training sessions, and were repeatedly reminded this cue prior to every session and between sets. The initial portion of the 4RM test (i.e., prior to the first 4RM attempt) involved performing 10, 5, 3, 2, and 1 repetition sets at loads of barbell (weighing 6.8 or 20 kg depending on the strength of the individual), 40, 60, 80, and 85% of the predicted 4RM; respectively, with appropriate rest periods allocated between each set [10]. The first attempt for the 4RM was at ~91 (i.e., ~90 – 92%) of the predicted 4RM based on published strength assessment attempt selection data [19]. Thereafter, loads were appropriately adjusted on each subsequent 4RM attempt based on this attempt selection data [19], the researcher’s
discretion, the participant’s feedback, the participant’s subjective prediction of RIR, and objective barbell average concentric velocity (ACV) via the validated Vitruve linear position transducer (Madrid, Spain) [20], which was positioned at the end of the barbell shaft. The participant continued to perform appropriate incremental 4RM attempts with 5 – 7 minutes of rest between attempts until they were no longer able to successfully perform the lift for four consecutive repetitions (i.e., to concentric muscular failure). Both research spotters and spotter arms were implemented to ensure that all participants safely failed the concentric phase of the lifts during their testing sessions. The heaviest load that the participant was able to successfully perform for four consecutive repetitions was deemed the 4RM. For post-testing of all aforementioned dependent variables, sessions 27 and 28 were performed identically to sessions one and two; respectively.

5.2.3 Resistance Training Intervention

Sessions 3 – 26 involved the RT protocol (Table 5.1) comprised of the barbell back squat and barbell bench press performed on two non-consecutive days per week for 12 consecutive weeks. The barbell back squat and barbell bench press involved traditional fixed (PBT), subjective autoregulated (RBT), or objective autoregulated (VBT) load prescription in accordance with the respective group. The PBT group involved prescribing load based on pre-determined percentages of 1RM from the participant’s estimated 1RM obtained in the 4RM pre-testing: the 4RM was deemed 90% of the individual’s 1RM (i.e., the 4RM load was divided by 0.90 to obtain the estimated 1RM load) [21]. The RBT group involved prescribing and adjusting load based on the participant’s subjective estimation of their number of RIR. The VBT group involved prescribing and adjusting load based on the participant’s objective barbell back squat and barbell bench press individualized last repetition average concentric velocity (LRV)-RIR profile.
### Table 5.1 Resistance Training Protocol for the Fixed Percentage-, Subjective Autoregulated-, and Objective Autoregulated- Load Prescription Groups

<table>
<thead>
<tr>
<th>Week</th>
<th>Sets</th>
<th>Repetitions</th>
<th>PBT Group (percentage of estimated 1RM)</th>
<th>RBT Group (subjective estimation of RIR)</th>
<th>VBT Group (LRV value corresponding to RIR)</th>
<th>Sets</th>
<th>Repetitions</th>
<th>PBT Group (percentage of estimated 1RM)</th>
<th>RBT Group (subjective estimation of RIR)</th>
<th>VBT Group (LRV value corresponding to RIR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>10</td>
<td>70</td>
<td>3 – 5</td>
<td>3 – 5</td>
<td>3</td>
<td>8</td>
<td>75</td>
<td>3 – 5</td>
<td>3 – 5</td>
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<tr>
<td>2</td>
<td>4</td>
<td>9</td>
<td>72.5</td>
<td>3 – 5</td>
<td>3 – 5</td>
<td>4</td>
<td>7</td>
<td>77.5</td>
<td>3 – 5</td>
<td>3 – 5</td>
</tr>
<tr>
<td>3</td>
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<td>75</td>
<td>2.5 – 4.5</td>
<td>2.5 – 4.5</td>
<td>4</td>
<td>6</td>
<td>80</td>
<td>2.5 – 4.5</td>
<td>2.5 – 4.5</td>
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<tr>
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<td>75</td>
<td>2.5 – 4.5</td>
<td>2.5 – 4.5</td>
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<td>77.5</td>
<td>2 – 4</td>
<td>2 – 4</td>
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<td>5</td>
<td>82.5</td>
<td>2 – 4</td>
<td>2 – 4</td>
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<td>6</td>
<td>80</td>
<td>1.5 – 3.5</td>
<td>1.5 – 3.5</td>
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<td>4</td>
<td>85</td>
<td>1.5 – 3.5</td>
<td>1.5 – 3.5</td>
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<tr>
<td>8</td>
<td>4</td>
<td>6</td>
<td>80</td>
<td>1.5 – 3.5</td>
<td>1.5 – 3.5</td>
<td>4</td>
<td>4</td>
<td>85</td>
<td>1.5 – 3.5</td>
<td>1.5 – 3.5</td>
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<tr>
<td>9</td>
<td>4</td>
<td>5</td>
<td>82.5</td>
<td>1 – 3</td>
<td>1 – 3</td>
<td>4</td>
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<td>87.5</td>
<td>1 – 3</td>
<td>1 – 3</td>
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<td>82.5</td>
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<td>1 – 3</td>
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<td>87.5</td>
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<td>1 – 3</td>
</tr>
<tr>
<td>11</td>
<td>4</td>
<td>4</td>
<td>85</td>
<td>0.5 – 2.5</td>
<td>0.5 – 2.5</td>
<td>4</td>
<td>2</td>
<td>90</td>
<td>0.5 – 2.5</td>
<td>0.5 – 2.5</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>3</td>
<td>87.5</td>
<td>0.5 – 2.5</td>
<td>0.5 – 2.5</td>
<td>2</td>
<td>1</td>
<td>92.5</td>
<td>0.5 – 2.5</td>
<td>0.5 – 2.5</td>
</tr>
</tbody>
</table>

LRV: individualized last repetition average concentric velocity, PBT: percentage-based training, RBT: rating of perceived exertion-based training, RIR: repetitions in reserve, VBT: velocity-based training, 1RM: one-repetition maximum

The sets and repetitions were matched between all three groups. The percentage of 1RM and RIR was intended to be similar amongst groups based on the relationship between these variables [22]. For example, during training session one, the PBT group was prescribed 70% of 1RM for 10 repetitions. Therefore, the RBT group was prescribed 10 repetitions at 3 – 5 RIR, since approximately 12 – 15 repetitions can be performed at 70% of 1RM on average in the barbell back squat and barbell bench press for most individuals [21]. Likewise, the VBT group was prescribed 10 repetitions at an LRV corresponding to 3 – 5 RIR based on their individualized LRV-RIR profile.

### 5.2.4 Autoregulated Load Adjustments

Load was fixed (i.e., non-adjusted) for the PBT group; however, load was autoregulated (i.e., adjusted) from set-to-set based on subjective feedback for the RBT group and objective feedback for the VBT group. The PBT group was prescribed specific percentages of their estimated 1RM, in which the 1RM was estimated based on the presumption that the baseline pre-testing 4RM load was 90% of the 1RM load [21]. The RBT and VBT groups were prescribed target RIR ranges contingent upon the session (Table 5.2).
Table 5.2 Set-to-Set Load Adjustment Protocol for the Subjective Autoregulated-, and Objective Autoregulated- Load Prescription Groups

<table>
<thead>
<tr>
<th>RIR</th>
<th>RT Week 1 – 2</th>
<th>RT Week 3 – 4</th>
<th>RT Week 5 – 6</th>
<th>RT Week 7 – 8</th>
<th>RT Week 9 – 10</th>
<th>RT Week 11 – 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>10+</td>
<td>120</td>
<td>122</td>
<td>124</td>
<td>126</td>
<td>128</td>
<td>130</td>
</tr>
<tr>
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<td>116</td>
<td>118</td>
<td>120</td>
<td>122</td>
<td>124</td>
<td>126</td>
</tr>
<tr>
<td>8</td>
<td>112</td>
<td>114</td>
<td>116</td>
<td>118</td>
<td>120</td>
<td>122</td>
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<tr>
<td>7</td>
<td>108</td>
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<tr>
<td>6</td>
<td>104</td>
<td>106</td>
<td>108</td>
<td>110</td>
<td>112</td>
<td>114</td>
</tr>
<tr>
<td>5</td>
<td>Participant Choice</td>
<td>102</td>
<td>104</td>
<td>106</td>
<td>108</td>
<td>110</td>
</tr>
<tr>
<td>4.5 (definitely 4; maybe 5)</td>
<td>Participant Choice</td>
<td>Participant Choice</td>
<td>102</td>
<td>104</td>
<td>106</td>
<td>108</td>
</tr>
<tr>
<td>4</td>
<td>Participant Choice</td>
<td>Participant Choice</td>
<td>Participant Choice</td>
<td>102</td>
<td>104</td>
<td>106</td>
</tr>
<tr>
<td>3 (definitely 3; maybe 4)</td>
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<td>Participant Choice</td>
<td>Participant Choice</td>
<td>Participant Choice</td>
<td>102</td>
<td>104</td>
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<td>2.5 (definitely 2; maybe 3)</td>
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<td>Participant Choice</td>
<td>Participant Choice</td>
<td>Participant Choice</td>
<td>Participant Choice</td>
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<tr>
<td>1.5 (definitely 1; maybe 2)</td>
<td>94</td>
<td>96</td>
<td>98</td>
<td>Participant Choice</td>
<td>Participant Choice</td>
<td>Participant Choice</td>
</tr>
<tr>
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<td>94</td>
<td>96</td>
<td>98</td>
<td>Participant Choice</td>
<td>Participant Choice</td>
</tr>
<tr>
<td>0 – 1 (maybe 1)</td>
<td>90</td>
<td>92</td>
<td>94</td>
<td>96</td>
<td>98</td>
<td>Participant Choice</td>
</tr>
<tr>
<td>0</td>
<td>88</td>
<td>90</td>
<td>92</td>
<td>94</td>
<td>96</td>
<td>98</td>
</tr>
</tbody>
</table>

RIR repetitions in reserve, RT resistance training

Participants in the RBT group subjectively estimated their number of RIR immediately upon completing each work set. Participants estimated RIR values with an RIR scale as defined by the left-most column of Table 5.2. For training sessions one and two (i.e., the initial two training sessions of the RT intervention), the researchers assisted the participants to select a load on their first set that they collaboratively believed would achieve an estimated RIR within the target RIR range. During all subsequent sessions, the researchers presented the participants with all their previous session performance recordings (i.e., week number and session number with the associated set number, repetitions, loads, target RIR ranges, and actual achieved subjectively estimated RIR values) to assist the participants at self-selecting their loads on the first set. If the participant’s estimated RIR of the set was within the target RIR range for the session, the participant had a choice for the load on the subsequent set with the stipulation that they were to select a load that they believed would achieve a subjectively estimated RIR within the target RIR range. Conversely, if the participant’s estimated RIR of the set was outside the target RIR range for the session, the load was adjusted in accordance with Table 5.2 for the subsequent set, which is in alignment with the load adjustments prescribed in similar investigations [11, 13].

Participants in the VBT group evaluated their LRV and objectively determined their number of RIR immediately after performing each work set based on their lift-specific individualized LRV-RIR profiles. The LRV-RIR profiles were established on both lifts for every participant in the VBT group; thus, each participant had two individualized LRV-RIR profiles: one for the barbell back squat and one for the barbell bench press. The LRV-RIR profiles were formulated from the baseline 4RM testing session. On the final 4RM attempt (i.e., the unsuccessful 4RM attempt), the ACV on each repetition was recorded, in which the participant
performed three repetitions and reached momentary muscular failure on the fourth repetition. A second order polynomial regression equation was developed between ACV and RIR from the ACVs of the first repetition (2 RIR), second repetition (1 RIR), and third repetition (0 RIR) of this attempt in order to determine the ACV corresponding to each RIR value exemplified in the left-most column of Table 5.2; thereby, establishing each participant’s lift-specific individualized LRV-RIR profile. Similar to the RBT group, the participants in the VBT group were assisted by the researchers to select a load on their first set during training sessions one and two that they expected would elicit an LRV corresponding to the target RIR range for the session; however, participants self-selected the load on their first set in all future sessions based on all their previous session performance recordings (i.e., week number and session number with the associated set number, repetitions, loads, target LRV ranges from the target RIR ranges, and actual achieved LRV and RIR values). In the case that the participant’s LRV corresponded to an RIR within the target RIR range, the participant chose the load on the following set with the goal of selecting a load that they expected would elicit an LRV corresponding to the target RIR range. In the case that the participant’s LRV corresponded to an RIR outside the target RIR range, the load was adjusted for the following set according to Table 5.2. Further, in the event that the LRV corresponded to an RIR value not exhibited in the left-most column of Table 5.2, the RIR was rounded to the nearest value exhibited in the left-most column of Table 5.2. For example, if an LRV corresponded to an RIR of 2.8, it was rounded to 3 RIR, whereas if an LRV corresponded to an RIR of 2.7, it was rounded to 2.5 RIR.

5.2.5 Statistical Analyses

The statistical analyses were performed with IBM SPSS Statistics. Statistical significance was assessed with an *a priori* significance level of $\alpha = 0.05$ ($p \leq 0.05$). There were no interactions involving sex; therefore, we removed sex as a factor to improve statistical power: strength outcomes, muscle size, power measures, and functional assessments were assessed with a 3-group (PBT, RBT, and VBT) by 2-time (pre- vs post-test) repeated measures analysis of variance (ANOVA). To interpret any interactions, absolute change scores between groups were assessed with a one-way ANOVA with Fischer’s LSD post-hoc testing to determine differences between groups.
5.3 Results

The overarching flow of the participants during the study is illustrated in Figure 5.1. Due to participant dropouts (Figure 5.1), the final sample was comprised of the following: PBT ($n = 11$; 5 males and 6 females), RBT ($n = 10$; 5 males and 5 females), VBT ($n = 9$; 6 males and 3 females). The male in the PBT group dropped out as they failed to arrive for their scheduled RT sessions, and we were unable to re-contact. In the RBT group, the male dropped out due to a medical reason outside of the study, and the female dropped out due to an injury unrelated to the RT intervention. In the VBT group, the three females dropped out due to the following reasons: one due to personal reasons; one due to a family emergency; and one due to a lower body mild abductor muscle strain injury sustained during the squat on session 2 in week 1 of the RT intervention. The PBT group had an age, height, and weight of $66.7 \pm 8.3$ y, $166.9 \pm 9.7$ cm, and $82.2 \pm 18.3$ kg while the corresponding values were $60.4 \pm 5.5$ y, $165.2 \pm 9.2$ cm, and $78.2 \pm 15.9$ kg for the RBT group, and $58.0 \pm 7.4$ y, $172.7 \pm 10.1$ cm, and $78.5 \pm 18.2$ kg for the VBT group; respectively. The PBT group was significantly older than the VBT group ($p = 0.012$); however, the RBT group did not significantly differ from the PBT nor VBT groups. There were no significant differences in the other demographic variables (height and weight) between RT groups. No significant differences between each group in any of the assessment measures (dependent variables) at baseline (pre-testing) were observed.
Figure 5.1 CONSORT flow diagram demonstrating participant flow throughout the study
As presented in Table 5.3, there was no significant group x time interaction for 4RM back squat strength \((p = 0.11)\); however, there was a significant time main effect \((p < 0.001)\). Conversely, there was a significant group x time interaction for 4RM bench press \((p = 0.042)\). Change in 4RM bench press was significantly greater for VBT compared to PBT \((p = 0.014)\), while change for RBT did not significantly differ from the other groups. There was a significant group x time interaction for knee extensors muscle thickness \((p = 0.05)\), but no group x time interaction for elbow extensors and pectoralis major muscle thickness (Table 5.3). VBT resulted in a significantly greater absolute change \((p = 0.020)\) in knee extensor muscle thickness compared to RBT. There was a significant time main effect for elbow extensors muscle thickness \((p < 0.001)\). For the muscular power measures and functional assessments there were no significant group x time interactions (Table 5.4). There were significant time main effects for stair climb power and all the functional assessments \((p <0.05)\).

### Table 5.3 Changes in strength and hypertrophy assessment measures from pre- to post-intervention for each resistance training group

<table>
<thead>
<tr>
<th>Measure</th>
<th>Percentage-based training ((n = 11))</th>
<th>RPE-based training ((n = 10))</th>
<th>Velocity-based training ((n = 9))</th>
<th>Time effect (p)-value</th>
<th>Group x time (p)-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back Squat 4RM (kg)</td>
<td>53.6 ± 34.8</td>
<td>71.5 ± 37.0</td>
<td>80.9 ± 39.8</td>
<td>63.8 ± 25.2</td>
<td>92.2 ± 24.1</td>
</tr>
<tr>
<td>Bench Press 4RM (kg)</td>
<td>40.6 ± 24.4</td>
<td>47.4 ± 25.0</td>
<td>54.0 ± 27.3</td>
<td>46.2 ± 17.1</td>
<td>58.5 ± 20.8^</td>
</tr>
<tr>
<td>Knee Extensors (cm)</td>
<td>2.50 ± 0.39</td>
<td>3.08 ± 0.66</td>
<td>3.29 ± 0.85</td>
<td>2.64 ± 0.54</td>
<td>3.35 ± 0.65^</td>
</tr>
<tr>
<td>Elbow Extensors (cm)</td>
<td>2.64 ± 0.61</td>
<td>2.76 ± 0.52</td>
<td>3.21 ± 0.47</td>
<td>2.69 ± 0.40</td>
<td>3.21 ± 0.47</td>
</tr>
<tr>
<td>Pectoralis major (cm)</td>
<td>3.39 ± 0.71</td>
<td>3.52 ± 0.57</td>
<td>3.51 ± 0.62</td>
<td>2.96 ± 0.77</td>
<td>3.26 ± 0.61</td>
</tr>
</tbody>
</table>

Data are presented as mean ± standard deviation
Pectoralis major assessed in male participants only: percentage-based training \((n = 5)\); RPE-based training \((n = 5)\); velocity-based training \((n = 6)\)

^Change from pre to post is significantly greater for the velocity-based training than percentage-based training group \((p \leq 0.05)\)

^Change from pre to post is significantly greater for the velocity-based training than RPE-based training group \((p \leq 0.05)\)

\(^{\text{RPE}}\) rating of perceived exertion, 4RM four-repetition maximum
Table 5.4 Changes in power and functional assessment measures from pre- to post-intervention for each resistance training group

<table>
<thead>
<tr>
<th>Measure</th>
<th>Percentage-based training</th>
<th>RPE-based training</th>
<th>Velocity-based training</th>
<th>Time effect p-value</th>
<th>Group x time p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n = 11)</td>
<td>(n = 10)</td>
<td>(n = 9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal Isometric Force (N)</td>
<td>368.0 ± 162.1</td>
<td>377.6 ± 159.1</td>
<td>399.6 ± 131.0</td>
<td>0.298</td>
<td>0.226</td>
</tr>
<tr>
<td>Maximal Rate of Force Development (N s⁻¹)</td>
<td>1760.5 ± 1686.4</td>
<td>1711.5 ± 1115.7</td>
<td>1306.4 ± 793.0</td>
<td>0.423</td>
<td>0.929</td>
</tr>
<tr>
<td>Stair-Climb Power Test (W)</td>
<td>33.85 ± 10.89</td>
<td>35.44 ± 10.64</td>
<td>34.03 ± 8.53</td>
<td>0.048</td>
<td>0.824</td>
</tr>
<tr>
<td>5-Times Chair Sit-to-Stand (s)</td>
<td>6.32 ± 3.10</td>
<td>5.08 ± 1.43</td>
<td>4.99 ± 0.59</td>
<td>0.004</td>
<td>0.280</td>
</tr>
<tr>
<td>Timed Up-and-Go (s)</td>
<td>5.30 ± 1.42</td>
<td>4.52 ± 0.95</td>
<td>4.74 ± 0.48</td>
<td>&lt;0.001</td>
<td>0.730</td>
</tr>
<tr>
<td>6-meter Fast Gait Speed (m s⁻¹)</td>
<td>2.36 ± 0.45</td>
<td>2.42 ± 0.44</td>
<td>2.36 ± 0.29</td>
<td>0.007</td>
<td>0.612</td>
</tr>
</tbody>
</table>

Data are presented as mean ± standard deviation
ms⁻¹ meters per second, N newtons, Ns⁻¹ newtons per second, RPE rating of perceived exertion, W watts

5.4 Discussion

The primary outcome of this randomized trial was that VBT resulted in significantly greater 4RM bench press strength adaptations than PBT, in addition to significantly greater knee extensor muscle thickness hypertrophy than RBT; however, there were no significant differences observed in muscular power nor functional performance between any of the three RT groups. The results for strength regarding VBT compared to PBT in our study are consistent with previous findings in resistance-trained males [23-25]. Banyard et al. [23] and Orange et al. [24] demonstrated that both methods of RT (VBT and PBT) produced considerable increases in 1RM back squat strength, albeit there were no differences between RT methods. The findings from Dorrell et al. [25] are in alignment with ours: VBT generated significantly greater bench press strength improvements, whereas there were no differences observed for the back squat between VBT and PBT. Specifically, Dorrell et al. [25] found that the relative 1RM bench press improvements were approximately two-times greater for VBT compared to PBT (8 vs 4%). Similarly, our data indicated that the absolute change in 4RM bench press was nearly twice as large in the VBT group (12.2 vs 6.8 kg). Dorrell et al. [25] integrated group load-velocity profiles, velocity zones, and velocity stops, whereas our investigation utilized a VBT model of individualized LRV-RIR profiles. Collectively, both studies suggest that these strategies of VBT
are effective at resulting in significantly greater strength adaptations than PBT in the bench press exercise in younger males and older adults.

With reference to the comparison between RBT and PBT for strength, our results are in partial agreement with the present literature in younger adults [11, 13, 12]. Similar to our study, Helms et al. [11] found no differences in back squat and bench press strength gains between RBT and PBT in resistance-trained males. Although Arede et al. [13] also found no between group differences in the back squat, RBT was significantly superior for increasing bench press strength in youth (i.e., 15 – 17 years old) female athletes. In disagreement with our study, Graham and Cleather [12] demonstrated significantly greater strength improvements in the back squat and front squat for RBT after 12-weeks. Our strength outcomes contradict Shattock and Tee’s [4] preliminary study directly comparing the two primary methods of load autoregulation. In this study, VBT yielded significantly greater 1RM back squat and bench press adaptations along with favored moderate-to-large effect sizes and greater than two-fold percentage improvements compared to RBT following a 12-week randomized crossover RT protocol [4].

The main difference between our study and that conducted by Shattock and Tee [4] is the population: our study utilized older adult males and females that were relatively untrained (baseline back squat estimated 1RM: 65 ± 36 kg; baseline bench press estimated 1RM: 49 ± 24 kg), whereas Shattock and Tee [4] employed younger male rugby athletes that were markedly greater trained (baseline back squat 1RM: 145 ± 25 kg; baseline bench press 1RM: 109 ± 20 kg). Therefore, similar to the concept that advanced RT modalities (i.e., periodization) generate significantly greater strength improvements in trained populations but not in untrained populations [26], objective autoregulation (VBT) may be most beneficial at augmenting strength adaptations with higher training statuses, although further research in different populations of training statuses should be conducted to establish a clearer consensus.

Our hypothesis that there would be no significant differences between all three groups in muscle hypertrophy was partially supported, as no differences were observed in all muscle groups, with the exception that VBT elicited significantly greater muscle thickness of the knee extensors than RBT. A recent meta-analysis revealed that individuals underestimate RIR to a greater extent in lower body exercises (~1.5 repetitions) compared to upper body exercises (~0.9 repetitions) [27]; thus, it is plausible that in our study, the RBT group trained with less intra-set fatigue (i.e., magnitude of velocity loss) during the back squat than the bench press; thereby,
potentially resulting in significantly less hypertrophy in the lower body, but not in the upper body compared to the VBT group as intra-set fatigue was designed to be at ~20 – 25% in the VBT group. Although the literature is conflicting whether metabolite accumulation (i.e., blood and intramuscular lactate) mediates hypertrophy [28, 29], recent meta-analytic evidence from Hickmott et al. [2] has suggested that there may be an intra-set fatigue threshold of ~20 – 25% velocity loss – which is highly correlated to lactate and ammonia accumulation [30] – in which further increases in velocity loss do not result in greater hypertrophy adaptations. Despite the overall pooled analysis by Jukic et al. [31] demonstrating no significant difference in hypertrophy between traditional sets and alternative set structures when relative volume was matched (i.e., total repetitions and load were matched), the sub-group analysis demonstrated a large effect favoring traditional sets compared to cluster sets (SMD = 0.98); however, there was no meaningful difference between traditional sets compared to intra-set rest (SMD = 0.06). Cluster sets are associated with velocity loss values <~20% [32], whereas intra-set rest are associated with velocity loss values of ~20 – 25% since intra-set rest protocols are comprised of performing 50% of the repetitions with a repetition maximum load [32], which further supports the potential ~20 – 25% velocity loss threshold for hypertrophy even if relative volume is matched between protocols and RT is not performed to momentary muscular failure.

Our hypothesis that muscular power and functional assessments would be significantly greater for the autoregulation groups compared to the PBT group and that these improvements would be most profound in the VBT group were unsupported. Our hypotheses were on the basis that VBT inherently encourages maximal indented concentric velocity by enhancing competitiveness [33], which has been supported to generate superior power outcomes: Shattock and Tee reported significantly greater countermovement jump height improvements (i.e., a proxy for muscular power) coupled with a large effect size favoring VBT over RBT (+8.2 vs +3.8%). The lack of a significant group x time interaction in maximal isometric force and maximal rate of force development of the knee extensors is plausibly due to the methodological design of the study whereby load was intended to be similarly matched amongst groups, and meta-analytic evidence suggests that low- vs high-load RT does not generate significantly different isometric power/strength adaptations [34]. Furthermore, the lack of significant time effects in these measures of lower body power, despite the presence of significant time effects in 4RM back squat amongst all three RT groups may be that the increases in back squat strength were
primarily attributable to motor skill improvements rather than exclusively neuromuscular adaptations, particularly since our sample was comprised of relatively untrained participants [35]. Moreover, this may also explain the robust strength improvements in the back squat (~54%) compared to the bench press (~22%), as it may be argued that the back squat requires greater technical proficiency from a motor learning and control perspective, and our participants appeared to be less proficient in the technical skill of the back squat at the commencement of the study, but rapidly improved within the initial few weeks of the RT intervention. Finally, the results for the functional outcomes in our study appear to be consistent with a meta-analysis by Steib et al. [36] demonstrating that loading intensity (i.e., low- vs moderate- vs high-load) does not result in significant differences in the same functional outcomes that were employed in our study. In other words, it also appears that autoregulating load to match performance has a negligible difference compared to a fixed loading paradigm on functional improvements in older adults.

Due to feasibility constraints, the ACV was not recorded on all repetitions of every set for each participant in the PBT and RBT groups; however, future investigations may seek to collect this data to obtain an improved understanding of the rationale for the observed outcomes. It is also important to acknowledge that establishing individualized LRV-RIR profiles requires greater commitment from the researcher (or practitioner) to comprehensively formulate and teach to their participants (or athletes) to limit burden and enhance application.

Overall, our results suggest that all three methods of RT (PBT, RBT, and VBT) are effective at eliciting significant improvements in back squat and bench press strength, in addition to muscular hypertrophy and functional outcomes. VBT appears to generate the most profound improvements in bench press strength and knee extensor hypertrophy. Future research should further explore the concept of autoregulation in clinical settings of older adults, to discern whether autoregulation may pose a benefit in those with contraindications to certain modalities of RT. Finally, an interesting area to explore may be to evaluate if certain personality types benefit greater from certain methods of autoregulated RT with a randomized crossover design.

5.5 References


6. CONCLUSION

6.1 Conclusion

This PhD thesis provides novelty on the efficacy of individualized average concentric last repetition velocities as an autoregulating and monitoring method in resistance training on muscular adaptations and performance outcomes. Chapter 1: the systematic review and meta-analysis synthesized that autoregulated load prescription results in significantly greater strength adaptations than traditional load prescription [1]. Moreover, autoregulating volume with low-moderate and moderate-high intra-set fatigue is optimal for strength and hypertrophy adaptations; respectively [1]. This meta-analytic data suggests that appropriately applying autoregulation strategies augments muscular adaptations [1]. Chapter 2: the narrative review disseminated the advantages and limitations of the current traditional prescription methods (percentage-based training; PBT), load autoregulation methods (rating of perceived exertion based-training; RBT, velocity zones, and load-velocity profiles), and volume autoregulation methods (rating of perceived exertion stop; RPE stop, and velocity loss thresholds). In this regard, it also conceptualized a theoretical model (the Individualized Last Repetition Velocity Model; LRV Model) for future directions and practical applications that shaped the foundation for the strategy (individualized average concentric last repetition velocity-repetitions in reserve profiles; LRV-RIR profiles) subsequently investigated in an acute (Chapter 3) and chronic (Chapter 4) applied setting to test its efficacy.

Chapter 3: the 4-session acute study demonstrated that objective individualized LRV-RIR profiles were significantly more accurate than subjective RIR-based scales at quantifying proximity to failure across numerous conditions: (1) 3 sets at a fixed load; (2) 3 sets at adjusted loads: and (3) 2 sessions. Individualized LRV-RIR profiles also exhibited considerable reliability (consistent stability) throughout the entire study. Of the two primary autoregulation steps (step one: measurement of performance; and step two: adjustment of prescription), these findings support that LRV-RIR profiles are superior for step one. Chapter 4: the 14-week longitudinal study in older adult males and females demonstrated that objective autoregulated load prescription via individualized LRV-RIR profiles resulted in significantly greater increases in
bench press strength than traditional fixed load prescription and significantly greater knee extensor muscle thickness than subjective autoregulated load prescription via RIR-based scales. Albeit there were no significant differences between groups for back squat strength, along with pectoralis major and elbow extensor muscle thickness. Similarly, there were no significant differences between groups for power (maximal isometric force, maximal rate of force development, and stair-climb power test) and functional improvements (5-times chair sit-to-stand, timed up-and-go, and 6-meter fast gait speed). Of the two primary autoregulation steps, these results support that LRV-RIR profiles are also superior for step two to generate the greatest improvements in bench press strength and knee extensor muscle thickness.

Although this PhD thesis suggests that individualized average concentric last repetition velocities are indeed an efficacious autoregulating and monitoring method in resistance training, it is not without limitations. The acute study (Chapter 3) only involved the barbell bench press; therefore, it is unclear whether these results can be replicated in additional exercises (i.e., barbell back squat, and barbell deadlift). The demographics should be expanded upon in future studies as our sample was 28.1 ± 9.6 years and possessed ≥2 years of resistance training experience. The longitudinal study (Chapter 4) involved relatively healthy older adults; however, it would be beneficial to investigate autoregulation in additional clinical settings for individuals that have certain contraindications to specific resistance training modalities (i.e., individuals with health-related conditions that are prone to considerable fluctuations in day-to-day performance, fatigue, and readiness). Autoregulation has primarily been limited to resistance training contexts; thus, future studies should investigate autoregulation strategies outside of resistance training contexts for additional types of training modalities (i.e., aerobic training settings), and concurrent training settings (i.e., combined resistance training and aerobic training). Moreover, autoregulation may be particularly advantageous in specific sports that are highly physiologically demanding and/or contain challenging competition schedules; therefore, future research should discern the contextual framework for optimally implementing autoregulation in different sport settings.

6.2 References