Velocity-based resistance training monitoring and prescription: the good, the bad, and the alternatives

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TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

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Abstract

Traditionally, resistance training (RT) is prescribed using percent-based training (PBT) methods that use the loads relative to a maximal load lifted for one repetition (%1RM) and set volume based on the theoretical relationship between a maximum number of repetitions individuals can do with a given %1RM. However, PBT cannot account for performance fluctuations. Thus, velocity-based approaches emerged from research showing that 1) load-velocity profiles (LVPs) can be used to adjust load per readiness; and 2) velocity loss (VL) can be used to terminate sets per the desired level of neuromuscular fatigue. While the reliability and utility of LVPs and confounding factors affecting them were previously examined, minimal research existed on the variability of acute responses to VL thresholds. Even assuming no variability, VL thresholds require costly velocity monitoring devices. Therefore, the purpose of this thesis was to examine novel velocity-based approaches while considering the effects of sex, training history, relative strength, and personality on their accuracy, and reduced or no-cost means of implementing VL thresholds. In Chapter 1, the benefits and shortcomings of velocity-based approaches, the thesis aims, and the structure are described. Chapter 2 consists of a systematic review and meta-analysis of acute and chronic effects of VL thresholds, highlighting VL threshold selection as an important consideration and high inter-individual variability in responses to different VL thresholds. In Chapter 3, the reproducibility and sensitivity of velocity monitoring devices of varying prices are examined, with GymAware emerging as the most reproducible and sensitive device. A cheaper alternative is the Vmaxpro; however, only if mean velocity is used. The variability in work completed before reaching different VL thresholds and factors impacting this variability are investigated in Chapter 4. Notably, work completed varies across people and testing sessions and is influenced by load, sex, training status, history, and personality. In Chapter 5, the validity of the relationship between VL and the percentage of repetitions completed out of the maximum possible ($\%_{repetitions}$) is examined. While relationships are highly individual, both general and individual VL-$\%_{repetitions}$ relationships poorly predict $\%_{repetitions}$ in subsequent testing sessions (prediction error > 10%). The validity of the fastest repetition in a set to predict the maximum number of repetitions than can be completed (XRM) is investigated in Chapter 6. Importantly, individual, but not general XRM-velocity relationships are valid (< 1.91

repetition errors) and are unaffected by sex, training status, history, or personality. In Chapter 7, the utility of modelling repetitions in reserve-velocity (RIR-velocity) relationships is examined. Again, individual, but not general RIR-velocity relationships have excellent goodness of fit (R^2 = 0.91-0.97; residual standard error [RSE] = 0.35-1.38); and acceptable prediction accuracy (< 2 repetitions) and can be averaged across loads without sacrificing accuracy. In Chapters 8 and 9, the effectiveness of cluster set (CS) and rest redistribution (RR) set structures for alleviating fatigue and inducing adaptations are examined, respectively. Both CS and RR effectively reduce mechanical fatigue, perceptual exertion, and metabolic stress and both induce similar or superior adaptations and performance improvements versus traditional sets (TS). In Chapter 10, whether CS and RR can be used as no-cost alternatives to RT monitoring and prescription method using VL is examined. Both CS and RR reduce acute fatigue and maintain repetition velocity above 20% VL. Finally, in Chapter 11, the thesis findings and practical applications are summarised and avenues for future research are explored.

Contents

List of common abbreviations

%$_{repetitions}$ Percentage of the completed repetitions out of the maximum possible

1RM One-repetition maximum

BCa Bias-corrected and accelerated

C Correction factor

CCC Concordance correlation coefficient

CI Confidence interval

CS Cluster set structure

CV Coefficient of variation

ICC Intraclass correlation coefficient

IMU Inertial measurement unit

IPIP International Personality Item Pool

LoA Limits of agreement

LVP Load-velocity profile

MC Mean change

ML Maximum likelihood

MOVER Method of variance estimates recovery

MV Mean velocity of the concentric muscle action

MVC Maximal voluntary contraction

OLP Ordinary least product

PPER Proportion of practically equivalent residuals

PV	Peak velocity of the concentric muscle action
R^2	Coefficient of determination
RR	Rest redistribution set structure
REML	Restricted maximum likelihood
RIR	Repetitions in reserve
RM	Repetition maximum
RPE	Rating of perceived exertion
RSE	Residual standard error
RT	Resistance training
RTF	Repetitions to failure
SDC	Smallest detectable change
SESOI	Smallest effect size of interest
SMC	Standardised mean change
SMD	Standardised mean difference
TS	Traditional set structure
TOST	Two one-sided tests
V1	Load that can be lifted at 1 m/s
VAF	Variance accounted for
VBT	Velocity-based training
VL	Velocity loss

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Attestation of authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

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Signature

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Date

Co-authored works

Peer-reviewed journal publications

Jukic I, Ramos AG, Helms ER, McGuigan MR, Tufano JJ. Acute effects of cluster and rest redistribution set structures on mechanical, metabolic, and perceptual fatigue during and after resistance training: a systematic review and meta-analysis. Sports Medicine. 2020 Dec;50(12):2209-36.

Jukic I, Van Hooren B, Ramos AG, Helms ER, McGuigan MR, Tufano JJ. The effects of set structure manipulation on chronic adaptations to resistance training: a systematic review and meta-analysis. Sports Medicine. 2021 May;51(5):1061-86.

Jukic I, Helms ER, McGuigan MR, García-Ramos A. Using cluster and rest redistribution set structures as alternatives to resistance training prescription method based on velocity loss thresholds. PeerJ. 2022 Mar 29;10:e13195.

Jukic I, Castilla AP, Ramos AG, Van Hooren B, McGuigan MR, Helms ER. The acute and chronic effects of implementing velocity loss thresholds during resistance training: A systematic review, meta-analysis, and critical evaluation of the literature. Sports Medicine. 2023 Jan;53(1):177-214.

Jukic I, Helms ER, McGuigan MR. The fastest repetition in a set predicts the number of repetitions completed to failure during resistance training: The impact of individual characteristics. Physiology & Behavior. 2023 Jun 1;265:114158.

Jukic I, King A, Sousa CA, Prnjak K, McGuigan MR. Implementing a velocity-based approach to resistance training: the reproducibility and sensitivity of different velocity monitoring technologies. Scientific Reports. 2023 May 2;13(1):7152.

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Jukic I, Prnjak K, Helms ER, McGuigan MR. Modelling the repetitions-in-reserve-velocity relationship is a valid method for resistance training monitoring and prescription and fatigue control. Physiological Reports.

Scientific conference presentations

Jukic I, King A, Prnjak K, McGuigan MR, Helms ER. One velocity loss threshold does not fit all: consideration of sex, training status, history, and personality traits when monitoring and controlling fatigue during resistance training. Oral presentation on the Sport and Exercise Science New Zealand (SESNZ) Annual Conference, Auckland, New Zealand, November 2022.

Jukic I, Prnjak K, McGuigan MR, Helms ER. Modelling the relationship between the repetitions left in reserve and movement velocity during resistance training: an accurate method for prescribing intensity and volume and controlling the level of fatigue. Oral presentation on the Sport and Exercise Science New Zealand (SESNZ) Annual Conference, Auckland, New Zealand, November 2022.

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Industry presentations

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Declaration of collaboration

Chapters 2 to 10 of this thesis represent separate manuscripts that have either been published or have been submitted to peer-reviewed scientific journals for consideration for publication. My contribution and the contributions of the various co-authors to each of these manuscripts are outlined below. All co-authors have approved the inclusion of the joint work in this doctoral thesis.

Chapter 2: *Jukic I, Castilla AP, Ramos AG, Van Hooren B, McGuigan MR, Helms ER. The acute and chronic effects of implementing velocity loss thresholds during resistance training: A systematic review, meta-analysis, and critical evaluation of the literature. Sports Medicine. 2023 Jan;53(1):177-214.*

IJ 90%, APC 3%, AGR 2%, BVH 2%, MRM 1%, ERH 2%.

Chapter 3: *Jukic I, King A, Sousa CA, Prnjak K, McGuigan MR. Implementing a velocity-based approach to resistance training: the reproducibility and sensitivity of different velocity monitoring technologies. Scientific Reports. 2023 May 2;13(1):7152.*

IJ 92%, AK 3%, CAS 2%, KP 3%, MRM 2%

Chapter 4: *Jukic I, Prnjak K, McGuigan MR, Helms ER. One velocity loss threshold does not fit all: consideration of sex, training status, history, and personality traits when monitoring and controlling fatigue during resistance training. Sports Medicine – Open (under review).*

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Chapter 5: *Jukic I, Prnjak K, King A, McGuigan MR, Helms ER. Velocity loss is a flawed method for monitoring and prescribing resistance training volume with a free-weight back squat exercise. European Journal of Applied Physiology (published ahead of print).*

IJ 91%, KP 3%, AK 2%, MRM 2%, ERH 2%

Chapter 6: *Jukic I, Helms ER, McGuigan MR. The fastest repetition in a set predicts the number of repetitions completed to failure during resistance training: The impact of individual characteristics. Physiology & Behavior. 2023 Jun 1;265:114158.*

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Chapter 7: *Jukic I, Prnjak K, Helms ER, McGuigan MR. Modelling the repetitions-in-reserve-velocity relationship is a valid method for resistance training monitoring and prescription and fatigue control. Physiological Reports. (under review).*

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Chapter 8: *Jukic I, Ramos AG, Helms ER, McGuigan MR, Tufano JJ. Acute effects of cluster and rest redistribution set structures on mechanical, metabolic, and perceptual fatigue during and after resistance training: A systematic review and meta-analysis. Sports Med. 2020;50(12):2209-36.*

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Chapter 10: *Jukic I, Helms ER, McGuigan MR, García-Ramos A. Using cluster and rest redistribution set structures as alternatives to resistance training prescription method based on velocity loss thresholds. PeerJ. 2022;10:e13195.*

IJ 85%, ERH 1%, MRM 1%, AGR 13%

We, the undersigned, hereby agree to the percentages of participation in the Chapters identified on previous pages:

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Ethics approval

Ethical approval for the thesis research was granted by the Auckland University of Technology Ethics Committee (AUTEC) on the 26th of May 2020 for a period of three years (approval number: 20/55). The amendment for the recruitment protocol and general procedures of this research was approved on the 21st of August 2020, also for a period of three years. In addition, ethical approval for Chapter 10, which was conducted at the University of Granada was granted by the University of Granada's Ethics Committee on the 15th of October 2019 for an indefinite period of time (approval number: 935/CEIH/2019). Procedures of all studies were conducted in accordance with the Helsinki Declaration.

Chapter 1: Introduction

1.1 Background and rationale for this research

Resistance training (RT) is widely recognised as an effective and efficient mode of training for stimulating a vast array of neuromuscular adaptations. Many variables play a part in designing an efficacious RT program such as exercise selection, training load, volume and frequency, rest periods, movement velocity, and set structure configuration, among others [1, 2]. Of these, RT intensity of load and volume have received comparably more attention from the scientific literature as the manipulation of these training variables often determines the magnitude of RT-induced adaptation such as increases in muscle strength and hypertrophy [3, 4].

RT intensity of load is traditionally prescribed by selecting the load relative to the individual's one-repetition maximum (1RM). On the other hand, RT volume is often defined as the number of sets and repetitions performed in a training session. Thus, when the number of sets for a training session is fixed, volume is prescribed and largely determined by the number of repetitions performed per set (i.e., set volume). Set volume prescription is often based on the theoretical relationship between the maximum number of repetitions individuals can do with a given percentage of 1RM (%1RM). Therefore, an inherent connection exists between traditional RT intensity of load and volume prescription. While this RT prescription approach is relatively simple and ideal for implementation in practice, it has several limitations. From the load monitoring and prescription perspective, the 1RM test can be physically and psychologically demanding and time-consuming and can also compromise the safety of an individual doing the test [5]. Additionally, while 1RM tests are generally reliable [6], using them to continuously prescribe RT intensity of load can be erroneous as they do not account for inherent variation in human performance due to normal biological variability and factors such as sleep [7], nutrition [8], life stress [9], mood state [10], and multimedia exposure [11]. From the set volume monitoring and prescription perspective, the maximal number of repetitions that can be completed to failure with different exercises and loads varies substantially among individuals [12]. This variability suggests that prescribing the same relative load with a fixed number of repetitions will likely lead to heterogeneous training stimuli across individuals. To combat these fundamental issues with traditional RT intensity of load and set volume prescription, sport scientists attempted to establish more objective methods to monitor and prescribe RT programs over the last decade.

One such approach to monitoring and prescribing RT loads is based on the mean velocity of the concentric muscle action (MV) during lifting which constitutes the basis of velocity-based resistance training (VBT). The monitoring power of VBT relies on the strong inverse relationship between MV and %1RM for a variety of exercises [13-15] which allows for the establishment of load-velocity profiles (LVP) for individuals. The LVP of an individual can be established during a 1RM assessment whereby the MV of each lifted load is also recorded. The practical utility of this monitoring and prescription method relies on the stability of MV, whereby MV stays constant although absolute load might change (e.g., strength levels might increase) [13, 16]. For instance, if an individual lifts the same absolute load at a higher velocity two weeks after the establishment of an LVP, it would mean that their strength increased and therefore, the same absolute load now does not represent the same %1RM as two weeks prior. However, it is important to highlight that performing concentric muscle actions at the maximal intended velocity is the main prerequisite for reliable adjustment of training loads using LVPs. If this criterion is not satisfied, changes in velocity could merely represent a lack of effort expressed by the individuals during RT, and not changes in readiness to train per se. Nevertheless, VBT methodology allows sport scientists and coaches to adjust RT loads based on individuals' daily readiness to train (i.e., taking into account strength fluctuations), and thus presents a step forward compared to using only the 1RM test for monitoring and prescription of RT loads.

Instead of performing a fixed, predetermined number of repetitions, researchers have suggested the use of velocity loss (VL) thresholds to modify RT set volume prescription [14]. This particular VBT method dictates that a set can be terminated when repetitions are not performed above a certain velocity which is usually determined as a percentage of the fastest repetition in the set. Theoretically, this ensures all repetitions performed are "quality" repetitions (i.e., performed with more power as velocity is maintained above a threshold), and accumulation of acute fatigue is mitigated. Indeed, researchers from several early studies concluded that the choice of VL threshold during RT can modulate the magnitude of RT-induced training adaptations [17]. For instance, experiencing higher VL during training seems suitable to maximise the hypertrophic response, but tends to induce a fast-to-slow shift in muscle phenotype [17]. In contrast, training with lower VL might lead to similar strength gains and superior improvements in vertical jump performance despite a relatively lower amount of work completed, thus increasing the efficiency of the overall training session [17].

Although prescribing RT set volume using VL thresholds can determine the magnitude of resultant training adaptations, it can be challenging to monitor the actual volume of work completed across individuals. At the commencement of this doctoral project in 2019, only Gonzalez-Badillo et al. [14] had attempted to establish a relationship between the magnitude of VL and the amount of work completed – expressed as a percentage of the repetitions completed out of the maximum possible ($\%_{repetitions}$) – in the exercise set. Despite the widespread use of the VL-$\%_{repetitions}$ relationship in practice, this method for regulating set volume during RT involves two important limitations. Firstly, the exact number of repetitions completed until reaching different VL thresholds remains unknown. This is important to highlight as the main limitation of traditional methods of prescribing RT set volume is often evidenced by the inter-individual variability in how many repetitions one can do until muscle failure with different loads in each exercise [12]. However, it can be posited that the VL method may suffer from the same problem. Secondly, the exact number of repetitions left in reserve after completing the set also remains unknown. This is important because the last repetitions of a set contribute more to the alteration of muscle energy balance and the abrupt increase in metabolites such as ammonia [15, 18, 19]. Therefore, it would be of great interest to quantify the potential variability in the amount of work completed until reaching different VL thresholds across individuals and establish velocity-based methods which can quantify the exact number of repetitions completed and left in reserve after terminating the RT set.

At the commencement of this doctoral work, no studies exploring the utility of VL thresholds during RT had examined the potential confounding effects of sex, training status (e.g., relative strength) and training history. This is surprising as researchers have previously reported that these factors should all be considered when designing a RT program and monitoring changes in neuromuscular function [12, 20, 21]. Furthermore, since VL is used to monitor RT-induced fatigue and prescribe RT, personality traits such as emotional stability and conscientiousness could also affect the responses to different VL thresholds due to their association with how individuals cope with fatigue [22]. Considering sex, training history, relative strength and personality traits is crucial before attempting to generalise the utility (or lack thereof) of VL thresholds in practice. Finally, and most importantly, no attention has been given to the predictive validity of VL-$\%_{repetitions}$ relationships to date despite their widespread use both in research and in practice. As previously stated, González-Badillo et al. [14] already examined the goodness of fit of this relationship across several testing sessions during the Smith machine bench press exercise with different loads. Since this goodness of fit was generally very high, the conclusion was that the VL-$\%_{repetitions}$ relationship can safely be used to reliably, and with high precision, prescribe and monitor RT set volume. Unfortunately, these findings are of limited ecological validity for free-weight exercises and provide limited empirical support for the use of VL-$\%_{repetitions}$ relationships to monitor and prescribe RT set volume in general. This is because practitioners cannot establish a VL-$\%_{repetitions}$ relationship in every single training session with their athletes, patients, or clients. Therefore, it would be of utmost importance to know whether the established VL-$\%_{repetitions}$ relationship for a given individual during an initial testing session predicts future data – specifically, the $\%_{repetitions}$ completed in subsequent training sessions – reasonably well. Such evidence is important to guide the VL approach to monitoring and prescribing RT set volume with free-weight exercises.

A further major barrier to implementing the VBT methodology into practice to this date remains the availability of affordable and practical technology that accurately measures MV. Consequently, new, more affordable, wireless devices keep coming to the market every year. Two such devices are iso-inertial measurement units (IMU) PUSH2 (PUSH Inc., Toronto, ON, Canada) and Vmaxpro (alias EnodePro; Blaumann & Meyer—Sports Technology UG, Magdeburg, Germany) which are now widely used among sport scientists and coaches. While these manufacturers claim their devices are reliable, research to validate these claims did not yet exist. Since training load and set volume adjustments using VBT are based on minor yet significant changes in MV, it is important to determine the reliability of devices frequently used in practice. Additionally, it would be useful to examine the sensitivity of devices to detect minimal changes in velocity that correspond to true changes in performance. However, at the commencement of this doctoral work, no studies had examined the reproducibility and sensitivity of the PUSH2 and Vmaxpro devices according to these criteria. Therefore, research assessing the reliability of devices that account for biological variation while determining the sensitivity of devices based on practically relevant criteria is required.

Despite some evidence supporting the use of VL thresholds to monitor and prescribe RT set volume, some professionals may not implement VL thresholds due to their reliance on technology which is costly and can sometimes fail unexpectedly. Therefore, costless, ad-hoc approaches to preserve MV during RT to control fatigue could also prove beneficial. Without decreasing training loads or training volume, likely the simplest and most effective way to mitigate acute fatigue is to adjust rest periods; specifically, adding intra-set rest. Although the addition of intra-set rest usually serves its purpose, these so-called cluster sets (CS) might not always be feasible from a practical perspective since they extend total training time [23]. One alternative to lengthy CS structures is to redistribute the total rest time of traditional set structures to include shorter and more frequent rest intervals [24]. This strategy, known as rest redistribution (RR), can maintain velocity and power output within individual sets compared to traditional sets [24-26]. Therefore, simply performing fewer repetitions during a set might serve as a practical VBT method where the quality of the repetitions will be preserved and therefore equal strength and power adaptations may occur when compared to using VL thresholds.

1.2 Purpose of this research

The overall purpose of this thesis was to examine current and novel velocity-based approaches to RT monitoring and prescription while also considering the potential effects of sex, training history, relative strength, and personality traits on the accuracy of these monitoring and prescription tools. Emphasis was also given to reduced or no cost means of implementing VBT methodology in practice. In addition to addressing the gaps in the literature with scientific rigour, research from this thesis was intended to directly influence the practice of sport scientists, strength and conditioning coaches, physiotherapists, and athletic trainers who already use, plan to use or are logistically constrained to implement the velocity-based approach to RT monitoring and prescription in their work.

Therefore, the specific objectives of this thesis were to:

1. Quantify the variability in responses to different VL thresholds and examine the accuracy of RT prescriptions based on VL.
2. Determine the utility of novel velocity-based approaches to RT monitoring and prescription.
3. Investigate whether considerably cheaper, wireless IMU devices are reproducible and of sufficient sensitivity to detect meaningful changes in performance when compared to commonly used linear position transducers.
4. Determine whether the beneficial performance effects of terminating sets after reaching moderate VL demonstrated in prior literature can be achieved by using CS and RR while avoiding the financial and logistical constraints associated with the use of velocity monitoring devices.

1.3 Significance of this research

There is substantial interest in understanding the variability in responses to different VL thresholds, and subsequently, the individualisation of velocity-based approaches to RT monitoring and prescription. At the commencement of this thesis project, the vast majority of existing VBT studies – including almost exclusively males using Smith machine exercises – generalised various concepts stemming from this approach to broader RT monitoring and prescription. For instance, it has been recommended that the MV associated with each %1RM is very similar across individuals for a given exercise [27]. Similarly, generalisations were made for the $\%_{repetitions}$ an individual can complete before reaching different VL thresholds [14]. While LVPs in some free-weight exercises were already shown to be highly individual [28], whether RT monitoring and prescription based on VL should also be individualised remains unknown. Furthermore, although the VL-$\%_{repetitions}$ relationship is often used in practice by strength and conditioning, physiotherapy and sport science professionals, its stability in time as well as predictive validity has not been thoroughly examined to date. It is evident that previous research is of limited ecological validity for free-weight exercises and generally provide limited empirical support for the use of VL-$\%_{repetitions}$ relationships to monitor and prescribe RT set volume. Also, factors such as sex, training history, relative strength and personality traits have received limited attention in the VBT literature. This information will provide much-needed insight into whether individual characteristics should be considered when monitoring and prescribing RT using VL thresholds.

Even if the VL-$\%_{repetitions}$ relationship is proven valid and stable across time, this method for regulating set volume during RT still does not allow for prospective quantification of the actual volume of work completed until reaching different VL thresholds or the number of repetitions left in reserve once the set is terminated. Those limitations are substantial as they prevent practitioners from truly quantifying the training load imposed on the individuals and from controlling for the level of effort across individuals. Therefore, establishing methods that ensure all proposed benefits of the velocity-based approach to RT monitoring and prescription occur, while allowing for quantification of the actual volume of work completed and the level of effort experienced, would be of great interest to practitioners.

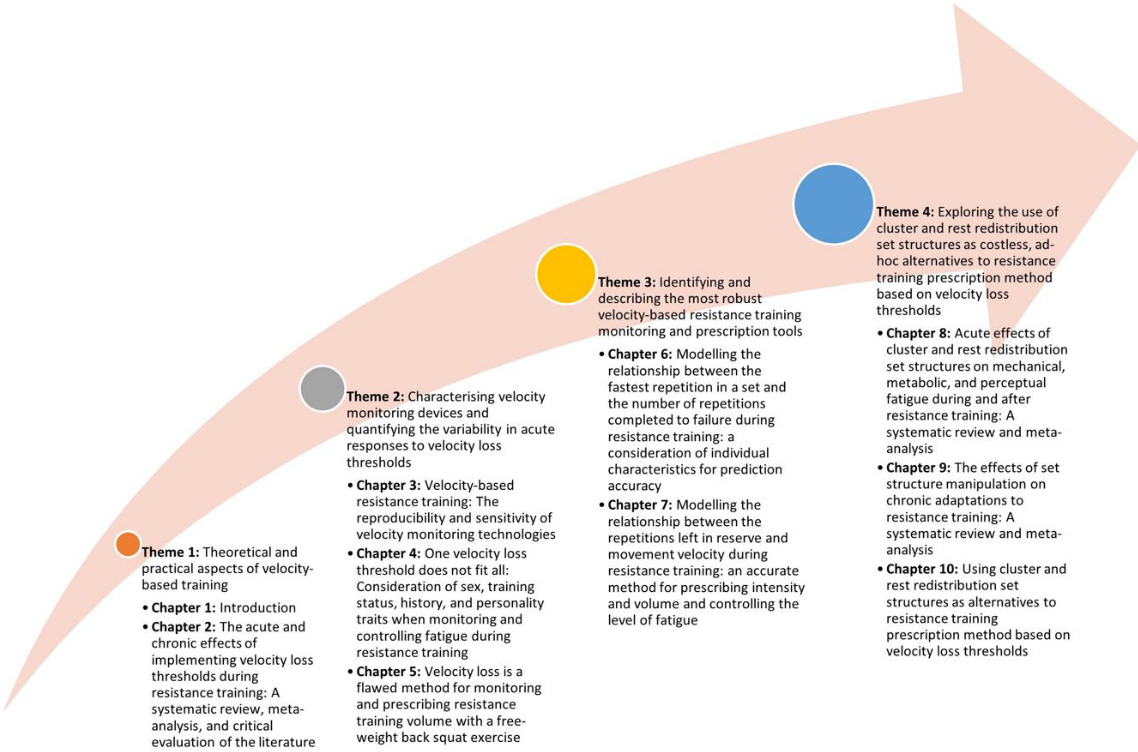
The efficacy of the velocity-based approach to RT monitoring and prescription depends upon the reliability of devices used to record MV. Unfortunately, reliable velocity monitoring devices can be very expensive for many, preventing the implementation of VBT in practice. Thanks to technological advancements, new, more affordable, and wireless devices are coming to the market every year. However, before those more affordable devices can be used in practice, their reproducibility and sensitivity must be examined first and aligned with those that are already regarded as highly reliable in the scientific literature. Despite the technological advancements and ever-increasing number of more affordable velocity monitoring technologies, they are still not affordable to many. Even if reliable velocity monitoring devices are available, their use with groups of people can be an impractical task. This is problematic as it directly prevents many people from benefiting from this monitoring tool, which could also negatively affect adherence to RT in the long run. In that regard, more heuristic approaches to monitoring VL during RT which do not impose a financial burden would be extremely beneficial for practitioners.

In summary, there is substantial theoretical and practical significance in thoroughly examining the existing velocity-based RT monitoring and prescription methods, as well as expanding on their already identified limitations. In this regard, the present thesis addresses several theoretical and practical gaps in the literature. This information will have implications for RT monitoring and prescription, and therefore, direct practical application for practitioners working with athletes and recreational trainees.

1.4 Thesis organisation

This thesis is comprised of four primary themes (Figure 1-1) and follows AUT's Manuscript Format (i.e., Manuscript Format 2). Therefore, all chapters, within primary themes, excluding the first and final were written in the format of a published journal article. In addition, Chapters 2-10 begin with a preface briefly explaining how each Chapter links and builds upon one another to ensure clarity and cohesiveness of this thesis. The present chapter introduces the primary concepts and frameworks used in this thesis while also detailing its structure. Chapter 2 consists of a systematic review and meta-analysis where we synthesised the available evidence on the acute and chronic effects of implementing VL thresholds during RT. In this Chapter, an overview of the factors which might differentially influence the magnitude of acute and chronic responses to different VL thresholds is provided and methodological issues with VL implementation in practice are discussed, finishing with a specific focus on avenues for future research. The second theme characterises novel, more affordable velocity monitoring devices and quantifies the variability in acute responses to VL thresholds. In Chapter 3, the reproducibility and sensitivity of several velocity monitoring devices are examined, of which, the most reliable one was used in later Chapters. In Chapter 4, the variability in the amount of work completed until reaching different VL thresholds are explored while considering the effects of sex, training history, relative strength, and personality traits. In Chapter 5 – the final Chapter of the second theme – the predictive validity of the VL-$\%_{repetitions}$ relationship and its stability in time are evaluated while also considering the abovementioned confounding factors. In the third theme of his thesis, two novel velocity-based approaches to RT monitoring and prescription are established after combining velocity-based and either repetition maximum or repetitions in reserve concepts. More specifically, in Chapter 6, the utility of modelling the relationship between the fastest repetition in the set and the maximum number of repetitions possible in the set (i.e., XRM-velocity relationship) is explored, whereas, in Chapter 7, the monitoring and prescription power of the relationship between MV and the repetitions left in reserve (i.e., RIR-velocity relationship) is described. In the final theme of this doctoral work, free, ad-hoc alternatives to implementing VL thresholds in practice are evaluated and described. Within this theme, acute and chronic responses to CS and RR organisation of RT sets are systematically reviewed and meta-analysed (Chapters 8 and 9) to determine their effectiveness and efficiency. Thereafter, the ability of RR and CS to maintain high MV during RT without dropping below 20% VL is experimentally tested in Chapter 10. Finally, in Chapter 11, all findings stemming from this thesis are summarised, discussed, and put into the perspective of the larger body of research on RT monitoring and prescription. This is followed by conclusions, practical applications, and future avenues of research.

Figure 1-1 Thesis organisation.



Chapter 2: The acute and chronic effects of implementing velocity loss thresholds during resistance training: A systematic review, meta-analysis, and critical evaluation of the literature

Preface

This Chapter aids future chapters of the thesis by identifying 1) methodological issues of using velocity loss thresholds to monitor and prescribe resistance training, 2) means by which velocity-based resistance training monitoring and prescription could be improved, and 3) free and ad-hoc alternatives to resistance training monitoring and prescription using velocity loss thresholds. To achieve these goals, a systematic review was conducted to synthesise the available evidence on 1) the acute effects of different velocity loss thresholds on markers of fatigue and the number of repetitions per set during resistance training, and 2) the chronic effects of different velocity loss thresholds on training adaptations. This review also provides an overview of the factors which might differentially influence the magnitude of acute and chronic responses to different velocity loss thresholds, thus providing a more nuanced look at the dose-response relationship between velocity loss, acute fatigue accumulation, and various training adaptations. Such information is important to inform resistance training prescription strategies based on velocity loss thresholds, ultimately allowing for better fatigue management and attainment of intended training adaptations.

This chapter is published in *Sports Medicine* journal.

2.1 Introduction

Resistance training (RT) can produce many adaptations including strength, power, hypertrophy, and endurance, and for this reason plays an integral role in many long-term athlete development programmes. While these adaptations may improve performance of athletic tasks such as jumping, sprinting, and change of direction [1, 2], RT also plays an important role in injury prevention and rehabilitation and has numerous beneficial effects on health and quality of life [29-32]. Designing an effective RT program requires careful consideration of many training variables such as the choice and order of the exercises, load, repetition range, volume, rest, intended velocity, and set structure configuration. Among these, training load and volume appear to be the most important training variables dictating the type and extent of acute and chronic adaptations to RT [33, 3, 34]. Traditionally, load is prescribed relative to a one-repetition maximum (%1RM) while RT volume is manipulated by modifying the total number of sets performed and/or the number of repetitions performed per set. Although this approach is relatively simple and efficient, it does not account for physiological and psychological stressors that might affect an individual's day-to-day RT performance as well as inter-individual variability in RT performance [35]. For instance, load prescription based on %1RM might be less accurate since maximal strength can fluctuate daily [36] when an individual is fatigued or significantly increase within a few weeks due to training adaptations [37]. Further, the number of repetitions that can be completed with a given %1RM is highly variable as it is both individual- and exercise-specific [12, 15]. In this regard, sport scientists have explored velocity-based training (VBT) approaches to load and volume prescription as an alternative method that may circumvent some of these limitations [35].

Load and volume prescription with VBT rests on the premise that there is an inverse linear relationship between barbell velocity and %1RM; heavier loads cannot be lifted with the same velocity as lighter loads [35]. Furthermore, if an exercise is performed with maximal concentric effort and fatigue ensues, barbell velocity inevitably decreases [15]. Indeed, very strong correlations exist between intra-set velocity loss (VL) and mechanical, perceptual, and metabolic markers of fatigue [15, 14, 38], as well as between VL and the number of completed repetitions relative to the maximum number of repetitions possible in a set [14, 39]. For instance, in the squat, terminating a set after reaching 20% VL would typically result in 50% of the possible repetitions being completed [15], whereas a 40 or 50% VL would result in repetitions performed to, or very near, muscle failure [17]. Therefore, VL may be used as an indicator of fatigue during RT, and thus, may be used to regulate volume and proximity to failure with reasonable precision [15, 40, 14, 38, 39].

Indeed, several studies have been conducted to investigate the acute effects of different VL thresholds on various correlates and markers of fatigue and generally reported nearly linear increases in fatigue as VL increased across the sets [15, 14, 38, 41]. For instance, Rodríguez-Rosell et al. [38] observed a gradual increase in blood lactate accumulation as VL thresholds increased from 10-45% and 15-55% during sets of back squat and bench press, respectively. Weakley et al. [42] observed the same trend with 10, 20, and 30% VL, while also reporting a gradual decline in countermovement jump height and gradual increases in perceived exertion of the lower limbs and breathlessness after each set. Finally, Pareja-Blanco et al. [43] reported that for a given %1RM, a higher magnitude of VL in a set results in greater impairment of neuromuscular performance immediately after the training session and slower post-exercise recovery 24 and 48 hours later. While these findings illustrate the utility of monitoring VL for RT prescription, some researchers suggested that the effects of different VL experienced during a set on the magnitude of neuromuscular, metabolic, and perceptual fatigue accumulation might be depended upon the exercise and the load used [38, 44]. In addition, the magnitude of VL itself could be affected by the reference repetition for determining VL (i.e., first vs fastest) [45] and the criteria for set termination (e.g., terminating a set after one or more repetitions passed a below a certain VL threshold) [45]. Finally, although VL is frequently used to prescribe RT volume, the exact number of repetitions performed before reaching certain VL thresholds is also likely affected by the load and exercise used, as well as inter-individual variability and perhaps reliability of velocity monitoring devices. Despite these limitations, different VL thresholds are often used with the aim of creating a more homogeneous RT stimuli among individuals, which in turn is thought to lead to more consistent and enhanced long-term adaptations [35], although more research is needed to confirm these speculations.

Considerable evidence is accumulating from longitudinal studies (> 4 weeks in duration) comparing the effectiveness of different VL thresholds to one another on muscular strength, hypertrophy, and endurance as well as performance of athletic tasks. In this regard, it has been suggested that the selected VL threshold can modulate adaptations to training in a dose-response fashion [17, 46-48]. For instance, Pareja-Blanco et al. [47] recently showed that there might be an upper and lower VL threshold that should be prescribed during RT to induce optimal training adaptations, indicating that the dose-response relationship might follow an inverted U-shape. Thus, it was concluded that low to moderate VL thresholds (i.e., 10 and 20%) should be chosen to optimise adaptations to RT since VL thresholds lower than 10% induced levels of fatigue that were too low to maximise adaptations, whereas high VL thresholds (i.e., > 40%) did not promote further strength or hypertrophy, and negatively affected the improvement of athletic tasks compared to moderate VL thresholds [47]. However, not all studies support this as similar improvements in maximal strength [49, 50], hypertrophy [50] and sprinting and jumping performance [49] were observed between lower and higher VL thresholds. To further confound matters, other factors such as training duration, choice of exercise, load, and participant strength levels likely moderate the effects of VL thresholds on various training adaptations.

In light of these considerations and inconsistencies in the scientific literature, there is a clear need for a comprehensive review and synthesis of the available evidence. Therefore, the aim of this systematic review and meta-analysis was to synthesise the available evidence on 1) the acute effects of different VL thresholds on markers of fatigue and number of repetitions per set during RT and 2) the chronic effects of different VL thresholds on training adaptations. This review also aimed to provide an overview of the factors which might differentially influence the magnitude of acute and chronic responses to different VL thresholds, thus providing a more nuanced look at the dose-response relationship between VL, acute fatigue accumulation, and various training adaptations. Such information is important to inform RT prescription strategies based on VL thresholds, ultimately allowing for better fatigue management and attainment of intended training adaptations.

2.2 Methods

2.2.1 Registration of the systematic review protocol

A systematic review of the literature was performed according to the guidelines in the *Cochrane Handbook for Systematic Reviews of Interventions* (version 6.0) and following the checklist for the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 (PRISMA) [51]. The original protocol was prospectively registered at the Open Science Framework (https://osf.io/q4acs/). The protocol registration occurred after searches were conducted, but before screening was completed and data extraction started.

2.2.2 Eligibility criteria

All studies included met the following inclusion criteria: (1) the study was published in English; (2) evaluated the acute effects of one or more VL thresholds during resistance training on neuromuscular, metabolic and perceptual markers of fatigue, and/or examined their chronic effects on muscular strength, hypertrophy, endurance or power adaptations; (3) RT was prescribed using VL thresholds; (4) intensity of load (%1RM) and frequency were matched between conditions; (5) participants had no known medical condition or injury; (6) in acute studies, neuromuscular, metabolic or perceptual responses (and variability thereof) to these thresholds were considered; (7) in longitudinal studies the outcomes were assessed pre- and post-intervention for muscular strength with a repetition maximum (RM) component, or maximum voluntary contraction (MVC) test, hypertrophy (lean body mass changes or changes at the muscle level), endurance (total repetitions performed or mechanical work), and power adaptations (jump height, sprint and change of direction times, or velocity at a fixed load); and (8) training interventions in longitudinal studies lasted a minimum of 4 weeks.

2.2.3 Information sources and search strategy

A PICO strategy consisting of terms for different VL thresholds, resistance training, and neuromuscular, perceptual, and metabolic outcomes as well as muscular strength, endurance, hypertrophy, and power adaptations was used to build search criteria for electronic databases. To ensure the inclusiveness of the search terms, the Word Frequency Analyser tool (http://sr-accelerator.com/#/help/wordfreq) was used to suggest potentially relevant search terms [52]. In addition, the Research refiner tool (https://ielab-sysrev2.uqcloud.net/) was used to optimise the sensitivity and specificity of the search for PubMed, while the Polyglot Search Translator Tool (https://sr-accelerator.com/#/polyglot) was used to adapt the search to other databases [52, 53]. The search string used for MEDLINE/PubMed is reported in Appendix F Ch. 2 File 1. The following bibliographic databases were searched from inception to December 6th, 2020: PubMed/MEDLINE, SCOPUS, CINAHL (Cumulative Index to Nursing and Allied Health), SPORTDiscus, and Web of Science. No year restrictions were applied. Secondary searches included: (a) screening the reference lists of all included studies and relevant review papers; (b) examining the studies that cited the included studies (i.e., forward citation tracking) through Google Scholar; (c) search alerts to monitor any new search results after the date of the last search up to June 21, 2022.

2.2.4 Study selection

Duplicate references were first removed using the EndNote reference manager (version X9.0.3, Clarivate Analytics, Philadelphia, USA). Two authors (IJ and AGR) then independently screened titles and abstracts to determine initial eligibility using the systematic review software Rayyan. The authors were blinded to avoid bias during this process. Thereafter, the authors (IJ and AGR) independently screened the full texts to determine inclusion eligibility. Disagreements in eligibility at any stage were resolved through discussion, or with a third reviewer (BVH) when required.

2.2.5 Data extraction

The following data were extracted from the included studies into an Excel spreadsheet: (1) study design and identification information; (2) adherence and study duration; (3) sample size; (4) participants' age, body mass, height, sex, strength levels, and training experience; (5) relevant information regarding VL thresholds used, including various methodological factors (e.g., reference repetition, velocity variable, prescription method); and (6) means and standard deviations as well as raw mean changes and standard deviations of changes for pre- and post-intervention assessments of the relevant outcome measures. If insufficient data were reported, the authors of those studies were contacted by email. Web Plot Digitizer software (Version 4.1; TX, USA) was used to extract data from figures when the authors did not report or provide the data. Data extraction was completed independently by three authors (IJ, AGR, and APC) using two pilot-tested forms (one for acute and one for longitudinal studies) on five randomly selected studies which were then modified accordingly. Coding files were cross-checked between the authors, and any differences were resolved via discussion and agreement, or with a fourth reviewer (BVH).

2.2.6 Risk of bias assessment

Risk of bias assessment was performed using a modified Cochrane Collaboration tool for assessing the risk of bias in randomised trials [54]. Modifications included the removal of the performance bias and blinding of outcome assessment bias criteria and adding effort bias, feedback bias, training prescription bias (for longitudinal studies only), outcome assessment bias, and familiarisation bias. The blinding of outcome assessment bias was excluded since visual and verbal velocity feedback were used in the reviewed studies to ensure participants' maximal intent which improves the reliability of performance. Similar to previous systematic reviews and meta-analyses on exercise intervention studies [55, 56], the performance bias criterion was removed because it is impossible to blind participants and personnel in supervised exercise intervention studies. Assessments were completed independently by two reviewers (IJ and ERH) while any observed differences were resolved via discussion and agreement before merging the scores into a single spreadsheet.

2.2.7 Statistical analysis

Acute effects of velocity loss thresholds

While we *a priori* planned to examine the acute effects of different VL thresholds during RT on repetition volume, neuromuscular, metabolic, and perceptual responses, and potential moderating effects of exercise, training prescription method, reference repetition for VL calculation, load, and strength levels of individuals, this was not done due to one or more of the following reasons 1) low number of studies reporting these outcomes; 2) large amount of missing data; and 3) authors' non-responsiveness to data request e-mails or refusal to provide data necessary for calculating effect sizes (usually baseline means and standard deviations, standard deviations of difference scores or pre-post correlations). Attempts were made to circumvent these issues while making assumptions about baseline data based on other studies and estimating missing data using the data that were available following the procedures outlined by Elbourne et al.

[57] and Borenstein et al. [58]. However, these procedures often resulted in spurious calculations (e.g., r > 1) which discouraged us from pursuing the meta-analysis. Nevertheless, to aid the interpretation of the findings, we used the data reported in the original studies and created visualisations which could be used to observe potential trends and interactions between the variables. Importantly, this was done only when a whole range of VL thresholds were investigated for a given outcome.

Chronic effects of velocity loss thresholds

The nature of our research question with regards to chronic effects of different VL thresholds on muscle strength, hypertrophy, and endurance, as well as sprint, countermovement jump, and velocity against submaximal loads performance required the inclusion of a VL threshold, as a continuous moderator, in all meta-analytic models. This was needed as each study compared different VL thresholds to one another, rather than to no training at all (i.e., no control groups were included in the studies).

Calculation of effect size and variance

Standardised mean changes (SMC) were computed to quantify the effect of the intervention using different VL thresholds relative to the baseline, thereby permitting synthesis of the same outcome variable (e.g., strength, hypertrophy) from different procedures or scales. However, raw mean changes (MC) were computed and used as a summary measure of effect size when a given outcome was assessed using the same procedure or scale to aid the interpretation of the findings. SMC for each group was calculated as the difference between post-test and pre-test scores, divided by the pre-test standard deviation with an adjustment (C) for small sample bias [59-61]:

$$SMC = C\left(\frac{M_{post} - M_{pre}}{SD_{pre}}\right);\ C_j = 1 - \frac{3}{4(n_j - 1) - 1}$$

The SMC magnitude was interpreted as: small (0.20 – 0.49), moderate (0.50 – 0.79) and large (> 0.80) [62].

No studies reported the pre- to post-intervention correlations required to determine the variance. Therefore, when the authors did not provide correlations upon our request, standard deviations of the pre- to post-intervention change were used to calculate pre-to-post correlations using the following formula:

$$r_j = \frac{SD_{j,pre}^2 + SD_{j,post}^2 - SD_{j,change}^2}{2 * SD_{j,pre} * SD_{j,post}}$$

The corresponding authors were contacted when the standard deviations of the pre- to post-intervention change were not reported. From all the corresponding authors, one did not respond [63], whereas the corresponding author of the following studies included in this review [64-66] declined to provide the requested data. The rest of the authors provided the necessary data to calculate the variance. For the missing standard deviation of the pre- to post-intervention change, the median correlation using all other studies for a given outcome was imputed. This ensured that the maximum number of studies were included. The variability in designs among eligible studies required several decisions to ensure the data could be appropriately combined for the calculation of effect sizes. These decisions are detailed in Appendix F Ch. 2 File II.

Statistical synthesis of effect sizes

Most studies in the quantitative part of the synthesis (81.2%) provided two or more effect sizes while comparing the effects of different VL thresholds. Effect sizes from the same study are likely more similar than effect sizes from different studies [67]. Thus, the inclusion of multiple effect sizes from a single study violates the assumption of independence in effect sizes in traditional meta-analyses (e.g., [68, 69]). As such, a 3-level meta-analysis (i.e., a multilevel model) was used to account for dependencies among effect sizes from the same study [70]. A multilevel meta-analysis accounts for the hierarchical nature of the data (e.g., effects sizes nested within studies) and, in so doing, the extraction of multiple effects from each study preserves information improving statistical power [67]. This approach also decomposes the variance components of the pooled effect into sampling variance of the observed effect sizes (level 1), and variance within (level 2) and between studies (level 3) [68]. A multilevel meta-analysis was conducted for every outcome separately except for velocity at submaximal loads. For velocity against submaximal (low and moderate) load outcomes, a multivariate mixed-effects meta-regression was performed. In addition, cluster-robust variance estimation methods [71] with small-sample adjustments [72] were implemented to calculate standard errors of the overall effect size estimates, with clustering at the study level. This was done since 1) most studies reported change in velocity against low and moderate loads; and 2) all these studies reported multiple effect sizes for both sub-outcomes (i.e., moderate and low loads), and different VL thresholds. Therefore, these two sub-outcomes were highly correlated as the data from the same participants were analysed multiple times for both sub-outcomes, giving rise to both hierarchical and correlated effects for this outcome. The correlation (ρ) between moderate and low loads was assumed to be 0.6. Observations were weighted by the inverse of the sampling variance, and all (final) model parameters were estimated by the restricted maximum likelihood estimation (REML) method. Tests of individual coefficients in all models, and their corresponding confidence intervals, were based on a t-distribution. Multilevel and multivariate models were fitted in R language and environment for statistical computing (4.0.5, R Core Team, Vienna, Austria) using the *metafor* package [73], while the cluster-robust variance estimation method was implemented using the *clubSandwich* package [74].

Moderator and sensitivity analyses

All meta-analytic models (i.e., multilevel and multivariate mixed-effects meta-regressions) included VL as a continuous moderator. Further, other theoretically relevant moderators were included when 1) the number of effect sizes was sufficient (at least 8-10 per moderator); and 2) the range of observations (or levels in case of categorical predictors) was not very narrow or identical among the studies. These moderators included study duration (continuous predictor), exercise (upper or lower body exercise), loads (higher and lower than 70% of 1RM), and strength levels (continuous predictor). The exercise moderator was categorised because back squat and bench press were the most prevalent exercises among the studies. In addition, the loads moderator was categorised as the majority of primary studies used progressive overload across the weeks and averaging these loads to a single number might not accurately represent the loads used in a given study. Due to the inclusion of both fixed and random effects, REML was used to evaluate the final models for each outcome. Furthermore, their contribution — and the contribution of modelled interactions among predictors — to the explanatory power of any of the explored models was examined using a likelihood ratio test, deviance statistic and Akaike information criterion score for small sample sizes before selecting the final model to obtain the best-fit while maintaining model parsimony. During this process, models were fitted – and subsequently compared – using the maximum likelihood (ML) method as likelihood ratio tests cannot be used to compare models with nested fixed effects using REML estimates [75]. Finally, a dose-response relationship considering 1) individual study effect sizes; 2) average effect sizes of individual VL thresholds; and 3) average effect sizes of low (15% VL), moderate (> 15% < 30% VL), and high (> 30% VL) grouped VL thresholds was also evaluated for each outcome to aid interpretation of the findings.

For all meta-analytic models, *Leverage*, *outlier*, and *influential* case diagnostics were performed by calculating *hat*, *Cook's distance,* and *studentised residuals*, respectively [76-78]. Cases were red flagged with their hat and Cook's distance's values greater than 3 times their respective mean, and with a studentised residual's value greater than 3, in absolute values. For the multivariate model investigating the effects of VL thresholds on velocity against submaximal loads, a range of correlations between the outcomes were imputed (ρ = 0.4 – 0.8) to ensure the robustness of the estimates.

Publication bias was not assessed as we were not interested in the effects of training interventions in individual studies, but as a moderator effect of VL thresholds examined within those studies. In addition, there was no reason to expect that a certain training intervention would not result in a significant improvement over time in at least some of the outcomes given the absence of control groups (interpreted here as groups who would not train at all).

Statistical heterogeneity

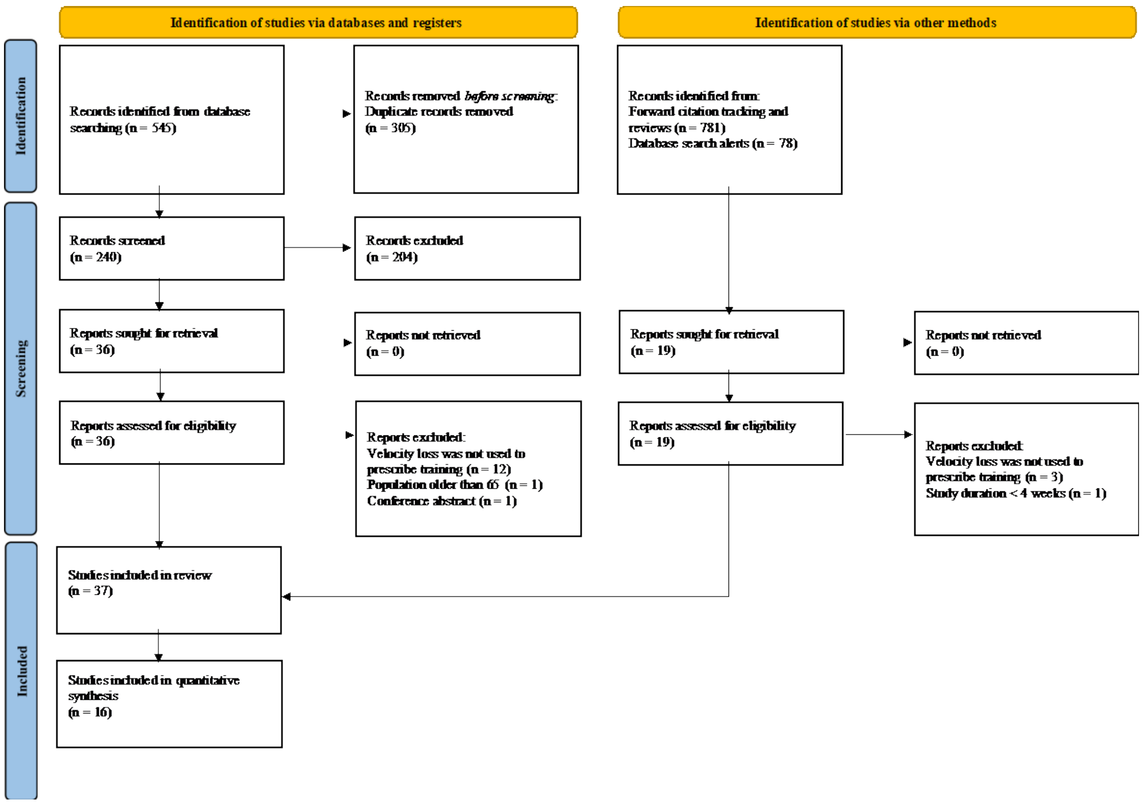
Since all multilevel models included moderators (i.e., VL), statistical indices of heterogeneity were evaluated using I^2 and τ^2 which represented relative and absolute values of residual heterogeneity or the amount of the unaccounted-for variability that is due to residual heterogeneity [79]. This heterogeneity was then partitioned across two levels (i.e., within- and between-study heterogeneity). Importantly, for all multilevel models, the estimated proportional reduction in the total variance was computed using the variance accounted for (VAF), a pseudo R^2 value (i.e., the amount of heterogeneity accounted for by the moderators) [80]. For the cluster-robust multivariate meta-regression, the amount of heterogeneity (τ^2) for each outcome was calculated as well as the correlation between the outcomes (ρ).

2.3 Results

2.3.1 Search results

The primary search yielded 545 results, of which 22 met the inclusion criteria. Forward citation tracking as well as monitoring newly published, relevant literature yielded an additional 15 studies, resulting in 37 studies included in this review. The stages of the search and study selection process are presented in Figure 2-1.

Figure 2-1 Literature search flow chart.



Note. n, number of studies.

2.3.2 Study characteristics

Out of 37 studies included, 18 were randomised cross-over acute studies, and 19 were training intervention studies. The total number of participants pooled across studies was 846 (767 males and 69 females). However, upon inspection, it was clear data from the same participants were used in multiple studies [41, 81-83]. This reduced the total number of participants to 735 (656 males and 69 females). Only five studies [84-86, 50, 87] included males and females, two of them only females [88, 89] while the rest included only males. Back squat was the most frequently used exercise (26 studies), followed by bench press (12 studies), deadlift (2 studies), bench pull, overhead press, leg press, loaded countermovement jump, and pull-up (1 study each). Eleven studies used free-weight exercises, while the remaining used a Smith machine. A large range of VL thresholds were examined (0 to 55%) with 10, 20, 30, and 40% VL thresholds being the most frequent (10 or more studies each). In addition, participants with a large range of strength levels (1RM/body mass) were examined with the average lower and upper body maximal strength of participants being 1.48 (range = 0.7 – 2.2) and 1.15 (range = 0.65 – 1.56) times body mass, respectively. VL thresholds were prescribed using the first repetition (14 studies), and the fastest repetition (23 studies) of the set as the reference point. Load was prescribed with percentage of 1RM (12 studies), generalised load-velocity profiles (22 studies), and individualised load-velocity profiles (4 studies). For longitudinal studies, the median study duration was 8 weeks (range 4 – 12). A more comprehensive description of the participants and the included studies can be found in Table 2-1, Table 2-2, and Table 2-3.

Table 2-1 Study characteristics

Author (year)	Study design	Participants	Sex: M/F	Age (years)	Height (cm)	Mass (kg)	Training experience (subjective description; years of RT experience; relative strength levels BM/1RM; exercise)
Alcazar et al. (2021) [81]	Chronic – randomly assigned	VL0: n = 14 VL10: n = 14 VL20: n = 13 VL40: n = 16	58/0	24 ± 4	175 ± 6	76 ± 10	Resistance trained individuals; 1.5-4; 1.3 ± 0.2; Smith machine full back-squat.
Andersen et al. (2021) [50]	Chronic – randomly assigned	VL15: n = 10 VL30: n = 10	3/7	23 ± 4	171 ± 8	68 ± 9	Healthy individuals; 4.5 ± 0.7; 1.2 ± 0.2; leg press.
Banyard et al. (2019) [90]	Acute – randomised crossover design	$VL20_{FS}$: n = 15 $VL20_{VS}$: n = 15	15/0	25 ± 4	180 ± 7	84 ± 11	Resistance trained individuals; 7 ± 2; 1.8 ± 0.3; free-weight full back-squat.
Dorrel et al. (2020) [91]	Chronic – randomly assigned	VL20: n = 8	38/0	23 ± 5	180 ± 6	89 ± 13	Resistance-trained individuals; ≥ 2; 1.5 ± 0.3, 1.1 ± 0.2, 0.7 ± 0.1, and 2.0 ± 0.3, free-weight perceived optimum depth back-squat, free-weight bench press, free-weight strict overhead press, and free-weight deadlift, respectively.
Fernandez-Ortega et al. (2020) [88]	Chronic – randomly assigned	VG: n = 15	0/15	14 ± 1	157 ± 7	47 ± 5	Adolescent soccer players; unexperienced; 0.7 ± 0.1; Smith machine full back-squat.
Galiano et al. (2020) [92]	Chronic – randomly assigned	VL5: n = 15 VL20: n = 13	28/0	22 ± 3 24 ± 3	175 ± 5 177 ± 5	73 ± 11 76 ± 9	Physically active individuals; ≥ 1.5; 1.3 ± 0.2; Smith machine full back-squat.

García-Sillero et al. (2021) [93]	Acute – randomised controlled pilot	VL30: n = 12 VL30: n = 12[b]	24/0	24 ± 1	180 ± 6	78 ± 8	Physically active sports science students; >2; 1.0 ± 0.2; free weight bench press.
González-García et al. (2020) [84]	Acute – randomised crossover design	$VL20_{OL}$: n =11 $VL20_{80\%RM}$: n = 11	10/1	25 ± 4	176 ± 8	77 ± 9	Unclear; unclear; 1.8 ± 0.3; Smith machine full back-squat.
Held et al. (2021) [87]	Chronic – randomly assigned	VL10: n = 11	9/2[a]	19 ± 2 20 ± 2	180 ± 10 184 ± 5	73 ± 9 76 ± 9	Highly trained rowers; ≥ 2; 1.7 ± 0.2, 2.2 ± 0.4, 1.5 ± 0.2 and 1.3 ± 0.2; free-weight back-squat, free-weight bench row, free-weight deadlift, and free-weight bench press, respectively.
Krzysztofik et al. (2021) [89]	Acute – randomised crossover design	VL10: n = 16	0/16	24 ± 5	170 ± 6	64 ± 5	Resistance-trained amateur female volleyball players; 3 ± 4; 1.5 ± 0.2; free-weight back-squat.
Martinez-Canton et al. (2020) [82]	Chronic – randomly assigned	VL20: n = 12 VL40: n = 10	22/0	23 ± 2	176 ± 6	76 ± 7	Physically active sports science students; 1.5 ± 4; 1.4 ± 0.2; Smith machine full back-squat.
Muñoz-López et al. (2021) [94]	Acute – randomised crossover design	VL20: n = 30 VL40: n = 30	30/0	22 ± 2	176 ± 7	74 ± 11	Healthy individuals; unclear; 1.5 ± 0.2; Smith machine full back-squat.
Nájera-Ferrer et al. (2021) [95]	Acute – randomised crossover design	VL20: n = 16 VL40: n = 16	16/0	36 ± 10	176 ± 7	77 ± 8	Resistance- and endurance-trained individuals; 2-5; 1.4 ± 0.3; Smith machine full back-squat.
Nilo Dos Santos et al. (2021) [96]	Acute – randomised crossover design	VL20: n = 12	0/12	25 ± 5	163 ± 6	59 ± 11	Young women; 4.5 ± 4.2; 10RM = 46.2 ± 13.8; Smith machine parallel back-squat.
Pareja-Blanco et al. (2017) [17]	Chronic – randomly assigned	VL20: n = 12 VL40: n = 10	22/0	23 ± 2	176 ± 6	76 ± 7	Physically active sports science students; 1.5 ± 4; 1.4 ± 0.2; Smith machine full back-squat.

Pareja-Blanco et al. (2017) [97]	Chronic – randomly assigned	VL15: n = 8 VL30: n = 8	16/0	24 ± 4	174 ± 7	76 ± 9	Professional soccer players; unclear; 1.3 ± 0.3; Smith machine full back-squat.
Pareja-Blanco et al. (2019) [43]	Acute – randomised crossover design	$VL20_{60\%RM}$: n = 17 $VL40_{60\%RM}$: n = 17 $VL20_{80\%RM}$: n = 17 $VL40_{80\%RM}$: n = 17	17/0	24 ± 4	180 ± 10	76 ± 11	Physically active sports science students; 3 ± 1.5; 1.4 ± 0.2; Smith machine full back-squat.
Pareja-Blanco et al. (2020) [46]	Chronic – randomly assigned	VL0: n = 15 VL15: n = 16 VL25: n = 15 VL50: n = 16	62/0	24 ± 4	175 ± 6	76 ± 10	Resistance trained individuals; ≥ 1.5; 0.9 ± 0.2; Smith machine bench press.
Pareja-Blanco et al. (2020) [47]	Chronic – randomly assigned	VL0: n = 14 VL10: n = 14 VL20: n = 13 VL40: n = 14	55/0	24 ± 4	175 ± 6	76 ± 10	Resistance trained individuals; 1.5 ± 4; 0.9 ± 0.2; Smith machine full back-squat.
Pearson et al. (2020) [98]	Acute – counterbalanced crossover design	VL10: n = 12 VL20: n = 12 VL30: n = 12	12/0	23 ± 2	180 ± 7	89 ± 13	Semi-professional rugby union athletes; ≥ 2; unclear; free-weight parallel back-squat.
Pérez-Castilla et al. (2018) [49]	Chronic – randomly assigned	VL10: n = 10 VL20: n = 10	20/0	22 ± 3 22 ± 2	175 ± 6 177 ± 6	74 ± 17 80 ± 15	Physically active sports science students; ≥ 2; 2.1 ± 0.4; Smith machine countermovement jump.
Riscart-López et al. (2021) [63]	Chronic – randomly assigned	$VL20_{LP}$: n = 11 $VL20_{UP}$: n = 10 $VL20_{RP}$: n =11 $VL20_{CP}$: n = 11	43/0	24 ± 6 24 ± 5 22 ± 3 23 ± 5	178 ± 5 177 ± 7 172 ± 6 180 ± 4	73 ± 8 71 ± 8 67 ± 6 75 ± 9	Physically active sports science students; 1.5-4; 1.3 ± 0.3; Smith machine full back-squat.

Rissanen et al. (2022) [99]	Chronic – reverse counterbalancing sequence	$VL20_{M}$: n = 12 $VL20_{F}$: n = 11 $VL40_{M}$: n = 11 $VL40_{F}$: n = 11	23/22	26 ± 4	184 ± 8 167 + 7 178 ± 6 165 + 7	82 ± 8 61 ± 5 82 ± 14 60 + 8	Physically active individuals; ≥ 1; 1.3 ± 0.3 and 0.8 ± 0.2; Smith machine full back-squat and Smith machine bench press.
Rodiles-Guerrero et al. (2020) [48]	Chronic – randomly assigned	VL10: n = 15 VL20: n = 15 VL30: n = 15	45/0	23 ± 2	173 ± 5	73 ± 6	Physically active individuals; ≥ 1; 1.0 ± 0.2; weight stack machine bench press.
Rodríguez-Rosell et al. (2018) [38]	Acute – randomised crossover design	$VL10_{SQ}$: n = 11 $VL20_{SQ}$: n = 11 $VL30_{SQ}$: n = 11 $VL45_{SQ}$: n = 11 $VL10_{BP}$: n = 10 $VL20_{BP}$: n = 10 $VL30_{BP}$: n = 10 $VL45_{BP}$: n = 10	21/0	24 ± 4	178 ± 4	78 ± 15	Physically active sports science students; 2-4; 1.5 ± 0.2 and 1.1 ± 0.2; Smith machine full back-squat and Smith machine bench press.
Rodríguez-Rosell et al. (2020) [41]	Acute – randomised crossover design	VL10: n = 11 VL20: n = 11 VL30: n = 11 VL45: n = 11	11/0	24 ± 4	177 ± 7	74 ± 12	Physically active sports science students; 2-4; 1.5 ± 0.2; Smith machine full back-squat.
Rodríguez-Rosell et al. (2020) [64]	Chronic – randomly assigned	VL10: n = 12 VL30: n = 13	25/0	23 ± 3 22 ± 3	177 ± 8 176 ± 7	75 ± 10 74 ± 9	Physically active sports science students; 1-3; 1.3 ± 0.3; Smith machine full back-squat.
Rodríguez-Rosell et al. (2021) [65]	Chronic – randomly assigned	VL10: n = 12 VL30: n = 12	36/0	23 ± 4 22 ± 2	176 ± 4 177 ± 7	71 ± 5 74 ± 9	Physically active sports science students; 1-3; 1.3 ± 0.2; Smith machine full back-squat.

		VL45: n = 12		22 ± 3	172 ± 8	72 ± 10	
Rodríguez-Rosell et al. (2021) [66]	Chronic – randomly assigned	$VL15_{LP}$: n = 16 $VL15_{UP}$: n = 16	32/0	24 ± 4 22 ± 3	176 ± 6 178 ± 7	76 ± 9 76 ± 8	Healthy and physically active sports science students; 1-3; 1.3 ± 0.3; Smith machine full back-squat.
Sánchez-Moreno et al. (2020) [100]	Chronic – randomly assigned	VL25: n = 15 VL50: n =14	29/0	27 ± 6 25 ± 6	176 ± 6 176 ± 5	74 ± 5 74 ± 8	Strength-trained individuals; 2-4; 0.5 ± 0.1; Prone-grip pull-up exercise.
Sousa-Fortes et al. (2020) [85]	Acute – randomised crossover design	VL20: n = 12	7/5	25 ± 5	169 ± 8	74 ± 18	Trained individuals; ~3; 1.3 and 1.1; free-weight half-squat and free-weight bench press.
Tsoukos et al. (2019) [101]	Acute – randomised crossover design	VL10; n = 10 VL30; n = 10	10/0	26 ± 7	182 ± 5	85 ± 13	Physically active individuals; ≥ 3; 1.3 ± 0.2; Smith machine bench press.
Tsoukos et al. (2021) [102]	Acute – randomised crossover design	VL10: n = 11 VL30: n = 11	11/0	26 ± 6	183 ± 5	85 ± 13	Resistance trained individuals; ≥ 3; 1.3 ± 0.2; Smith machine bench press.
Varela-Olalla et al. (2019) [86]	Acute – unclear	VL20-32; n = 5	4/1	23 ± 5	169 ± 7	72 ± 18	Spanish Olympic wrestlers; ≥ 1; 1.5 ± 0.5; free-weight bench press.
Varela-Olalla et al. (2020) [103]	Acute – observational	VL20; n = 15	15/0	23 ± 2	175 ± 6	73 ± 8	Recreationally active individuals; unclear; 0.7 ± 0.1; Smith machine half back-squat.
Weakley et al. (2020) [42]	Acute – randomised crossover design	VL10; n = 12 VL20; n = 12 VL30; n = 12	12/0	23 ± 3	179 ± 6	87 ± 12	Team sport athletes from a British University and Colleges Super Rugby Club; ≥ 2; unclear; free weight back-squat.
Weakley et al. (2020) [83]	Acute – randomised crossover design	VL10; n = 12 VL20; n = 12 VL30; n = 12	16/0	23 ± 2	180 ± 7	89 ± 13	Team sport athletes from a British University and Colleges Super Rugby Club; ≥ 2; unclear; free weight back-squat.

Note. BM, body mass; M, male; F, female; RT, resistance training; n, number of participants; VL##, whereby ## refers to the velocity loss threshold used (e.g., VL20 is 20% velocity loss threshold). Subscripts after VL## (e.g., $VL20_{80\%RM}$) refer to the following: FS, fixed number of sets; VS, variable number of sets; OL, optimal load that maximised power production; ##%RM, whereby ## refers to the percentage of repetition maximum; LP, linear programming model; UP, undulating programming model; RP, reverse programming model; CP, constant programming model. SQ, protocol performed with the back-squat exercise; BP, protocol performed with the bench press exercise; VG, velocity training group.

[a] Sex distribution of participants included in statistical analysis was not specified.

[b] Percussion therapy.

Table 2-2 Summary of the acute studies included in the review.

Author (year)	Velocity loss threshold used; Number of sets; load; inter-set rest	Exercises; load prescription method	Velocity variable; reference repetition for velocity loss calculation; Number of repetitions performed below the threshold before termination of the set	Outcomes (methods of assessment)
Banyard et al. (2019) [90]	20%; 4.2 ± 0.9 (until reaching a total of 25 reps); 80%1RM; 2	Free-weight full back-squat; 1RM percentage-based	Mean velocity; velocity of the single repetition performed at 80%1RM in the warm-up; 1	Mean velocity (4 linear position transducers); average number of repetitions per set
García-Sillero et al. (2021) [93]	30%; 4; 70%1RM; 3 30%; 4; 70%1RM; 3	Free-weight bench press; 1RM percentage-based	Mean velocity; fastest repetition; 1	Mean velocity (linear position transducer); average number of repetitions per set
González-García et al. (2020) [84]	20%; 2; optimal load (60.9 ± 5.9%1RM); unclear 20%; 2; 80%1RM; unclear	Smith machine half back-squat; 1RM percentage-based	Mean velocity; fastest repetition; 1	Mean velocity (rotatory encoder); CMJ height (force platform); RPE (Borg CR-10 Scale); average number of repetitions per set
Muñoz-López et al. (2021) [94]	20%; 3; 63.3 ± 2.1% 1RM; 5 40%; 3; 63.3 ± 2.1% 1RM; 5	Smith machine full back-squat; generalised load-velocity relationship-based	Mean propulsive velocity; fastest repetition obtained in the first 3 repetitions; 1	Mean propulsive velocity (linear encoder); average number of repetitions per set
Nájera-Ferrer et al. (2021) [95]	20%; 3; 60%1RM; 2[a] 40%; 3; 60%1RM; 2[a] 20%; 3; 60%1RM; 2[b] 40%; 3; 60%1RM; 2[b]	Smith machine deep back-squat; 1RM-percentage-based	Mean propulsive velocity; fastest repetition; 1	Mean propulsive velocity, mean propulsive velocity attained against the absolute load that elicited 1.00 $m \cdot s^{-1}$ (linear velocity transducer); blood lactate concentration (portable lactate analyser); CMJ height (infrared timing system); average number of repetitions per set

Nilo Dos Santos et al. (2021) [96]	20% (32 ± 7%); 4; 10RM; 2	Smith machine parallel back-squat; 1RM-percentage-based	Mean propulsive velocity; fastest repetition obtained in the first 3 repetitions; 1	Mean propulsive velocity (linear velocity transducer); average number of repetitions per set; RPE (OMNI-RES effort scale); rating of discomfort (Borg CR-10 scale).
Pareja-Blanco et al. (2019) [43]	20%; 3; 60%1RM; 4 40%; 3; 60%1RM; 4 20%; 3; 80%1RM; 4 40%; 3; 80%1RM; 4	Smith machine full back-squat; generalised load-velocity relationship-based	Mean propulsive velocity; fastest repetition; 1	Mean propulsive velocity, percent change in velocity loss against the load that elicited a 1 $m \cdot s^{-1}$ (linear velocity transducer); percent change in CMJ height loss (infrared timing system); percent change in running sprint time loss (photocells); average number of repetitions performed during the 3 sets
Pearson et al. (2020) [98]	10%; 5; ≈ 70%1RM; 3 20%; 5; ≈ 70%1RM; 3 30%; 5; ≈ 70%1RM; 3	Free-weight parallel back-squat; generalised load-velocity relationship-based	Mean velocity; velocity reference of 0.70 $m \cdot s^{-1}$; 1	Mean velocity (linear position transducer); average number of repetitions per set
Rodríguez-Rosell et al. (2018) [38]	10%; 3; 50%1RM; 4 10%; 3; 60%1RM; 4 10%; 3; 70%1RM; 4 10%; 3; 80%1RM; 4 20%; 3; 50%1RM; 4 20%; 3; 60%1RM; 4 20%; 3; 70%1RM; 4 20%; 3; 80%1RM; 4 30%; 3; 50%1RM; 4 30%; 3; 60%1RM; 4 30%; 3; 70%1RM; 4	Smith machine full back-squat; generalised load-velocity relationship-based	Mean propulsive velocity; fastest repetition; 1	Mean propulsive velocity, percent change in velocity loss against the load that elicited a 1 $m \cdot s^{-1}$ (linear velocity transducer); blood lactate concentration (portable lactate analyser); average number of repetitions performed during the 3 sets

	30%; 3; 80%1RM; 4 45%; 3; 50%1RM; 4 45%; 3; 60%1RM; 4 45%; 3; 70%1RM; 4 45%; 3; 80%1RM; 4			
	15%; 3; 50%1RM; 4 15%; 3; 60%1RM; 4 15%; 3; 70%1RM; 4 15%; 3; 80%1RM; 4 25%; 3; 50%1RM; 4 25%; 3; 60%1RM; 4 25%; 3; 70%1RM; 4 25%; 3; 80%1RM; 4 40%; 3; 50%1RM; 4 40%; 3; 60%1RM; 4 40%; 3; 70%1RM; 4 40%; 3; 80%1RM; 4 55%; 3; 50%1RM; 4 55%; 3; 60%1RM; 4 55%; 3; 70%1RM; 4 55%; 3; 80%1RM; 4	Smith machine bench press; generalised load-velocity relationship-based		
Rodríguez-Rosell et al. (2020) [41]	10%; 3; 50%1RM; 4 10%; 3; 60%1RM; 4 10%; 3; 70%1RM; 4	Smith machine full back-squat; generalised load-velocity relationship-based	Mean propulsive velocity; fastest repetition; 1	Mean propulsive velocity, percent change in velocity loss against the load that elicited a 1 $m{\cdot}s^{-1}$ (linear position transducer), blood lactate

	10%; 3; 80%1RM; 4 20%; 3; 50%1RM; 4 20%; 3; 60%1RM; 4 20%; 3; 70%1RM; 4 20%; 3; 80%1RM; 4 30%; 3; 50%1RM; 4 30%; 3; 60%1RM; 4 30%; 3; 70%1RM; 4 30%; 3; 80%1RM; 4 45%; 3; 50%1RM; 4 45%; 3; 60%1RM; 4 45%; 3; 70%1RM; 4 45%; 3; 80%1RM; 4			concentration (portable lactate analyser); percent change in CMJ height (infrared timing system)
Sousa-Fortes et al. (2020) [85]	20%, 5; 15RM; 3:20 min	Free-weight half back-squat and bench press; 1RM-percentage-based	Mean velocity; unclear; 1	Mean velocity (linear position transducer); average number of repetitions per set
Tsoukos et al. (2019) [101]	10%; 40%1RM; 1; 0 10%; 60%1RM; 1; 0 30%; 40%1RM; 1; 0 30%; 60%1RM; 1; 0	Smith machine bench press throw; 1RM percentage-based	Mean velocity; fastest repetition; 1	Mean propulsive velocity (linear position transducer); average number of repetitions per set
Tsoukos et al. (2021) [102]	10%; 1; 80%1RM; 0 30%; 1; 80%1RM; 0	Smith machine bench press; 1RM-percentage-based	Mean velocity; fastest repetition; 1	Mean velocity (linear position transducer); average number of repetitions per set
Varela-Olalla et al. (2019) [86]	20-27.3%; 1; 40-45%1RM; 0 22.1-29.4%; 1; 55-60%1RM; 0	Free-weight bench press; generalised load-velocity relationship-based	Mean velocity; fastest repetition; 2	Mean velocity (linear position transducer); average number of

	20.7-31.1%; 1; 70-75%1RM; 0			repetitions per set; RPE (OMNI-RES scale).
Varela-Olalla et al. (2020) [103]	20%; 1; ≈ 85%1RM; 0	Smith machine half squat; generalised load-velocity relationship-based	Mean propulsive velocity; fastest repetition; 1	Mean propulsive velocity (linear position transducer); blood lactate concentration (portable lactate analyser); CMJ height (smartphone app)
Weakley et al. (2020) [42]	10%; 5; ≈ 70%1RM; 3 20%; 5; ≈ 70%1RM; 3 30%; 5; ≈ 70%1RM; 3	Free-weight parallel back-squat; generalised load-velocity relationship-based	Mean velocity; velocity reference of 0.70 $m \cdot s^{-1}$;1	Blood lactate concentration (portable lactate analyser); CMJ (force plate); average number of repetitions per set; Differential-RPE of the lower peripheries and the breathlessness (verbal anchors on the CR100 scale)
Weakley et al. (2020) [83]	10%; 5; ≈ 70%1RM; 3 20%; 5; ≈ 70%1RM; 3 30%; 5; ≈ 70%1RM; 3	Free-weight parallel back-squat; generalised load-velocity relationship-based	Mean velocity; velocity reference of 0.70 $m \cdot s^{-1}$;1	Mean velocity (linear position transducer); average number of repetitions per set

Note. 1RM, one-repetition maximum; RPE, rate of perceived effort; CMJ, countermovement jump

a, endurance training followed by resistance training; b, resistance training followed by endurance training.

Note: Only outcomes of interest were reported in this table; for more extended version see Appendix F Ch. 2 File III.

Table 2-3 Summary of the longitudinal studies included in the review.

Author (year)	Training protocol (duration in weeks; sessions/w; exercise; loads)	Velocity loss threshold; number of sets; inter-set rest	Velocity loss used for all exercises ?	Adherence	Outcomes (methods of assessment)	Comparisons between the groups (outcomes)
Alcazar et al. (2021) [81]	8; 2; Smith machine full back-squat; from 70%1RM to 85%1RM	VL0; 3; 4 VL10; 3; 4 VL20; 3; 4 VL40; 3; 4	Yes	100%	1RM, F0, v0, Pmax, a, and a/F0 (2 force plates synchronised with a linear velocity transducer)	VL0 = VL10 = VL20 = VL40 (L-F0, L-v0, L-Pmax, L-a, H-F0, H-v0, H-Pmax, and H-a/F0 VL0 and VL10 > VL40 (H-v0))
Andersen et al. (2021) [50]	9; 2; leg press and leg extension; 85%1RM (leg press) and 75%RM (leg extension)	VL15; 4 (sessions 1-2) and 6 (sessions 3-9) for the leg press and 4 (sessions 1-5) and 6 (sessions 6-9) for leg extension; 2.5 VL30; 2 (sessions 1-2) and 3 (sessions 3-9) for the leg press and 2 (sessions 1-5) and 3 (sessions 6-9) for leg extension; 2.5	No	96.1%	1RM, mean velocity attained at 30%1RM (MV30%1RM), 45%1RM (MV45%1RM), 60%1RM (MV60%1RM), 75%1RM (MV75%1RM), mean power attained at 30%1RM (MP30%1RM), 45%1RM (MP45%1RM), 60%1RM (MP60%1RM), 75%1RM (MP75%1RM), as well as L0 and v0 obtained from the load-velocity relationship (linear encoder) MVC, RFD for the period between 20% and 80% of MVC (RFD20-80%MVC) in addition to 50 ms (RFD50ms), 100 ms (RFD100ms), and 200 ms (RFD200ms) - (force platform) Thickness and architecture of VL and RF (B-mode ultrasound)	VL15 = VL30 (1RM, MV30%1RM, MV45%1RM, MV60%1RM, MV75%1RM, MP30%1RM, MP45%1RM, MP60%1RM, MP75%1RM, L0, v0, MVC, RFD20-80%MVC, RFD50ms, RFD100ms and RFD200ms; VL, RF, PA, and FL)

Dorrell et al. (2020) [91]	6; 2; back squat, bench press, strict overhead press (only sessions 1, 3, 5, 7, 9, 11, and 12), and deadlift (only sessions 2, 4, 6, 8, 10, 11, and 12); from 70%1RM to 95%1RM	VL20 (below the target velocity of each specific zone); 3; unclear	No	100%	1RM (linear position transducer) CMJ height (Jump mat)	VL20: back squat 1RM (↑), bench press 1RM (↑) strict overhead press 1RM (↑), deadlift 1RM (↑), CMJ height (↑)
Fernandez -Ortega et al. (2020) [88]	12; 3; Smith machine full back-squat and cycle ergometer; 65%1RM (0.70 m·s-1) (squat) and 65% of the load applied in the initial assessment (5.3% of body weight) (cycle ergometer)	VL20 (squat) RPML20 (cycle ergometer); 4; 3	No	Unclear	CMJ and SJ height (infrared timer system) T0-30 (infrared-light photocell system) 1RM Maximum power (absolute [Pmax-C] and relative [Pmax-RC]) and velocity (Vmax-C) on the cycloergometer (Wingate test) Maximal power (Pmax-S) and velocity (Vmax-S) in the squat (squat test with loads of 30, 40, 45, 60, 70, and 80%1RM) (linear velocity transducer)	VL20: T0-30 (↑), 1RM (↑), CMJ height (↑), SJ height (↑), Pmax-C (↑), Pmax-RC (↑), Vmax-C (↑), Pmax-S (↑), Vmax-S (↑)
Galiano et al. (2020) [92]	7; 2; Smith machine full back-squat; ~1.14 ± 0.03 m·s-1 (~50%1RM)	VL5; 3; 3 VL20; 3; 3	Yes	100%	1RM, AV, and AV≥1 (linear velocity transducer) T0-20 (photocells) CMJ height (infrared timing system)	VL5 = VL20 (1RM, AV, AV≥1, AV<1, T20, and CMJ height)

Held et al. (2021) [87]	8; 2; power clean, squat, bench row, deadlift, and bench press; 80%1RM	VL10; 4; 2-3	No	~94%	1RM	VL10: squat 1RM (↑), bench row 1RM (↑), deadlift 1RM (↑), bench press 1RM (↑), and 1RMtotal (↑)
Martinez-Canton et al. (2020) [82]	8; 2; Smith machine full back-squat; from 0.82 m·s-1 (~70%1RM) to 0.60 m·s-1 (~85%1RM)	VL20; 3; 4 VL40 (from VL20 to VL50); 3; 4	Yes	100%	Fatigue test (as many repetitions as possible against 60%1RM load until the velocity felt below 0.50 m·s-1), FT-MNR, and FT-AV (linear velocity transducer)	
Pareja-Blanco et al. (2017) [17]	8; 2; Smith machine full back-squat; from 0.82 m·s-1 (~70%1RM) to 0.60 m·s-1 (~85%1RM)	VL20; 3; 4 VL40 (from 20% to 50%); 3; 4	Yes	100%	1RM, AV, AV>1, and AV<1 (linear velocity transducer) T0-20 (photocells) CMJ height (infrared timing system) Muscle volume of QF, RF, VM and VL+VI (1.5-T scanner) Muscle CSA (1.5-T scanner) Fibre CSA, CSA-I, CSA-IIA, CSA-IIAX, and CSA-IIX (muscle biopsy)	VL20 = VL40 (1RM, AV<1, T20, QF, RF, and VM) VL20 > VL40 (AV, AV>1, CMJ height, CSA, CSA-I, CSA-IIA, CSA-IIAX, and CSA-IIX) VL40 > VL20 (VL, VI)
Pareja-Blanco et al. (2017) [97]	6; 3; Smith machine full back-squat; from ~1.13 m·s-1 (~50%1RM) to ~0.82 m·s-1 (~70%1RM)	VL15; 2 (sessions 1, 4, 7, 11, 15, and 18) or 3 (sessions 2, 3, 4, 6, 8, 9, 10, 12, 13, 14, 16, and 17); 4 VL30; 2 (sessions 1, 4, 7, 11, 15, and 18) or 3 (sessions 2, 3, 4,	No	85%	1RM and AV (linear velocity transducer) YIRT T0-30 (photocells) CMJ height (infrared timing system)	VL15 = VL30 (1RM, AV, YIRT, and T0-30) VL15 > VL30 (CMJ height)

		6, 8, 9, 10, 12, 13, 14, 16, and 17); 4				
Pareja-Blanco et al. (2020) [46]	8; 2; Smith machine bench press; from 0.65 ± 0.07 m·s-1 (70%1RM) to 0.41 ± 0.05 m·s-1 (85%1RM)	VL0; 3; 4 VL15; 3; 4 VL25; 3; 4 VL50; 3; 4	Yes	100%	MIF, RFDmax, slope of the force-time curve obtained over 50 ms (RFD0-50), 100 ms (RFD0-100), 150 ms (RFD0-150), 200 ms (RFD0-200), and 400 ms (RFD0-400) - (dynamometric platform) 1RM, v0 (bar weight < 0.2 kg), AV, AV>0.8, and AV<0.8 (linear velocity transducer) Fatigue test (as many repetitions as possible against 70%1RM load until the muscle failure), FT-MNR, and FT-AV (linear velocity transducer) Muscle CSA of PM (B-mode ultrasonography)	VL0 = VL15 = VL25 = VL50 (MIF, RFDmax, RFD0-50, RFD0-100, RFD0-150, RFD0-200, RFD0-400, 1RM, v0, AV, AV>0.8, AV<0.8, FT-MNR, FT-AV, and PM) VL50 > VL0 (PM)
Pareja-Blanco et al. (2020) [47]	8; 2; Smith machine full back-squat; from 70%1RM to 85%1RM	VL0; 3; 4 VL10; 3; 4 VL20; 3; 4 VL40; 3; 4	Yes	100%	T0-10, T10-20, and T0-20 (photocells) CMJ height (infrared timing system) MVIC, RFDmax, RFD0-50, RFD0-100, and RFD0-150 (dynamometric platform) 1RM, AV, AV>1, and AV<1 (linear velocity transducer) Fatigue test (as many repetitions as possible against 70%1RM load until the velocity fell below 0.5 m·s-1), and FT-MNR (linear velocity transducer)	VL0 = VL10 = VL20 = VL40 (T0-10, T10-20, T0-20, CMJ, MVIC, RFDmax, RFD0-50, RFD0-100, RFD0-150, 1RM, AV, AV>1, AV<1, FT-MNR, CSA, PA, and FL) VL0 > VL10

					Muscle CSA and architecture of VL (B-mode ultrasonography)	
Pérez-Castilla et al. (2018) [49]	4; 2; Smith machine countermovement jump; 1.20 m·s-1 (~40%1RM)	VL10; the number of sets was extended until completing 36 repetitions; 4 VL20; the number of sets was extended until completing 36 repetitions; 4	No	100%	CMJ height, F0, v0, Pmax, and a (infrared platform) 1RM, MPV attained at 20 (MPV20), 40 (MPV40), 60 (MPV60), and 80 (MPV80) kg T0-15 (photocells)	VL10 = VL20 (F0, v0, a, Pmax, 1RM, MPV20, MPV40, MPV60, MPV80, CMJ height, and T0-15)
Riscart-López et al. (2021) [63]	8; 2; smith machine full back-squat; from 50%1RM to 85%1RM with increments of 5%1RM every 2 sessions (LP), from 85%1RM to 50%1RM with decreases of 5%1RM every 2 sessions (RP), from 50%1RM to 85%1RM with changes in %1RM every session (UP), and ~67.5%1RM (CP)	VL20; 3; 4	Yes	100%	1RM, AV, AV>1, and AV<1 (linear velocity transducer) T0-20 (photocells) CMJ height (infrared timing system)	LP = RP = UP = CP (1RM, AV, AV>1, AV>1, T0-20, and CMJ height)

Rissanen et al. (2022) [99]	8; 2; Smith machine full back-squat and Smith machine bench press; from 65%1RM to 75%1RM	VL20 males; 2 (session 1), 3 sessions 2-3-6-7-11), 4 (sessions 4-8-12-13) and 5 (sessions 5-9-10-14-15); 3 VL20 females; 2 (session 1), 3 sessions 2-3-6-7-11), 4 (sessions 4-8-12-13) and 5 (sessions 5-9-10-14-15); 3 VL40 males; 2 (session 1), 3 sessions 2-3-6-7-11), 4 (sessions 4-8-12-13) and 5 (sessions 5-9-10-14-15); 3 VL40 females; 2 (session 1), 3 sessions 2-3-6-7-11), 4 (sessions 4-8-12-13) and 5 (sessions 5-9-10-14-15); 3	No	VL20 males; 98 ± 3% VL20 females; 95 ± 6% VL40 males; 97 ± 5% VL40 females; 95 ± 4%	1RM, "low" MPV values (<70%1RM) and "high" MPV values (>70%1RM) (linear velocity transducer) CMJ height (force platform) Muscle CSA of vastus lateralis (B-mode ultrasound)	VL20 males = VL20 females = VL40 males = VL40 females (Smith machine full back-squat and bench press 1RM, Smith machine full back-squat and bench press "low" and "high" MPV values, CMJ height, vastus lateralis CSA)
Rodiles-Guerrero et al. (2020) [48]	5; 3; weight stack machine bench press; from 0.67 m·s-1 (~65%1RM)	VL10; 4; 3 VL30; 4; 3 VL50; 4; 3	Yes	Unclear	1RM, AV, AV≥0.8, and AV<0.8 (linear velocity transducer)	VL10 = VL30 = VL50 (1RM, AV, AV≥0.8, and AV<0.8)

	to 0.39 m·s-1 (~85%1RM)					
Rodríguez-Rosell et al. (2020) [64]	8; 2; Smith machine full back-squat; from ~0.84 m·s-1 (~70%1RM) to ~ 0.60 m·s-1 (~85%1RM)	VL10; 3; 4 VL30; 3; 4	Yes	100%	1RM, AV, AV>1, AV<1, MPV attained against 30 kg (MPV30), MPV40, 50 kg (MPV50), MPV60, 70 kg (MPV70), and MPV80 (linear velocity transducer) T0-10 and T0-20 (photocells) CMJ height (infrared timing system) Fatigue test (as many repetitions as possible against an absolute load move to ~0.84 m·s-1 (~70%1RM until the MPV fell below 0.5 m·s-1), and FT-MNR (linear velocity transducer)	VL10 = VL30 (1RM, AV, AV>1, AV<1; MPV30, MPV40, MPV50, MPV60, MPV70, MPV80, CMJ height, and FT-MNR) VL10 > VL30 (T0-10, and T0-20)
Rodríguez-Rosell et al. (2021) [66]	8; 2; Smith machine full back-squat; from ~1.16 m·s-1 (~50%1RM) to ~0.68 m·s-1 (~80%1RM) using LP and UP	VL15; 3; 4	Yes	100%	1RM, AV, AV>1, and AV<1 (linear velocity transducer) CMJ height (infrared timing system) Fatigue test (as many repetitions as possible against ~1.16 m·s-1 (~60%1RM) load until the MPV fell below 0.5 m·s-1), and FT-MNR (linear velocity transducer)	LP > UP (1RM, AV, AV>1, AV<1, and FT-MNR) LP = UP (CMJ height)
Rodríguez-Rosell et al. (2021) [65]	8; 2; Smith machine full back-squat; from ~1.08 m·s-1 (~55%1RM) to ~0.84 m·s-1 (~70%1RM)	VL10; 3; 4 VL30 (from VL20 to VL30); 3; 4 VL45 (from VL20 to VL45); 3; 4	Yes	100%	1RM, AV, AV>1, AV<1, MPV30, MPV40, MPV50, MPV60, MPV60, and MPV80 (linear velocity transducer) T0-10 and T0-20 (photocells timing gates) CMJ height (infrared timing system)	VL10 > VL30 and VL45 (CMJ height, AV, and AV>1) VL30 = VL45 (CMJ height, AV, and AV>1) VL10 = VL45 = VL30 (T0-10, T0-20, 1RM, AV<1, MPV30, MPV40,

					Fatigue test (as many repetitions as possible against ~0.84 m·s-1 (~70%1RM) load until the MPV fell below 0.5 m·s-1), and FT-MNR (linear velocity transducer)	MPV50, MPV60, MPV70, MPV80, and FT-MNR)
Sánchez-Moreno et al. (2020) [100]	8; 2; prone-grip pull-up; body mass	VL25; 2 (sessions 1-3 and 16), 3 (sessions 4-8 and 15) or 4 (sessions 9-14); 3 VL50; 2 (sessions 1-3 and 16), 3 (sessions 4-8 and 15) or 4 (sessions 9-14); 3	Yes	95%	1RM, AV, and MPVbest (linear velocity transducer) Fatigue test to failure, FT-MNR and FT-AV (linear velocity transducer)	VL25 > VL50 (1RM, AV, and MPVbest, and FT-AV) VL25 = VL50 (FT-MNR)

Note. 1RM, one-repetition maximum; *a*, slope of the force-velocity relationship; a/F_0, curvature of the force-velocity relationship; AV, average velocity attained against all absolute loads common to pre-test and post-test; AV>0.8, average velocity attained against absolute loads that were lifted faster than 0.8 $m \cdot s^{-1}$; AV<0.8, average velocity attained against absolute loads that were lifted slower than 0.8 $m \cdot s^{-1}$; AV≥1, average velocity attained for absolute loads moved at velocities equal to or faster than 1 $m \cdot s^{-1}$; AV<1, the average velocity attained for absolute loads moved slower than 1 $m \cdot s^{-1}$; CP, constant programming; CSA, cross-sectional area; F_0, maximal force; FL, fascicle length; FT-AV, average velocity attained against the same number of repetitions during the fatigue test; FT-MNR, maximum number of repetitions during the fatigue test; L_0, maximal load; LP, linear programming; MIF, maximal isometric force; MPV, mean propulsive velocity; MPV_{best}, the fastest MPV attained without additional weight; MVC, maximal voluntary contraction; PA, pennation angle; P_{max}, maximal force; PM, pectoralis major; QF, quadriceps femoris; RF, rectus femoris; RIR, reps in reserve; RP, reverse programming; RFD_{max}, maximal rate of force development; T_{0-10}, 10-sprint time; T_{0-20}, 20-sprint time; T_{0-30}, 30-sprint time; T_{10-20}, time to cover 10- to 20-m; T_{0-15}, 15-sprint time; UP, undulating programming; v_0, maximal velocity; VM, vastus medialis; VL, vastus lateralis; VL##, whereby ## refers to the velocity loss threshold used (e.g., VL20 is 20% velocity loss threshold); VL+VI;, vastus lateralis and vastus intermedius; YIRT, total distance covered in the Yo-Yo Intermittent Recovery Test level 1.

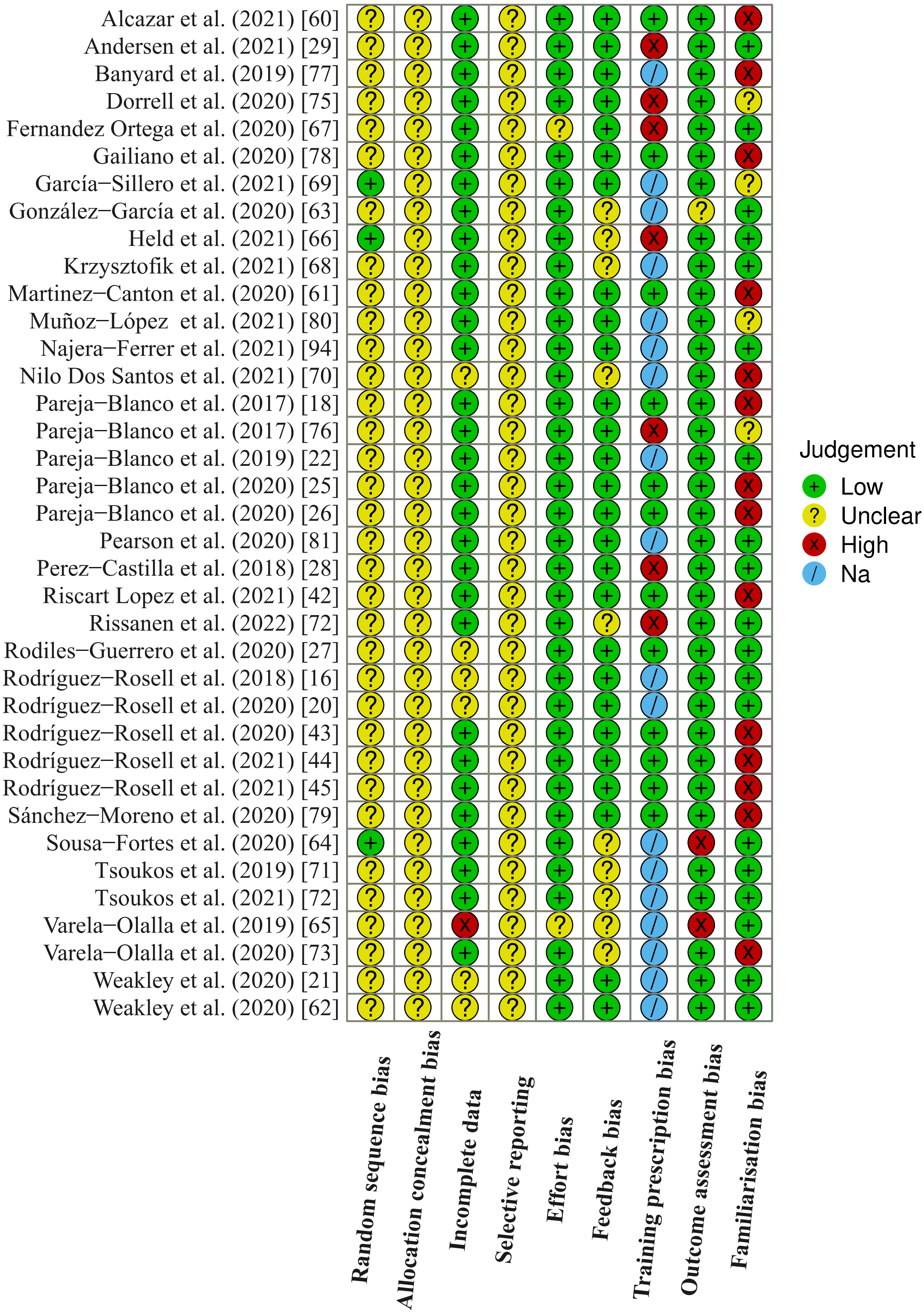
↑ reflects an improvement in performance, ⟷ no significant change, and ↓ a decrease in performance. Andersen et al. [50] did not provide statistical inferences for pre-post changes per group. Therefore, ⟷ reflects a < moderate effect size and ↑ reflects a > moderate effect size. Held et al. [87], Fernandez Ortega et al. [88] and Dorrell et al. [91] evaluated only one VL threshold. Therefore, group differences column for these studies represents pre-post changes.

Note: Only outcomes of interest were reported in this table; for more extended version see Appendix F Ch. 2 File IV.

2.3.3 Risk of bias assessment

Only three studies [69, 66, 64] provided sufficient information regarding the method of randomisation and were therefore at low risk of an order effect bias. The remaining studies were classified as an unclear risk since they did not provide sufficient information regarding the method of randomisation. No studies provided information regarding allocation concealment. One study [65] was at a high risk of attrition bias, excluding randomised participants (or their data) from the analysis without sufficient reason. Six studies [16, 43, 20, 70, 21, 62] did not provide sufficient information on the number of participants assessed and included in the analysis after reporting that some of them did not complete the entire intervention or all procedures and hence, had an unclear risk of attrition bias. No studies pre-registered their protocols on a publicly available registry platform, so it was unclear whether selective reporting bias was present. Two studies [65, 67] had an unclear risk of effort bias since they did not provide information regarding the instructions to perform the concentric actions as fast as possible. The remaining studies were low risk of effort bias since the instruction to perform concentric actions as fast as possible was given. Ten studies [63, 66, 70, 64, 71, 72, 65, 73, 68, 74] did not provide any information on the provision of velocity feedback and hence, had an unclear risk of feedback bias. The rest of the studies either provided feedback to all groups or standardised the conditions between groups by not providing any feedback. Seven studies [29, 75, 67, 76, 66, 28, 74] were at a high risk of training prescription bias since the participants performed other forms of training (additional non-standardised resistance training, endurance training or playing sports), or because not all exercises used VL thresholds, but rather a combination of training prescriptions. Two studies [64, 65] used a linear encoder that was not, to our knowledge, validated in peer-reviewed literature whereas all other studies used valid and reliable methods, equipment, or instruments to evaluate their outcomes of interest. Fourteen studies [77, 60, 78, 61, 18, 25, 26, 42-45, 79, 70, 73] were at high risk of bias for not having a familiarisation session. Four studies [75, 69, 80, 76] did not provide sufficient information regarding their familiarisation sessions and hence, had an unclear risk of bias The rest of the studies provided sufficient information about familiarisation sessions' procedures or specifically stated that all participants were accustomed to the study protocols (i.e., performed them in the past). The risk of bias assessment is also illustrated in Figure 2-2.

Figure 2-2 Risk of bias assessment for all included studies.

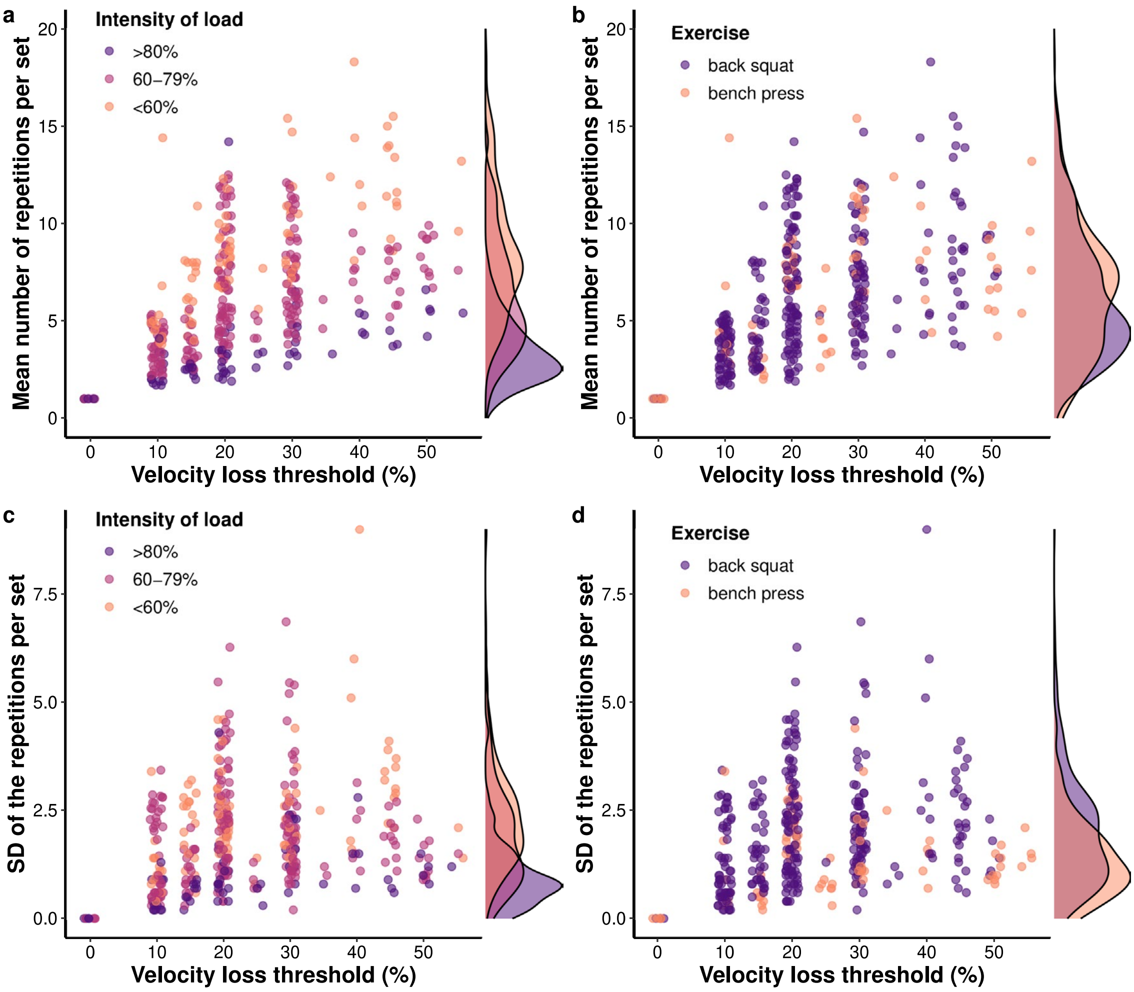


Note. Na, not applicable.

2.3.4 Acute studies

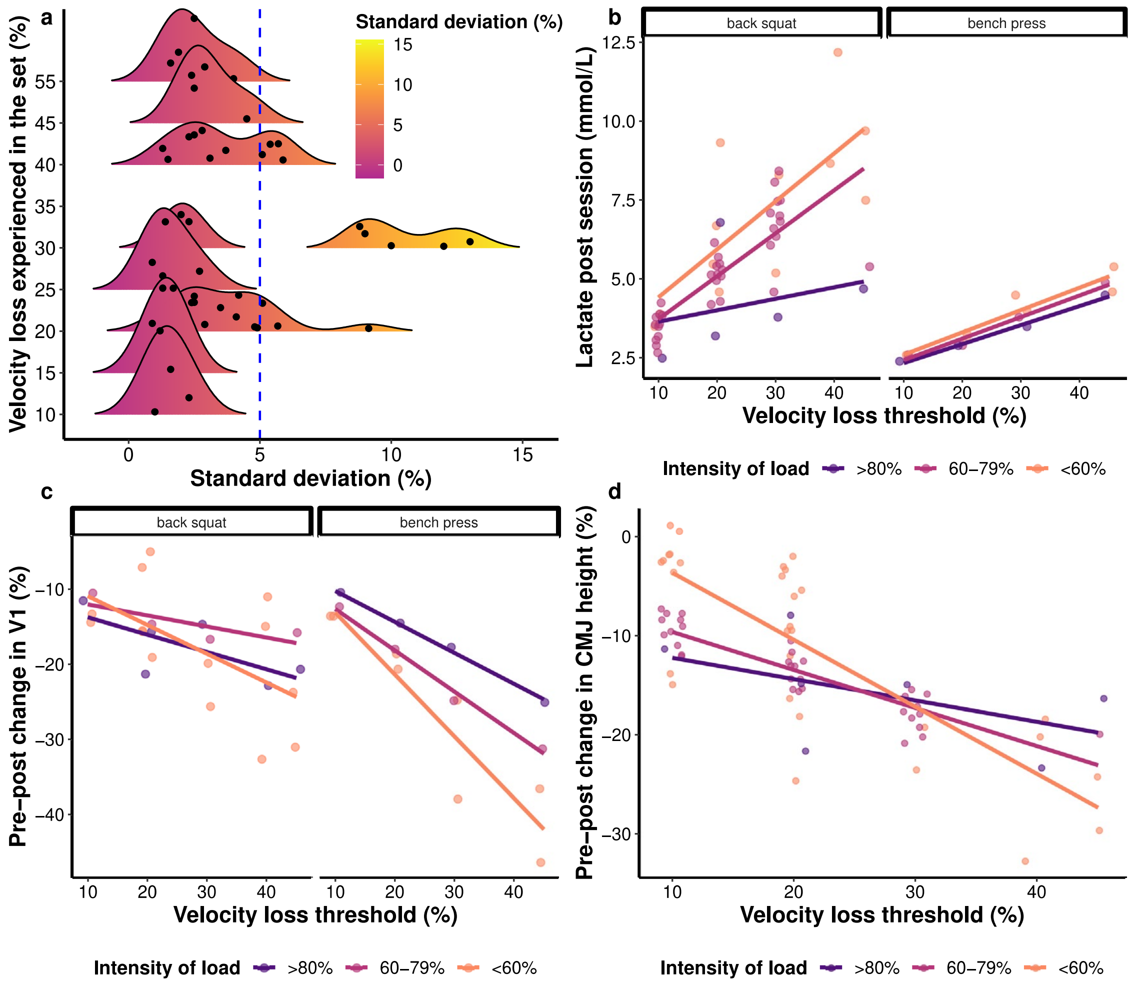
The following variables were visualised: (1) the mean and standard deviation of the number of repetitions performed in the set; (2) changes in countermovement jump height performance; (3) velocity against the load that can be lifted at 1 $m \cdot s^{-1}$ in a rested state (V1); and (4) blood lactate concertation after training sets or the entire session (Figure 2-3; Figure 2-4). In addition, to examine the discrepancy between the VL threshold prescribed and the actual VL experienced by the participants in each study, standard deviations of the actual VL experienced were visually represented using density plots (Figure 2-3).

Figure 2-3 Visual representation of the mean number of repetitions performed per set by intensity of load (a) and exercise (b), as well as standard deviation of the number of repetitions performed per set by intensity of load (c) and exercise (d) across the velocity loss thresholds reported in the literature



Note. Longitudinal studies were also included here when they reported the number of repetitions per set for each training session. Also note, one study outlier was removed from the figure as the participants completed more than 25 repetitions in a set.

Figure 2-4 Visual representation of the variability of the actual velocity loss experienced in a set (a), post-session blood lactate accumulation across velocity loss thresholds by exercise and intensity of load (b), pre-post percent change in velocity against the load that can be lifted at 1 m·s-1 (V1) by exercise and intensity of load (c), and pre-post percent change in countermovement jump (CMJ) height (d) across velocity loss thresholds reported in the literature.



2.3.5 Longitudinal studies

For all multilevel models, significant moderators and sensitivity analyses are described in the text, whereas their output is presented in Table 2-4 and visualised in Figure 2-5, Figure 2-6, and Figure 2-7. For the multivariate model, all information is described in the text, and model estimates are visualised in Figure 2-6. Dose-response relationships – as quantified by effect sizes – between VL and outcomes of interest are also illustrated.

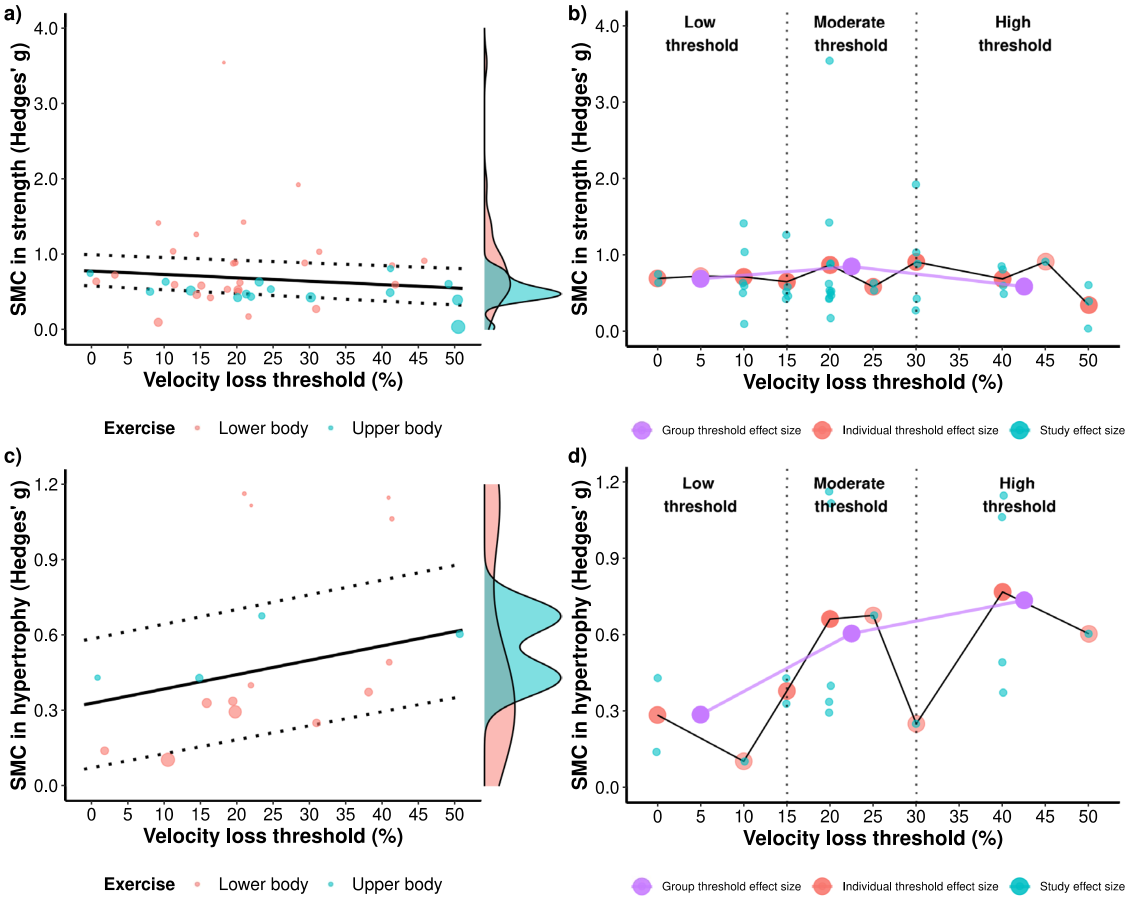
Muscle strength

The final multilevel model investigating the effects of different VL thresholds on maximal strength gains revealed exercise, strength levels, and study duration to be significant moderators (Table 2-4; Figure 2-5). Two individual groups from two different studies were identified as influential. Excluding these influential groups from the analysis affected the interpretation of the model with exercise (b = -0.163 [-0.416, 0.094]; p = 0.206) and strength levels (b = -0.181 [-0.655, 0.293]; p = 0.444) no longer being significant moderators.

Muscle hypertrophy

The final multilevel model investigating the effects of different VL thresholds on muscle hypertrophy revealed VL to be a significant moderator (Table 2-4; Figure 2-5). Two individual groups from two studies were identified as influential. Excluding these influential groups from the analysis affected the interpretation of the model with VL no longer being a significant moderator (b = 0.005 [-0.002, 0.013]; p = 0.144).

Figure 2-5 Multilevel mixed-effects meta-regression illustrating the effects of velocity loss thresholds on muscle strength gains (also see Table 2-4) after controlling for exercise, study duration and strength levels of the individuals (a), and the effects of velocity loss thresholds on muscle hypertrophy (c). Dose-response relationship considering 1) individual study effect sizes (green circles); 2) average effect sizes of individual velocity loss thresholds (red circles); and 3) average effect sizes of low (≤ 15%), moderate (> 15% < 30%), and high (> 30%) grouped velocity loss thresholds (purple circles and lines) between velocity loss and muscle strength (b) and hypertrophy (d) gains.



Note. Black (non-vertical) solid and dotted lines represent estimated relationships and corresponding upper and lower 95% confidence intervals, whereas vertical dotted lines represent boundaries between velocity loss thresholds. SMC, standardised mean change.

Muscle endurance

The final multilevel model investigating the effects of different VL thresholds on muscle endurance did not reveal VL to be a significant moderator (Table 2-4; Figure 2-7). Two individual groups from two different studies were identified as influential. However, the overall results were robust to their exclusion from the model since the interpretation of the model did not change.

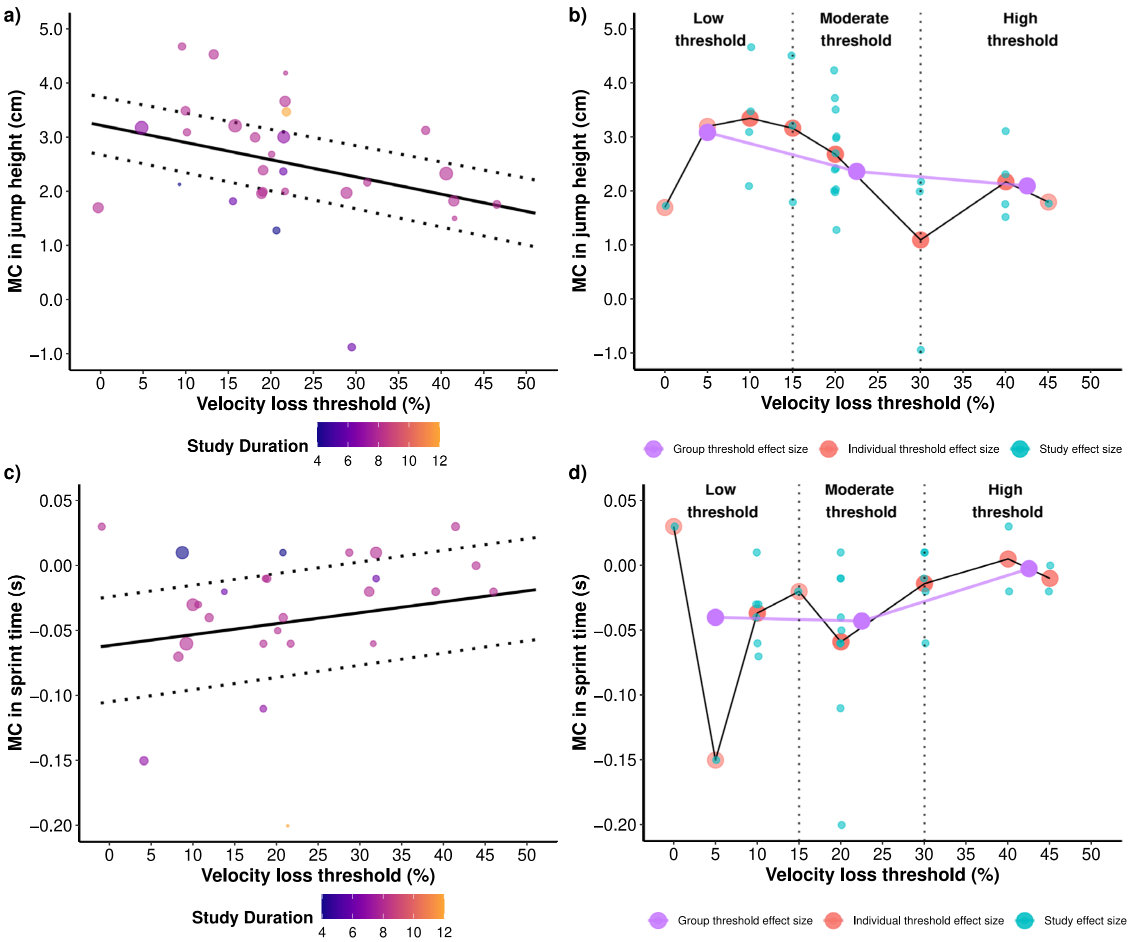
Countermovement jump height

The final multilevel model investigating the effects of different VL thresholds on countermovement jump revealed VL and study duration to be significant moderators (Table 2-4; Figure 2-6). Three individual groups from three different studies were identified as influential. However, the overall results were robust to their exclusion from the model since the interpretation of the model did not change. In fact, the confidence in the estimate for both VL ($b = -0.048$ [-0.073, -0.023]; $p = 0.001$) and study duration ($b = 0.400$ [0.105, 0.695]; $p = 0.010$) increased after their removal.

Sprint time

The final multilevel model investigating the effects of different VL thresholds on sprint time revealed VL and study duration as significant moderators (Table 2-4; Figure 2-6). Three individual groups from three different studies were identified as influential. Excluding these influential groups from the analysis affected the interpretation of the model with study duration no longer being a significant moderator ($b = -0.005$ [-0.031, 0.021]; $p = 0.696$).

Figure 2-6 Multilevel mixed-effects meta-regression illustrating the effects of velocity loss thresholds on countermovement jump (a) and running sprint time (c) after controlling for study duration (also see Table 2-4). For (a) and (c) larger data points received greater weighting than smaller data points. Dose-response relationship considering 1) individual study effect sizes (green circles); 2) average effect sizes of individual velocity loss thresholds (red circles); and 3) average effect sizes of low (≤ 15%), moderate (> 15% < 30%), and high (> 30%) grouped velocity loss thresholds (purple circles and lines) between velocity loss and countermovement jump (b) and running sprint (d) performance improvement.

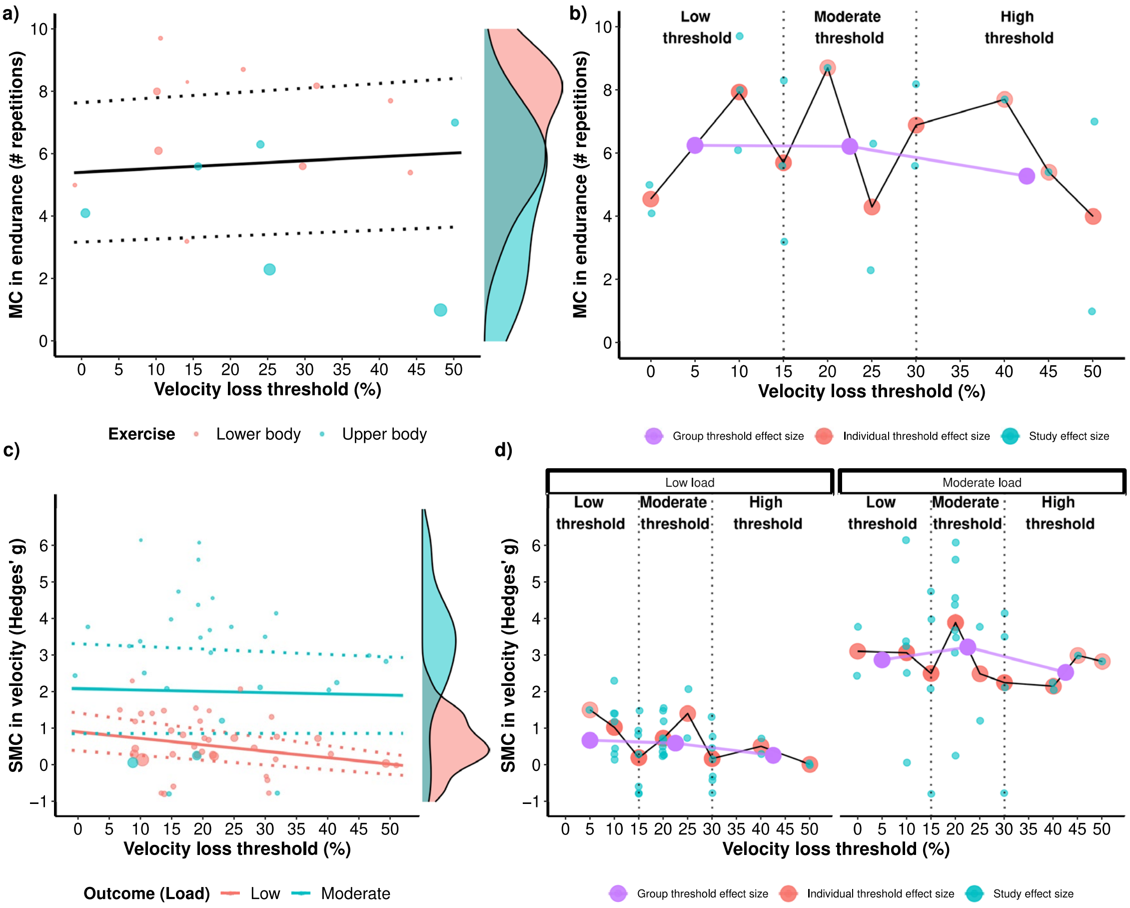


Note. Black, solid, and dotted (non-vertical) lines represent estimated relationships and corresponding upper and lower 95% confidence intervals, whereas vertical dotted lines represent boundaries between velocity loss thresholds. MC mean change.

Velocity against submaximal (low and moderate) loads

For the final multivariate model investigating the effects of different VL thresholds on velocity against low and moderate loads, seven groups from five studies were identified as influential. Due to the high number of influential groups, these were excluded, and estimates of the model without these influential groups were retained (Figure 2-7). This model revealed VL (b = -0.018 [-0.029, -0.006]; $t = -3.69$; $p = 0.010$) and load (b = 1.182 [0.342, 2.022]; $t = 3.12$; $p = 0.011$) as significant moderators (note that low load was a reference outcome). The interaction between the VL and outcome was not significant (b = 0.014 [-0.007, 0.035]; $t = 1.73$; $p = 0.146$). Heterogeneity for the low load outcome was considerably lower ($\tau2 = 0.235$) compared to the moderate load outcome ($\tau2 = 2.034$) with the model estimated correlation between the outcomes being high ($\rho = 0.844$). Imputing a range of different correlations between the low and moderate loads ($\rho = 0.4 – 0.8$) did not affect the interpretation of the model, confirming the robustness of the estimates.

Figure 2-7 Multilevel mixed-effects meta-regression illustrating the effects of velocity loss thresholds on muscle endurance quantified by the number of repetitions performed in a fatigue test (a). Multivariate mixed-effects meta-regression illustrating the effects of velocity loss thresholds on velocity against low (> 1 m·s^{-1}; red circles and lines), and moderate (< 0.8 m·s^{-1}; green circles and lines) loads (c). For (a) and (c) larger data points received greater weighting than smaller data points. Dose-response relationship considering 1) individual study effect sizes (green circles); 2) average effect sizes of individual velocity loss thresholds (red circles); and 3) average effect sizes of low (≤ 15%), moderate (> 15% < 30%), and high (> 30%) grouped velocity loss thresholds (purple circles and lines) between velocity loss and muscle endurance (b) and velocity against submaximal loads (d) performance improvement.



Note. Black, green, and red (solid and dotted) lines represent estimated relationships and corresponding upper and lower 95% confidence intervals, whereas vertical, dotted, and black lines represent boundaries between velocity loss thresholds. MC, mean change; SMC, standardised mean change.

Table 2-4 Moderator analyses (of multilevel models).

Outcome	Moderator	Studies (k)	Effect size (n)	β (95% CI)	t-value	p-value	Overall[a]	R^2 (Level 2)	R^2 (Level 3)	I^2 (Level 2)	I^2 (Level 3)
Maximal strength	Intercept[1]	17	41	0.785 (-0.435, 2.006)	1.305	0.200	F(4, 36) = 6.14	100.00	49.28	0.00	65.38
	Velocity loss	17	41	-0.004 (-0.008, 0.001)	-1.707	0.097					
	Upper body	17	41	-0.371 (-0.667, -0.076)	-2.546	0.015					
	Strength levels	17	41	-0.606 (-1.103, -0.110)	-2.476	0.018					
	Study duration	17	41	0.113 (0.030, 0.215)	2.257	0.030					
Muscle hypertrophy	Intercept	6	17	0.329 (0.050, 0.608)	2.612	0.024	F(1, 15) = 4.79	99.99	17.76	0.00	82.54
	Velocity loss	6	17	0.057 (0.001, 0.011)	2.187	0.045					
Muscle endurance	Intercept	6	17	5.411 (2.963, 7.858)	4.712	0.001	F(1, 15) = 0.29	0.00	0.00	8.71	75.51
	Velocity loss	6	17	0.012 (-0.037, 0.062)	0.535	0.600					
Counter-movement jump	Intercept	12	29	0.646 (-1.498, 2.789)	0.620	0.541	F(2, 26) = 6.11	100.00	13.93	54.84	0.00
	Velocity loss	12	29	-0.038 (-0.070, -0.007)	-2.503	0.019					
	Study duration	12	29	0.358 (0.087, 0.630)	2.712	0.012					
Sprint	Intercept	9	27	0.093 (-0.054, 0.239)	1.306	0.204	F(2, 24) = 8.62	76.93	33.75	2.93	86.79
	Velocity loss	9	27	0.001 (0.001, 0.002)	3.552	0.002					
	Study duration	9	27	-0.021 (-0.040, -0.002)	-2.230	0.031					

Note. [1]Lower body (reference level)

[a]Omnibus test

2.4 Discussion

The present systematic review evaluated the acute effects of different VL thresholds on volume and fatigue during RT and meta-analysed their chronic effects on training adaptations while considering several factors that might differentially influence the magnitude of these acute and chronic responses. Several interpretations stem from our findings: (1) while the number of repetitions per set generally increases as the VL increases, the variability in repetitions performed is modulated by exercise choice and load; (2) due to these increases in repetitions per set, blood lactate concertation and rating of perceived exertion increase whereas countermovement jump, sprinting, and V1 performance decrease proportionally as VL increases. However, the magnitude of these effects is highly influenced by exercise and load; (3) the specific VL threshold used does not have a profound effect on gains in strength and muscle endurance; however, (4) selecting moderate to high VL thresholds for hypertrophy, and low to moderate thresholds for enhancing countermovement jump, sprint, and velocity against submaximal loads may be a viable strategy to induce superior training adaptations. Therefore, many factors should be considered when prescribing RT using VL thresholds to create more homogeneous stimuli among individuals, thereby optimising fatigue management and intended training adaptations.

2.4.1 The effects of velocity loss thresholds on the number of repetitions completed per set

Researchers have recommended RT prescription with VL thresholds over traditional methods due to the strong relationship between the magnitude of VL and the number of repetitions performed with respect to the total number that can be completed before reaching failure [14, 39]. The argument is strengthened by the fact that the number of repetitions performed to failure with a given %1RM has a high inter-individual variability [12]. However, this argument does not discount that the number of repetitions performed before reaching different VL thresholds might also have a high inter-individual variability. Indeed, this contention seems to be empirically supported since data from two recent studies [98, 42] suggest that the number of repetitions performed until reaching 10, 20, and 30% VL in the free-weight back squat exercise is not only highly variable between individuals but is also unstable across sessions. In addition, this inter-individual variability may increase as the magnitude of VL increases [42]. Based on the studies included in the present review, it seems that exercise choice and load can further influence the actual number of repetitions performed and the variability thereof (Figure 2-3). Specifically, both the actual number of repetitions and its variability seem to be higher in the back squat compared with the bench press exercise across VL thresholds. Furthermore, both factors tend to have a strong inverse relationship with load, as higher loads allowed for fewer repetitions and produced lower variability in repetitions across VL thresholds. This is a previously overlooked outcome as studies often focus on the ability of VL thresholds to modulate, with acceptable reliability, the percentages of the completed repetitions per set with respect to the maximum number of repetitions possible [14, 39] and kinetic and kinematic outputs [42, 83, 98]. Although these aspects of VL thresholds present an advantage over traditional methods for prescribing RT volume, the effects of the variability of the actual number of repetitions performed before reaching a certain VL threshold has not yet been empirically investigated. It is possible that individuals completing different numbers of repetitions using the same VL threshold might experience different degrees of neuromuscular, metabolic, and perceptual fatigue, potentially influencing resultant training adaptations. In this regard, it is unknown whether the specific VL threshold is a more important variable than the actual number of repetitions performed, as no studies to date have compared different VL thresholds matched for volume. Collectively, based on the studies included in the present review, it seems the use of VL thresholds for RT prescription could result in the considerable variability of the actual number of repetitions per set completed which can further be confounded by other factors such as the choice of exercise and the load used. Whether this variability could modulate both the acute and chronic effects of VL thresholds presents an interesting avenue for future research.

2.4.2 Acute effects of velocity loss thresholds on neuromuscular, metabolic, and perceptual markers of fatigue

Fatigue is traditionally defined as a loss of force-generating capacity with the eventual inability to sustain exercise at the required or expected level [104, 105]. Muscle-shortening velocity decreases and relaxation time increases as fatigue ensues [106]. In this regard, velocity against a fixed load (e.g., V1) before and after RT is often used as a marker of neuromuscular fatigue in studies investigating the acute effects of different VL thresholds. Indeed, this marker has a high correlation ($r > 0.9$) with other markers of fatigue such as blood lactate and ammonia accumulation as well as countermovement jump height loss after RT [15, 14, 38, 41]. Therefore, it is not surprising that several studies reported an almost linear decrease in post-session V1, and countermovement jump height, as well as an increase in blood lactate accumulation as VL increased [15, 14, 38, 42]. However, the dose-response relationship of VL with these markers of fatigue seems to be modulated by the exercise and load used (Figure 2-4). For instance, as load decreases while using a given VL threshold, greater reductions in post-session V1 and countermovement jump height are observed [38]. Furthermore, Rodríguez-Rosell et al. [38] observed greater declines in post-session V1 in the bench press compared to the back squat, independent of load and VL. The authors attributed these V1 differences between exercises to the smaller muscles – with more type II fibres and higher fatiguability index – involved in the bench press than the squat exercise [107-109]. Rodríguez-Rosell et al. [38] also reported greater blood lactate accumulation during the back squat compared with the bench press, regardless of the load used and VL experienced. In addition, the rate at which metabolic stress increased, as the VL increased, was considerably lower with greater loads (i.e., 80% RM) during the back squat but not bench press, for which metabolic stress uniformly increased as the VL increased regardless of the load used. Therefore, it seems that VL thresholds induce differential neuromuscular and metabolic responses to RT depending on the exercise used.

One potential explanation for this phenomenon could lie in the actual number of repetitions performed before reaching different VL thresholds. Namely, while the RT protocols employing different exercises used the same VL threshold, it is plausible that performing more work (i.e., more repetitions) until reaching a given VL led to greater blood lactate accumulation [110, 111]. This is supported by the findings of Weakley et al. [112], which showed greater metabolic responses accompany increases in work completed during RT. Studies included in this review generally show that a higher number of repetitions are completed with the back squat compared to the bench press (Figure 2-3). Therefore, when completing more work with the back squat compared to the bench press for a given VL threshold, higher metabolic stress is a logical outcome.

Thus, the actual training volume completed in a set with a given VL threshold is an important consideration when prescribing RT. Considering the above, it seems that neuromuscular responses are less sensitive to subtle changes in volume during a set compared to metabolic responses, whereas greater neuromuscular fatigue is induced when using exercises involving smaller muscle groups (greater localised fatigue) with greater percentages of type II muscle fibres (a higher fatiguability index). However, countermovement jump height – also a valid marker of neuromuscular fatigue [113] – seems to be extremely sensitive to the changes in load (Figure 2-4). Since higher loads typically allow for less volume (i.e., repetitions) to be completed in a set, it is plausible that countermovement jump height would also be sensitive to subtle changes in training volume, highlighting that different neuromuscular fatigue assessments might differ in sensitivity. Nevertheless, future research should substantiate these contentions.

Based on the available literature, rating of perceived exertion also seems to increase as VL increases. For instance, Weakley et al. [42] found gradual increases in perceived exertion of the lower limbs and breathlessness after each set with 10, 20, and 30% VL. More specifically, the rate of increase in both perceptual measures seemed to be consistent for the 10% VL threshold, whereas perceived exertion of the lower limbs increased at a greater rate compared to breathlessness across sets with higher VL thresholds (20 and 30%), although the overall magnitude of both perceptual responses was similar. This finding is somewhat supported by Emanuel et al. [114] who reported that the most frequent cause of set termination during sets of back squats to volitional failure was perceived fatigue in the targeted muscles, whereas cardiovascular factors were not as frequent a cause. However, this likely depends on the training background of the individuals. Based on these findings, prescribing larger velocity loss thresholds (e.g., 20% and 30%) for back squats might lead to larger increases in perception of leg muscle exertion than breathlessness across repeated sets. Similar findings were reported by Dos Santos et al. [96] who found that both perceived exertion and discomfort linearly increased as the number of back squat sets increased with a 30% VL threshold. Although it has not been discussed in the literature, the intention of continuously performing repetitions as fast as possible might also impact perceptual responses, especially leg muscle exertion [42] and perceived discomfort [96].

Admittedly, this hypothesis is challenging to investigate since the provision of maximal intent is a prerequisite for reliable velocity outputs.

The time course of fatigue recovery following RT depends on a myriad of factors including training volume and load. Despite the proposed benefits of VL thresholds in the literature [35, 15, 14], only Pareja Blanco et al. [43] examined the time course of recovery after using different VL thresholds and loads during RT. For this purpose, the researchers examined vertical countermovement jump height, 20m sprint time, and V1 before RT, and immediately-, 6 hours-, 24 hours-, and 48 hours-post back squat training with a combination of 20 and 40% VL and 60 and 80% of 1RM. Interestingly, with 60% 1RM, regardless of the VL used (20 vs 40%), none of the performance tasks fully returned to pre-exercise values at 48 hours-post RT. In contrast, the RT protocol using higher loads (80% 1RM) and lower VL (20%) resulted in lower performance impairment immediately after RT, and greater sprint performance at 48 hours post-RT compared to baseline. Interestingly, sprint time generally recovered faster compared to countermovement jump height and V1, suggesting their superior sensitivity for detecting RT-induced neuromuscular fatigue, and the fact that recovery may be exercise dependent. Nevertheless, prescribing higher VL (e.g., 40%) and lower relative loads (e.g., 60% 1RM) could result in greater fatigue immediately after RT and a slower rate of recovery than lower VL (e.g., 20%) and higher relative loads (e.g., 80% 1RM). This finding is especially relevant for sports where RT precedes sport-specific training, in which case an appropriate VL may decrease interference with subsequent sports training.

2.4.3 Methodological considerations when implementing velocity loss thresholds and future research directions

Several research groups have suggested that implementing VL thresholds may allow for better fatigue management compared to traditional RT training prescription methods [15, 14]. It also has been suggested VL can serve as a valid indicator of fatigue due to its high correlation with other frequently used neuromuscular and metabolic markers of fatigue [15, 14, 38, 39]. While this presents a considerable advancement for RT monitoring and prescription, there are a few methodological factors that could compromise their utility both in research and practice. First, it is not clearly understood when exactly one should terminate a set after reaching a pre-determined VL threshold. In the literature, set termination after either one or two repetitions exceeding a VL threshold is common. The rationale for two repetitions is based on the fact that individuals can in some cases produce a velocity above a certain VL threshold, even after this threshold was exceeded for the first time [45]. On this note, some of the studies included in this review – all of which used VL to prescribe RT – reported considerable variability in the VL achieved at the end of a set (Figure 2-4). The magnitude of this variability reported in several studies [84, 96, 95, 94] ranged from 5 to 13%. At the extreme end of this range, one could theoretically expect an individual to reach 40% VL in a set when only 30 or 35% was intended. These limitations should be considered in practice and future research should investigate ways of reducing this variability. Second, the reference repetition from which the VL is calculated (i.e., the first or the fastest in the set) is an important consideration as it affects the VL achieved and subsequently the number of repetitions performed [45]. Since the first repetition is not always the fastest [115, 116, 45], it is important to use the fastest repetition as the reference for VL calculations to ensure more precise RT monitoring and prescription. Third, a reduction in the ability to accelerate the load at the beginning of the concentric phase will likely affect mean velocity more than peak velocity [117, 118]. In this regard, mean velocity should be used rather than peak velocity when implementing VL in training due to its higher sensitivity in detecting the fatigue progression during a set [45]. Fourth, while studies established a close relationship between VL and the percentage of the repetitions completed out of the maximum possible, these percentages may have high inter-individual variability [45]. In this regard, future research should investigate whether prescribing individualised VL thresholds could circumvent these uncertainties associated with prescribing the same VL for all individuals in a training session. Finally, while the effects of load and exercise selection were thoroughly discussed in the present review, there are other potentially relevant factors such as strength and height of the individual which might affect the utility of VL in practice [119]. Therefore, future research should continue exploring factors that could affect the precision of VL thresholds and subsequent acute and chronic effects of their implementation.

At least some of the limitations described before could be potentially alleviated by establishing the repetitions in reserve (i.e., the specific number of repetitions that remain uncompleted at set termination) velocity relationship. The rationale for establishing the repetitions in reserve velocity relationship is that despite the strong relationship between the percentage of repetitions completed out of the maximum possible with VL, the post-set repetitions in reserve remains unknown when using VL [40]. This is important since the last repetitions of a set contribute more to the alteration of muscle energy balance and the abrupt increase in metabolites such as ammonia [15, 19, 18]. In this regard, two studies attempted to establish the relationship between repetitions in reserve and velocity [40, 120]. Morán-Navarro et al. [40] examined the within-individual variability for the velocity associated with a given number of repetitions in reserve (i.e., 2, 4, 6, and 8) in the smith machine bench press, shoulder press, bench pull, and back squat. The authors concluded that regardless of the load used, velocity at a given repetition in reserve is very similar and highly reliable for a given exercise. However, within-individual variability was considerably higher for the bench press and shoulder press compared to other exercises, but this variability was lower among more RT experienced participants. Garcia Ramos et al. [120] also examined the repetitions in reserve velocity relationship, and while they found a high correlation for the smith machine bench press (r = 0.88), they also reported large between-individual variability for velocity at a given repetition in reserve (from 1 to 10). Based on these findings, it seems that a repetition in reserve velocity relationship, like a load velocity profile, should be established for each exercise, and for each individual. Doing so may alleviate many of the shortcomings identified for the VL prescription method. With that said, the literature on this relationship is still scarce with no information available for free-weight exercises, nor on the potential moderating effects of strength, training background or sex. Considering this, and the conflicting results already reported in the literature, future studies should be conducted to address the potential utility of this RT prescription method.

2.4.4 The effects of velocity loss thresholds on muscle strength, hypertrophy, and endurance training adaptations

Based on the results of the present meta-regression, the choice of VL during RT does not seem to affect the magnitude of strength gains when controlling for other factors such as choice of exercise, strength levels and training duration (Table 2-4; Figure 2-5). This is despite the fact that most studies reported considerable differences in training volume which linearly increased as the VL increased. These findings are somewhat in accordance with the meta-analysis by Ralston et al. [121] who found only trivial to small effects (effect size differences: 0.14-0.23) of higher (5+ sets) versus lower (1-4 sets) weekly set volumes on strength gains. However, it must be noted that participants in the majority of studies included in that meta-analysis performed sets to muscle failure. In contrast, different VL groups included in the present review differed not only in training volume, but also proximity to failure in each set. For instance, performing repetitions until 10% VL would result in not only lower training volume, but also more repetitions left in reserve compared to performing repetitions until 30% VL with the same load and exercise. Therefore, findings of the present review might be used to support both the notion of avoiding training to failure and also not needing to perform high volume protocols when the aim is to optimise strength gains. Indeed, although the majority of studies included in the present review found no statistically significant differences in strength gains between different VL thresholds, the magnitudes of improvement (as quantified by effect sizes) seem to suggest a slight advantage of low to moderate over high VL thresholds (Figure 2-5). The authors from the several studies [46-48, 81] suggested that an inverted U-shaped relationship might exist between VL experienced in a set and maximal strength gains. For instance, Pareja-Blanco et al. [46, 47] reported that once a moderate VL threshold was exceeded (e.g., 20 or 25% VL), further increases in strength gains were not observed. In addition, higher VL thresholds can cause a decrease in early rate of force development [47] and a reduction in expression of fast-twitch muscle fibres [17] following RT. Further, several researchers [46, 47] reported that a 0% VL, meaning performing only one repetition during a set, did not lead to optimal strength gains. Therefore, a minimal VL threshold (e.g., ≥ 5%) is needed to induce optimal strength gains. Considering all the above, low to moderate instead of high VL thresholds should be prescribed when the goal is to optimise neuromuscular adaptations to RT.

In contrast to gains in maximal strength, an increase in VL led to a somewhat linear increase in muscle hypertrophy (Figure 2-5). In this regard, a meta-analysis from Schoenfeld et al. [3] found a graded dose-response relationship between training volume and muscle hypertrophy. Since training volume concomitantly increases with VL, it is not surprising that moderate, and especially high VL thresholds induced the most muscle hypertrophy. Volume, rather than the VL threshold itself, seems to be the factor driving differences in hypertrophy as illustrated by Andersen and colleagues [50] who observed no significant differences between 15 and 30% VL threshold groups in the only longitudinal VL study examining muscle hypertrophy with equated volume. However, this finding is not universal as some studies found moderate VL (e.g., 20-25%) thresholds to be equally effective as higher (e.g., > 40%) VL thresholds at promoting hypertrophy [46, 47]. These discrepancies were not discussed in the scientific literature but could at least partially be explained by the combination of the following factors 1) training status of the participants (e.g., slight numerical differences in muscle cross-sectional area at baseline in favour of moderate thresholds), and 2) relatively low training frequency (~ 2x/week), study duration (~ 8 weeks; 16 sessions), and the number of sets (~ 6/week). Thus, moderate VL thresholds should be prescribed when the aim is to optimise hypertrophy without sacrificing neuromuscular adaptations.

Traditionally, performing many repetitions per set has been recommended when the goal is to induce positive muscle endurance adaptations during RT [122, 123]. Similar conclusions were drawn in a more recent meta-analysis [56]. Contrastingly, the results of the present meta-regression suggest that different VL thresholds, and thus varying number of repetitions performed per set, do not seem to modulate gains in muscle endurance during RT (Figure 2-7; Table 2-4). In fact, higher VL thresholds seemed to be slightly less effective at inducing muscle endurance gains (Figure 2-7). This is surprising given the observed differences in training volume which linearly increased as the VL increased. Moreover, one study [100] recently reported that the group who performed bodyweight pull-ups until reaching 25% VL improved muscle endurance in the same exercise (i.e., number of repetitions to failure) slightly more than the 50% VL group despite the differences in training volume. In this regard, studies [46, 47, 64, 65] often hypothesise that the superior gains in maximal strength observed for low to moderate compared to high VL thresholds might be responsible for these findings. This is a plausible explanation as the muscle endurance tests used a fixed load both at baseline and post-intervention, meaning that the group which experienced greater strength gains would perform the strength endurance test with a lower relative load compared to the group which improved the strength less, thus allowing more repetitions to be performed until failure. Indeed, high correlations ($r = 0.63 – 0.71$) have been reported between improvements in maximal strength and muscle endurance which could support this contention [64, 65]. In addition, similar dose-response curves for muscle strength and endurance, but not hypertrophy, were observed in a recent study [124] investigating the effects of training volume of muscle adaptations, which aligns with the results of the present meta-regression. However, a training program with a repetition range that mimics the endurance test generally leads to greater improvements in muscle endurance [125]. In this regard, it is unclear why higher VL thresholds, which generally allow for greater repetitions per set and therefore more closely mimic muscle endurance tests, did not prove to be superior for this outcome. Perhaps the fact that most studies in the present review terminated their muscle endurance tests when the barbell reached ~ 0.50 $m \cdot s^{-1}$ could be responsible for these findings, thus making the test relatively more similar to low to moderate, but not high VL thresholds. Future studies are needed to investigate these possibilities.

2.4.5 The effects of velocity loss thresholds on performance of athletic tasks and velocity against submaximal loads

Based on the results of the present meta-regression, there is an inverse relationship between VL and subsequent improvement in countermovement jump and sprint performance. In addition, study duration also seems to modulate the gains in jumping and sprinting performance with longer training interventions leading to greater gains in performance. This finding was observed despite the fact that only 2 out of 10 studies that investigated the effects of VL thresholds on jumping or sprinting performance incorporated sprinting or jumping in their training programs (either directly or through playing sport). Jumping and sprinting improvements were also unrelated to maximal strength gains, which were more similar between VL thresholds compared to athletic task performance. Therefore, some authors concluded the degree of RT transfer to actual physical performance was more dependent on the magnitude of VL attained in the set rather than gains in strength [64, 65]. This contention could be supported by the principle of training specificity [126]. In general, average velocity was higher for low to moderate than high VL thresholds. In this regard, significant correlations were reported between the velocity of the repetitions performed and changes in jumping and sprinting performance [64, 65], supporting the importance of repetition velocity for enhancing high-speed actions such as jumping and sprinting. The inverse could also explain these findings, as the number of repetitions performed at slower velocities was progressively greater as VL increased. Therefore, it could also be argued that the excessive amount of fatigue from high VL interferes with athletic task performance. However, more research is needed to determine the causal factor, as Perez Castilla et al. [49] found no significant differences in jumping and sprinting improvement between 10 and 20% VL threshold groups with equated volume, the only study to have controlled for volume. Admittedly, this study lasted only 4 weeks (below the average in the present review), compared only low to moderate VL thresholds, and included different jumping exercises in their training interventions, all of which could have affected the results.

Findings of the present meta-regression on the effects of different VL thresholds on velocity against submaximal loads might support the importance of actual repetition velocity during RT that is implemented with the intent of improving jumping and sprinting performance. Indeed, improvement in velocity against moderate (< 0.8 $m \cdot s^{-1}$), and especially low loads (> 1 $m \cdot s^{-1}$) progressively increased as the VL decreased (Figure 2-7). Since lower VL thresholds allow for greater velocities and therefore higher velocity adaptations against low loads, these findings collectively support the training specificity concept when it comes to RT transfer to performance of athletic tasks such as jumping and sprinting. A large degree of variability in velocity against moderate loads was observed, which could probably be explained by the large range of loads that fell into the moderate loads category. Nevertheless, it seems that moderate VL thresholds (Figure 2-7) were slightly more effective compared to low and high VL thresholds at improving velocity against moderate loads, further supporting the principle of training specificity. Collectively, these findings support the idea that training should be informed by changes in an individual's load-velocity profile, as doing so identifies the specific RT-induced adaptations along the load-velocity curve, thus providing a more comprehensive analysis of RT-induced changes compared to maximal strength changes alone.

2.4.6 Implications for training and research based on the findings from longitudinal studies

Overall, based on the findings of the present review it can be concluded that 1) while the differences in strength and muscle endurance adaptations between VL thresholds are small, low to moderate VL thresholds may be slightly more effective for inducing these adaptations compared to higher VL thresholds; 2) moderate to high thresholds are likely more effective for muscle hypertrophy compared to lower thresholds; 3) jumping and sprinting performance improve the most following lower VL threshold training; and 4) low to moderate VL thresholds will improve velocity against low loads, whereas moderate thresholds more effectively improve velocity against moderate loads. Considering less time is required when training with low to moderate VL thresholds, potential reductions in early rate of force development [47], percentage of fast-twitch muscle fibres [17], and likely delayed time course of recovery after RT with high VL thresholds [43], low to moderate VL thresholds should generally be prescribed when the goal is to optimise strength and performance adaptations. These findings are especially relevant for team sports where frequent matches throughout the season and extended competition periods alter the length of the preparatory period and its specific phases, but also individual sports where athletes often train multiple times a day and need to manage RT fatigue for both event performance and sport-specific training sessions.

It must be noted, however, that it is presently unclear if differential effects of low to moderate and high VL thresholds are indeed due to differences in VL (and therefore repetition velocity and proximity to failure), training volume, or a combination of both. In this regard, only two longitudinal studies equated training volume between different VL thresholds both of which found no significant differences between groups [49, 50]. Therefore, it may be that differences in training volume are the main drivers of differential adaptations following the use of different VL thresholds. In partial support of this, reductions in type IIx fibres and rate of force development have been shown to be larger following higher as compared to lower volume training [127]. Nevertheless, future studies should equalise training volume between VL thresholds to isolate their effects from the influence of total volume load to support or refute this contention. Furthermore, no studies investigating the effects of different VL thresholds have manipulated the number of sets. Manipulating the number of sets could be a viable strategy to further increase the effectiveness of low to moderate VL thresholds. Increasing the number of sets while keeping VL low to moderate might yield additional muscle hypertrophy, comparable to higher VL thresholds with fewer sets. Choosing to perform more sets with low to moderate VL thresholds to increase volume, rather than use high VL thresholds, might avoid the aforementioned downsides of high VL thresholds (neuromuscular fatigue, poorer strength and athletic task performance adaptations) while still producing (or perhaps even amplifying) the observed adaptations associated with low to moderate VL thresholds. Another area in need of study is the periodised use of VL thresholds over time (e.g., low to moderate VL phases following high VL in a linear fashion, or used concurrently in an undulating design). Such a multifaceted approach to training does have merit, especially in high-performance settings where multiple training qualities often have to be considered throughout a microcycle or mesocycle. Importantly, in a similar fashion to VL thresholds for those who do not have access to velocity-tracking devices, cluster or rest-redistribution set structures may be a viable alternative to maintain high repetition velocity while minimising neuromuscular fatigue during RT [128, 56, 129]. Indeed, Jukic & Tufano [116] recently reported that rest redistribution allowed almost all repetitions (~ 17.5 out of 18) in a clean pull exercise to be performed above 20% VL regardless of the load used across three sets and therefore suggested that rest redistribution could potentially serve as a free ad-hoc alternative to VL thresholds. However, future research is needed to explore these alternatives with a range of different exercises, loads, and athletic populations. Finally, acute responses to different VL thresholds discussed in the present review should also be considered when implementing them in RT programs since they are also likely to affect the magnitude of RT-induced adaptations.

2.4.7 Risk of bias assessment

Most of the studies included in this review did not provide sufficient information regarding the method of randomisation. Further, no studies provided information regarding allocation concealment and no studies pre-registered their protocols on a publicly available registry. As a result, these studies were of unclear risk of order effect, allocation concealment, and selective reporting bias. Therefore, researchers should improve their reporting of this information in future studies. Importantly, some studies also had an unclear risk of attrition bias due to not providing sufficient information as to the number of participants included in the analysis after reporting that some did not complete the entire intervention or all procedures. Future studies should report the predefined criteria for participant exclusion from analysis, and clearly state how many were included. We recommend the use of the CONSORT flow diagram [130]. Almost half of the studies included in this review were at high risk of familiarisation bias since the authors did not report or did not familiarise their participants with the testing procedures. This is especially important in the context of velocity-based training where participants need to provide maximal intent during all repetitions to ensure the reliability of velocity outputs. In addition, some studies failed to report details regarding the provision of velocity feedback or encouragement, both of which can affect the findings of a study. Therefore, future research should ensure that familiarisation sessions are performed, the procedures are fully reported, and the provision of velocity feedback or encouragement occurs and is documented. Most studies were at low risk of bias for other factors that could have affected their findings and used valid and reliable methods, equipment, or instruments to evaluate their outcomes of interest.

2.4.8 Limitations and considerations

Several aspects of this review should be considered when interpreting the findings. First, the visualisations made from the acute studies and their interpretation are limited by the data reported in the original studies. While attempts were made to perform a meta-analysis of the acute studies, missing data and subsequently authors' refusal to provide data prevented us from doing so. Second, there were considerably fewer female participants in both the acute and longitudinal studies, which limit the generalisability of our findings to female participants, and more research on VL thresholds should include females when possible. However, Rissanen et al. [99] recently reported robust and similar increases in strength and power performance in males and females over 8 weeks while performing repetitions until 20% or 40% VL. This suggests that males and females might be responding similarly to different VL thresholds; although, more research is needed to substantiate these claims. Third, while we attempted to consider the moderating effects of study duration, exercise, loads used, and strength levels of the individuals in all meta-analytic models, the number of studies and effect sizes per study meant this could only be performed for some outcomes. For instance, exercises in the vast majority of longitudinal studies were performed in Smith Machines. In this regard, the effects of exercise mode (i.e., Smith Machine vs free-weight exercises) have not been formally investigated. Therefore, it is presently unknown to what extent the findings of the present review can be translated to scenarios when only free-weight exercises are used, and thus, the findings of this review should be interpreted with this in mind. This also highlights a need for studies that directly compare the acute and chronic effects of different VL thresholds with exercises performed using free-weights or using both free-weights and Smith Machines (while keeping exercises the same) in a cross-over fashion. Fourth, some studies did not report all information required for meta-regression, therefore, we extracted the required information from figures or made estimations (e.g., pre-post assessment correlations) based on other studies. This likely introduced some error and we therefore urge researchers to report standard deviations of differences (and or pre-post assessment correlations) in training intervention studies. In addition, we also urge researchers to respond to data request e-mails and to provide data when there are no legal barriers to doing so. Fifth, a few longitudinal studies estimated 1RM rather than testing 1RM as a measure of maximal strength. Although not ideal, the fact that all these studies were consistent with their procedures before and after the intervention, used load-velocity relationships with high loads (up to 80-95% 1RM), and used smith machine exercises to predict maximal strength should minimise the impact on their findings. Finally, since there is no consensus regarding the actual velocities attained against low, moderate, and high loads (because these velocities are highly individual), what is considered a “moderate” or “low” load is subjective. Therefore, when interpreting the velocity against submaximal loads outcome in the present review, it should be noted that loads associated with > 1 $m \cdot s^{-1}$ and < 0.8 $m \cdot s^{-1}$ were classified as low and moderate loads, respectively.

2.5 Conclusion

Monitoring VL during RT may offer additional insights about training response not captured by more traditional methods of prescribing and monitoring RT. However, it is important to note that the acute neuromuscular, metabolic, and perceptual responses to different VL thresholds will likely depend upon the choice of exercise, loads used, number of sets performed, individual athlete characteristics, and more. In addition, factors that can specifically affect the consistency of VL determination such as reference repetition, use of peak or mean velocity, and criteria for set termination (repetitions allowed after the VL is exceeded) should all be considered when implementing VL in practice. Prescribing low to moderate VL thresholds during RT seems to be more time-efficient and a generally advantageous strategy compared to higher VL thresholds for optimising muscle strength and endurance, jumping and sprint performance, as well as velocity against submaximal loads. In contrast, higher VL thresholds may be more effective for promoting muscle hypertrophy. However, prescribing higher VL thresholds during RT can impair rapid force production capability, reduce the expression of fast-twitch muscle fibres, and prolong recovery from RT. In contrast, extremely low VL thresholds can sometimes lead to suboptimal training adaptations. Therefore, low to moderate VL thresholds may be a viable strategy for ensuring optimal performance improvement while preventing potentially negative effects of fatigue. To conclude, the findings of this review indicate that the specific choice of VL threshold will influence the subsequent RT adaptations, highlighting that VL threshold selection is an important consideration in RT program design.

Chapter 3: Implementing a velocity-based approach to resistance training: the reproducibility and sensitivity of different velocity monitoring technologies

Preface

Before addressing some of the methodological limitations of using velocity loss during resistance training identified in the previous chapter, several factors such as the cost of the technologies used to monitor velocity as well as their accuracy and practicality must be considered. Gold standard motion capture systems are expensive and require a lot of space and time for data processing making them highly impractical for most applied settings. Thanks to technological advancements, many different field-based devices such as linear position transducers (LPTs) and inertial measurement units (IMU) have recently emerged to combat these logistical constraints. However, before these devices should be used in practice, their sensitivity and reproducibility must be examined since very small changes in velocity can represent decisive changes in neuromuscular status and functional performance. Therefore, the following chapter comprehensively examined 1) the reproducibility of three widely used LPTs and IMUs by monitoring barbell velocity with two devices of each brand simultaneously during the free-weight back squat exercise; and 2) the sensitivity of these devices to detect minimal changes in velocity that correspond to a real change in resistance training performance. Such evidence is important to guide velocity-based resistance training monitoring and prescription and ultimately determine the most efficient and cost-effective devices for field use.

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3.1 Introduction

Resistance training (RT) is the principal mode of training for inducing muscle strength, hypertrophy, and power adaptations. Additionally, RT has an important role in injury prevention and rehabilitation, as well as general well-being due to its beneficial effects on quality of life [1, 30, 31] Consequently, RT is a part of many physical preparation programs of athletes and is a popular choice of exercise among recreational trainees. Several variables should be considered when designing an efficacious RT program, with RT intensity and volume receiving the greatest attention from the scientific community as they often determine the magnitude of resultant training adaptations [4, 3]. RT intensity is traditionally prescribed as a percentage of an actual or estimated one-repetition maximum (1RM) assessment. On the other hand, when the number of sets for a training session is fixed, volume is prescribed by the number of repetitions performed per set (i.e., set volume). Set volume prescription is often based on the theoretical relationship between the maximum number of repetitions an individual can complete with a given percentage of 1RM. Thus, both RT intensity and volume prescription rely upon the accuracy of 1RM assessments. While 1RM tests were shown to be valid and reliable, they are physically and psychologically demanding, time-consuming, and can compromise the safety of individuals performing the test [5]. Additionally, 1RM-based RT intensity and volume prescription might be insensitive to potential day-to-day variation in performance caused by normal biological and psychological variability (e.g., sleep, nutrition, and life stress) [10, 7]. This can lead to erroneous training prescriptions and sub-optimal training adaptations in the long term. To solve these fundamental issues with traditional RT intensity and volume prescription, sport scientists have proposed the use of movement velocity as more accurate monitoring and prescription tool for RT programs [35].

A strong, inverse relationship exists between barbell velocity and the percentage of one-repetiton maximum (%1RM) in many RT exercises. Indeed, this relationship is reliable in both the Smith machine and free-weight exercises [35, 28]. Thus, this relationship is useful for prescribing daily RT intensity by adjusting the absolute load to match the velocity associated with the intended %1RM depending on the trainee's preparedness. On the other hand, Miras-Moreno et al. [131] recently reported that movement velocity during RT can predict the maximum number of repetitions that can be completed in a set, allowing for RT set-volume prescription. Furthermore, when the exercise is performed with maximal concentric effort and fatigue ensues, velocity will decline [28]. In this regard, research has shown that monitoring velocity loss (VL) incurred in a set is an objective, practical and non-invasive indicator of the acute metabolic stress, hormonal response and mechanical fatigue induced by RT [15]. Although this velocity-based approach to RT monitoring and prescription is now widely used among different populations, several factors such as the cost of the equipment and its accuracy must be considered.

Regardless of the population in question, it is evident that the efficacy of the velocity-based approach to RT monitoring and prescription depends upon the reliability of devices used to record barbell velocity. This requirement also represents one of the main drawbacks of the velocity-based approach to RT monitoring and prescription since very small changes in velocity can represent decisive changes in neuromuscular status and functional performance [15, 16]. In this regard, 3-dimensional motion capture systems are considered gold-standard for movement velocity monitoring. However, the considerable cost, space requirements, and time for data processing make motion capture systems highly impractical for most applied settings. Thanks to technological advancements, many different field-based devices such as linear position transducers (LPTs), linear velocity transducers, and inertial measurement units (IMU) have recently emerged to combat logistical constraints associated with velocity monitoring devices. One such popular device available on the market is GymAware (GymAware Power Tool; Kinetic Performance Technologies, Canberra, Australia) LPT which is also well established in the scientific literature as an accurate velocity monitoring tool during RT [132]. Although reliable and valid, several drawbacks may limit GymAware's widespread use. Firstly, nonprofessional athletes and coaches as well as recreational trainees who have a limited budget could find it cost prohibitive. Secondly, the cable of this LPT must be attached to the barbell to record barbell velocity which may limit the number of lifting exercises it can effectively quantify. This has prompted a need for cheaper and wireless devices that could accurately record movement velocity during RT.

More recently, two wearable, wireless, IMU-based velocity monitoring devices PUSH2 (PUSH Inc., Toronto, ON, Canada) and Vmaxpro (alias EnodePro; Blaumann & Meyer—Sports Technology UG, Magdeburg, Germany) have grown in popularity among athletes and recreational trainees due to their versatility and relatively affordable price. Several studies [133-135] have examined the test-retest reliability of PUSH2 and Vmaxpro devices with free-weight exercises. However, it is important to highlight that the test-retest reliability assessment inevitably contains errors due to biological variation. Similarly, by quantifying the degree of agreement among individuals under a single testing condition and using only one device, the true technological error of a given device cannot be discerned from the biological variation. This is pertinent during RT, where fluctuations in strength and readiness to train can cause substantial alterations in velocity outputs despite the same relative load being used. Furthermore, Bland-Altman analyses (and plots) are often used to make conclusions about the reliability of a given device. While Bland-Altman analysis is extremely useful for such purposes, it requires the interpretation of the magnitude of errors according to some practical criteria. For instance, in the context of velocity monitoring devices during RT, it would be useful to examine the sensitivity of devices to detect minimal changes in velocity that correspond to true changes in performance. However, only a few studies have based their findings on these criteria [136-138], none of which examined the reproducibility and sensitivity of Vmaxpro and *body mode* PUSH2 devices. Therefore, research assessing the reliability of devices that account for biological variation while determining the sensitivity of devices based on practically relevant criteria is required.

To address these shortcomings in the literature, this study aimed to comprehensively examine 1) the reproducibility of GymAware, PUSH2, and Vmaxpro devices by monitoring barbell velocity with two devices of each brand simultaneously during the free-weight back squat exercise; and 2) the sensitivity of these devices to detect minimal changes in velocity that correspond to a real change in RT performance. Such evidence is important to guide velocity-based RT monitoring and prescription and ultimately determine the most efficient and cost-effective devices for velocity monitoring during free-weight RT.

3.2 Methods

3.2.1 Design

This study was a part of a larger investigation on the reliability of several different velocity-based monitoring and prescription methods for resistance training. Participants made five visits to the laboratory, with each visit separated by 48-72 hrs. The first session familiarised participants with the free-weight back squat movement, the equipment used during the experimental sessions, the instruction to move the barbell up as fast as they can during the concentric phase, and visual feedback indicating the velocity of the barbell on a screen (Figure 3-1). At the subsequent two sessions, participants completed a 1-repetition maximum test in the free-weight back squat. In the final two sessions and using the 1-RM load obtained from the second 1-RM session, participants completed a repetition to failure (RTF) test in which they performed sets to failure in the back squat exercise with 90, 80, and 70% of their pre-determined 1-RM. Mean velocity (MV) and peak velocity (PV) were recorded by two Gymaware, PUSH2, and Vmaxpro devices during all testing sessions.

3.2.2 Participants

Fifty-one resistance-trained participants (15 females and 36 males; 18 to 40 years of age; back squat 1RM/body mass = 1.24 ± 0.32 and 1.79 ± 0.35 for females and males, respectively) completed this study. To be eligible for inclusion, participants (a) abstained from additional lower-body training during their participation in the study; (b) were not taking medication known to alter metabolic or cardiovascular function; (c) were free of musculoskeletal injury; (d) were not reportedly using, or had a history of using anabolic steroids; and (e), had at least six months of resistance training experience in the back squat exercise, including at least two sessions per week and one performing the back squat, and no longer than two weeks without training in this period. Participants provided informed written consent before commencing the study. The study protocol was approved by the University Ethics Board (approval number (20/55), and The Code of Ethics of the World Medical Association.

3.2.3 Familiarisation session

Participants' body mass and height were recorded using an electronic column scale and a wall-mounted stadiometer (Seca Ltd., Hamburg, Germany). Thereafter, participants completed a standardised warm-up consisting of cycling at 100 rpm for 5 min; dynamic stretching for 2 min; 10 bodyweight lunges and squats; and 10 barbell squats. After the warm-up, participants were familiarised with the instruction to lift the barbell up as fast as they can during the concentric phase of the squat, and visual velocity feedback (using the right GymAware) displayed on a TV screen in front of them (~ 3 meters) indicating the velocity of the barbell, and the instruction to have at least a momentary pause (no longer than 2 seconds) between the repetitions. Participants then completed 3 repetitions at 20, 40, and 60% of their estimated 1RM, and 10 repetitions at 60% of their estimated 1RM. Participants practised lifting the barbell up as fast as they can, avoided pausing more than 2 seconds between repetitions and received visual feedback indicating the velocity of the barbell. At the end of each session, all participants understood and felt comfortable with these conditions, and had done at least two sets with very consistent velocities of the repetitions (± 0.02 m/s). To inform warm-up loads for the upcoming 1-RM sessions, participants were also asked to provide the log of their most recent (and heaviest) back squat session and to conservatively estimate their 1RM.

3.2.4 One repetition maximum sessions: Days 2-3

Participants completed the same standardised warm-up as in the familiarisation session. A 20-kg barbell (Rogue, Columbus, Ohio, USA) and calibrated weight plates (Eleiko; Halmstad, Sweden, the EU) were used. The 1RM protocol consisted of 3 repetitions at 20%, 3 repetitions at 40%, 3 repetitions at 60%, 1 repetition at 80%, and 1 repetition at 90% of an estimated 1RM, followed by 1RM attempts. After each successful attempt, the load was increased in consultation with the participant, using increments of 1 to 12.5 kg until no further weight could be lifted or until the movement technique was compromised. A maximum of five 1RM attempts were allowed for each participant. Three and four minutes of passive rest were provided between each submaximal set and 1RM attempts, respectively. Each participant adopted a shoulder-width stance and used a self-regulated eccentric velocity. Immediately upon reaching the bottom of their squat, participants were instructed to perform the concentric (upward) portion of each repetition as fast as possible. Verbal encouragement and visual feedback (indicating the velocity of the barbell) were provided throughout all trials. Participants were required to reach a depth of the squat at which the top of the thighs was at least parallel to the floor, as determined by the investigators and a camera positioned perpendicularly to the participant, for the repetition to be considered successful. During all repetitions, the feet were required to maintain contact with the floor (i.e., no jumping or lifting of the heels) and a slight pause was required after each repetition with full hip and knee extension. The rest between 1RM sessions was 48 hours.

3.2.5 Repetitions to failure sessions: Days 4-5

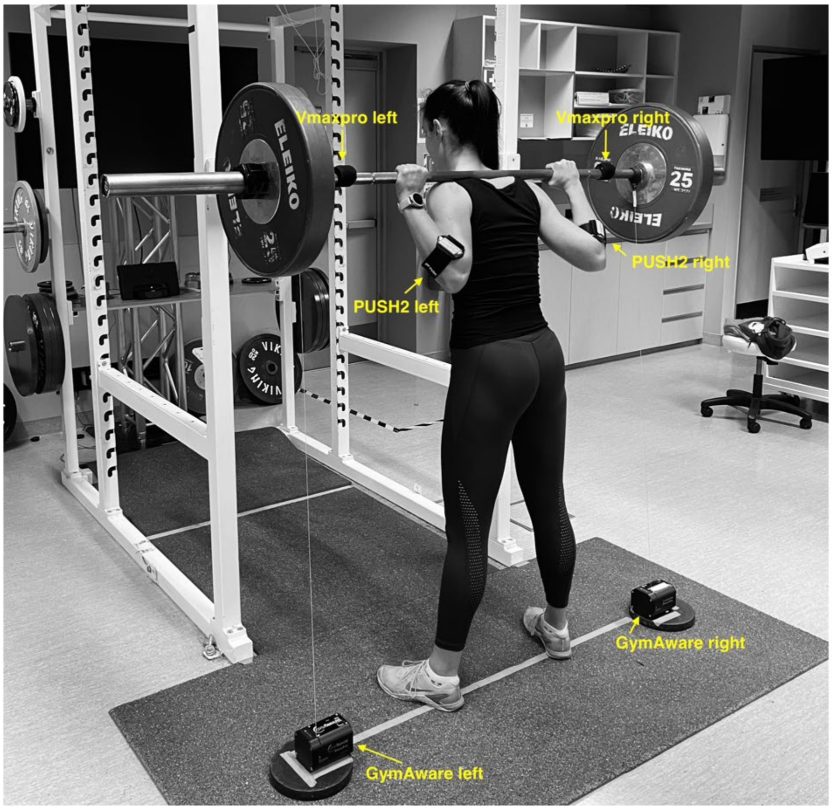
Participants completed the same standardised warm-up as in the familiarisation and 1RM sessions. Thereafter, they completed four sets of 10, 5, 3, and 1 repetition against 30%, 50%, 70%, and 90% of the 90% of their established 1RM (i.e., the heaviest load to be lifted that day), respectively. Participants were provided 3 minutes of rest between warm-up sets, and 4 minutes between the last warm-up set and the first set to failure. Thereafter, participants performed three sets with 90, 80 and 70% 1RM respectively, to muscular failure with 10 minutes of inter-set rest. Since the excessive fatigue caused by performing a high number of repetitions during RTF with lower loads (i.e., 70% 1RM) could have compromised the number of repetitions performed during subsequent RTF sets with greater loads (i.e., 80% and 90% of 1RM), the order of loads was not randomised. Instead, participants always performed RTF with the highest load (i.e., 90% 1RM) first while the last RTF set was always performed with the lowest load (i.e., 70% 1RM). Regarding the exercise execution (including lifting instructions, encouragement, and visual feedback), the same conditions were applied as during 1RM sessions. The rest between RTF sessions was 72 hours.

3.2.6 Data acquisition

A comprehensive description of data acquisition is provided in Appendix F Ch. 3 File I. Briefly, two GymAware, PUSH2, and Vmaxpro (alias, EnodePro) devices were used at the same time to measure MV and PV during all repetitions throughout the sessions. One GymAware and one Vmaxpro device were attached to the left and the right side of the barbel as shown in Figure 3-1. In contrast, one PUSH2 device was placed on each forearm (one device on each forearm) with the hand supinated, on top of the ulna, 1–2 cm distal to the elbow, and with the main button located proximally according to the manufacturer’s instructions (Figure 3-1).

Data obtained from GymAware and Vmaxpro were transmitted via Bluetooth to a tablet (iPad, Apple Inc., California, USA) using the GymAware v2.8.0 app and Vmaxpro app v4.2.0, respectively. Prior to each measurement, the Vmaxpro devices were calibrated according to the manufacturer’s instructions. Vmaxpro devices were placed on both sides of the barbell between the hands and the loaded barbell sleeves (using a Velcro strap) next to Gymaware's cables. Data obtained from PUSH2 were transmitted to the PUSH v7.6.0 app via Bluetooth connection with two smartphones (iPhone, Apple Inc., California, USA). All MV and PV data were recorded by the same two researchers in Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) during each session. Each device was labelled with the words "left" and "right" and was consistently used on their respective sides of the barbell or forearm. In addition, each app, for every respective device was run with iOS 14.0.1. The barbell was marked so that the positioning of the devices could be kept identical throughout all trials for all participants.

Figure 3-1 Velocity monitoring devices setup. The setup involved one GymAware and Vmaxpro device on each side of the barbell and one PUSH2 device on each forearm of the participant.



3.2.7 Statistical analysis

All data were normally distributed as determined by the graphical inspection and the indicator value range for skewness and kurtosis. Descriptive data are presented as Means and SDs unless otherwise stated. To examine within-unit reliability (right vs left device for each measuring device separately) for MV and PV, ordinary least products (OLP) regression was used. Estimated parameters of the OLP regression (intercept, slope, and residual standard error [RSE]) were used for further analysis, where the intercept and slope were considered to represent fixed and proportional bias, respectively. If the 95% confidence interval for the intercept did not include 0, then fixed bias was present. If the 95% confidence interval for the slope did not include 1, then proportional bias was present. To judge the practical significance of the within-device reliability, the smallest effect size of interest (SESOI) was used [139] In this study, SESOI was defined as the minimal change in the load that corresponds to ± 5% 1RM. To estimate velocity SESOI (for both MV and PV), pooled load-velocity profile was used to estimate the average change in velocity that corresponds to a change in the load of ± 5% 1RM.

To judge the magnitude of error, the proportion of practically equivalent residuals (PPER), smallest detectable change in velocity (SDC) and %1RM (SDC%1RM) were evaluated [138]. Statistical inference for all within-unit agreement parameters was provided using the stratified 12000 resamples bootstrap and 95% bias-corrected and accelerated (BCa) confidence intervals. A set of complimentary statistical parameters including Pearson correlation coefficient (r), intra-class correlation coefficient (ICC), coefficient of variation (CV) and Lin's concordance correlation coefficient (CCC) with 95% confidence intervals (CI) were also evaluated.

To examine whether the devices of the present study are sensitive enough to detect changes in load-velocity profiles (LVP) previously reported for the free-weight back squat exercise [28], a modified true value varies method of the Bland-Altman analysis for multiple observations per participant was used [140]. The bias and associated 95% limits of agreement (LoA) were evaluated and interpreted in the context of an *a priori* specified equivalent margin of ± 0.06 m/s and 0.11 m/s for MV and PV, respectively. These criteria were selected since they represent the SDC in velocity for individual LVPs in the free-weight back squat exercise [28]. All assumptions of the Bland-Altman analysis were satisfied. All analyses were done with a custom-written script in R statistical language, that is available together with the dataset at the Open Science Framework repository (https://osf.io/cbsar/).

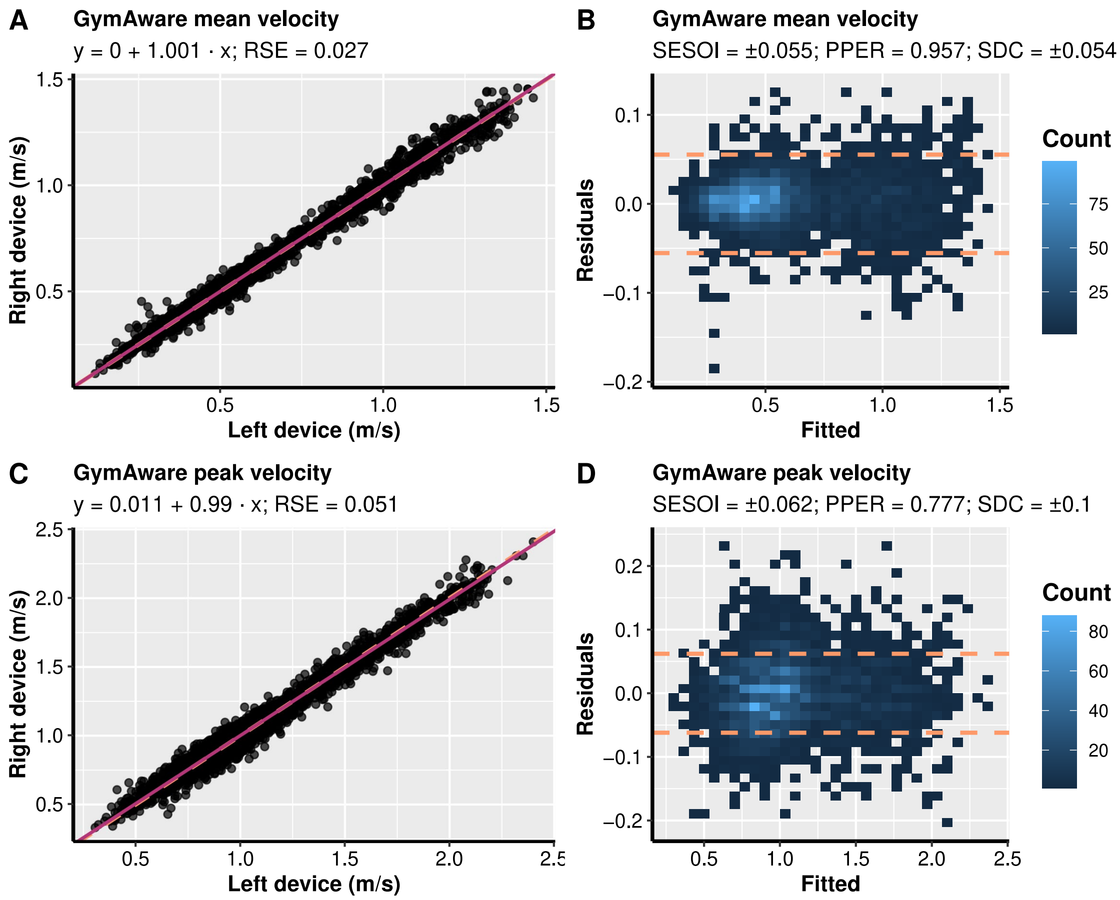
Three participants withdrew from the study due to injuries during their work or recreational sporting activity not related to the study whereas two participants dropped out of the study due to personal reasons after completing one or three experimental sessions. However, their data was not removed from the analyses. The number of participants, total repetition observations, missing observations for each measuring unit per day and testing protocol are presented in Appendix F Ch. 3 File II. More information regarding, (a) devices used and their software, (b) calculation of statistics relating to the magnitude of error, (c) statistical inference using stratified bootstrap, (d) Bland-Altman analysis, and (e) missing data points, is provided in Appendix F Ch. 3 File I.

3.3 Results

The scatterplots between left and right device (left-hand panels) and OLP model residuals plots (right-hand panels) for all six within-unit comparisons together with fixed bias, proportional bias, RSE, and SDC are illustrated in Figure 3-2, Figure 3-3, and Figure 3-4. The within-unit reliability estimators and their accompanying 95% BCa confidence intervals can be found in Appendix F Ch. 3 File III.

For the GymAware devices, statistically significant fixed and proportional bias were observed for PV (intercept = 0.011 m/s, 95% CI [0.006, 0.017]; slope = 0.99, 95% CI [0.985, 0.995]; Figure 3-2; Figure 3-5), but not MV (intercept = 0 m/s, 95% CI [-0.002, 0.002]; slope = 1.001, 95% CI [0.996, 1.005]; Figure 3-2; Figure 3-5). However, since the confidence intervals were within the SESOI limits (SESOI = ±0.062 m/s) for the PV intercept and considering that the confidence intervals were extremely narrow and very close to the value of 0 and 1 for intercept and slope, respectively, this difference could be considered practically irrelevant. Moreover, SDC for MV was within the SESOI limits for GymAware devices (SDC = 0.054 m/s). This was reflected by the SDC%1RM which was lower than the *a priori* selected load SESOI of 5% 1RM (SDC%1RM = 4.418%). In addition, SDC for PV was outside SESOI limits (SDC = 0.100 m/s) which resulted in SDC%1RM also being above SESOI of 5% (SDC%1RM = 6.515%). Overall, MV showed perfect within-device agreement while PV showed almost excellent within-device agreement for GymAware devices during the free-weight back squat exercise.

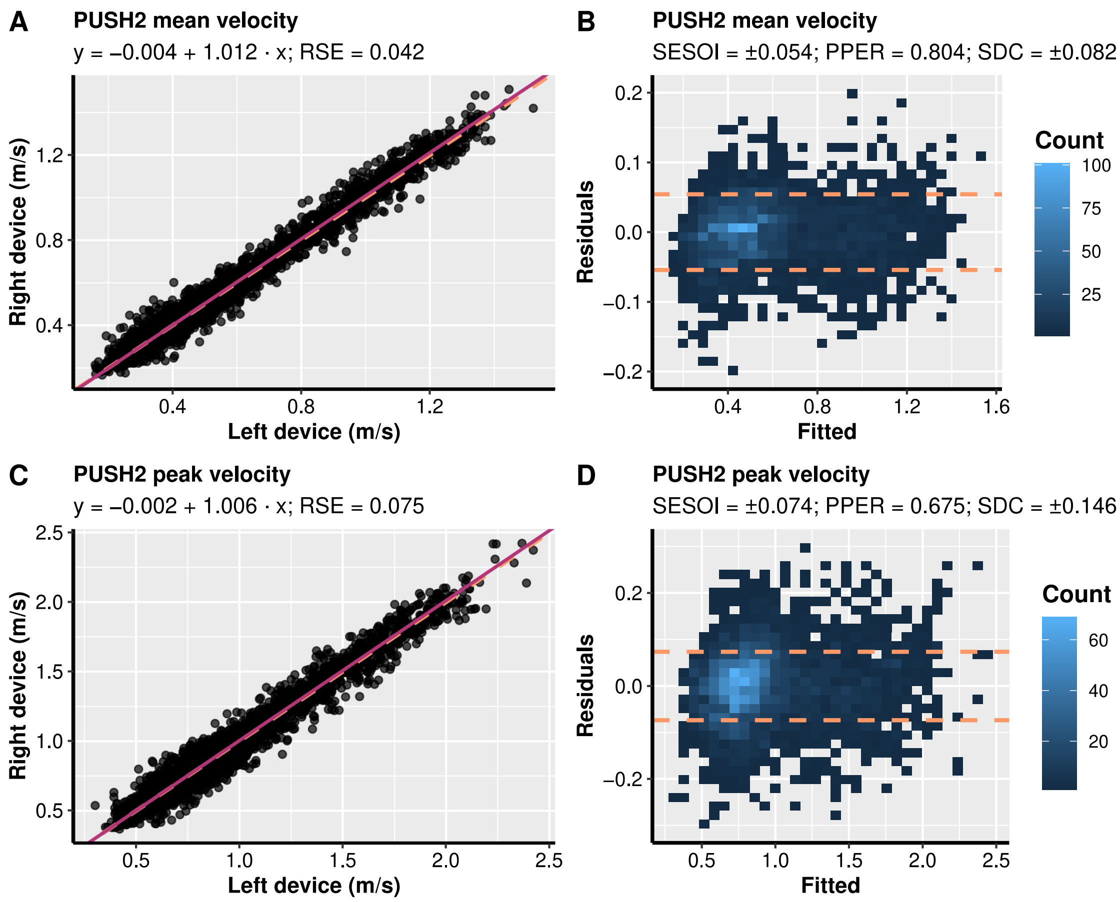
Figure 3-2 Scatterplots between left and right units (A and C) and ordinary least product (OLP) model residuals plots (B and D) for GymAware within-units comparisons. Left-hand panels show the identity line (orange dashed line) and OLP model prediction (magenta solid line). Ordinary least product model intercept (fixed bias), slope (proportional bias), and residual standard error (RSE) are listed in each panel. The residuals plot depicts a scatterplot between model fit on the x-axis and model residuals on the y-axis. The smallest effect size of interest (SESOI) area is surrounded by orange dashed lines. The proportion of practically equivalent residuals (PPER) represents the proportions of residuals that are within SESOI limits.



Note. SDC, smallest detectable change.

For the PUSH2 devices, statistically significant fixed and proportional bias were observed for MV (intercept = -0.004 m/s, 95% CI [-0.007, 0]; slope = 1.012, 95% CI [1.006, 1.018]; Figure 3-3) but not PV (intercept = -0.002 m/s, 95% CI [-0.009, 0.005]; slope = 1.006, 95% CI [0.999, 1.014]; Figure 3-3). However, since the confidence intervals for the MV intercept were within the SESOI limits (SESOI = ±0.054 m/s) and considering that the confidence intervals were extremely narrow and very close to the value of 0 and 1 for intercept and slope, respectively, this difference could be considered practically irrelevant. SDC for both MV (0.082 m/s) and PV (0.146 m/s) were outside the SESOI limits for the PUSH2 devices (SESOI = ±0.054 m/s for MV; and SESOI = ±0.074 m/s for PV) which resulted in SDC%1RM also being above SESOI of 5% (SDC%1RM ≥ 6.687%). Overall, while both MV and PV of PUSH2 devices do not seem to be affected by fixed and proportional bias, they do, however, possess higher SDC than the *a priori* selected load SESOI of 5%, especially PV.

Figure 3-3 Scatterplots between left and right units (A and C) and ordinary least product (OLP) model residuals plots (B and D) for PUSH2 within-units comparisons. Left-hand panels show the identity line (orange dashed line) and OLP model prediction (magenta solid line). Ordinary least product model intercept (fixed bias), slope (proportional bias), and residual standard error (RSE) are listed in each panel. The residuals plot depicts a scatterplot between model fit on the x-axis and model residuals on the y-axis. The smallest effect size of interest (SESOI) area is surrounded by orange dashed lines. The proportion of practically equivalent residuals (PPER) represents the proportions of residuals that are within SESOI limits.



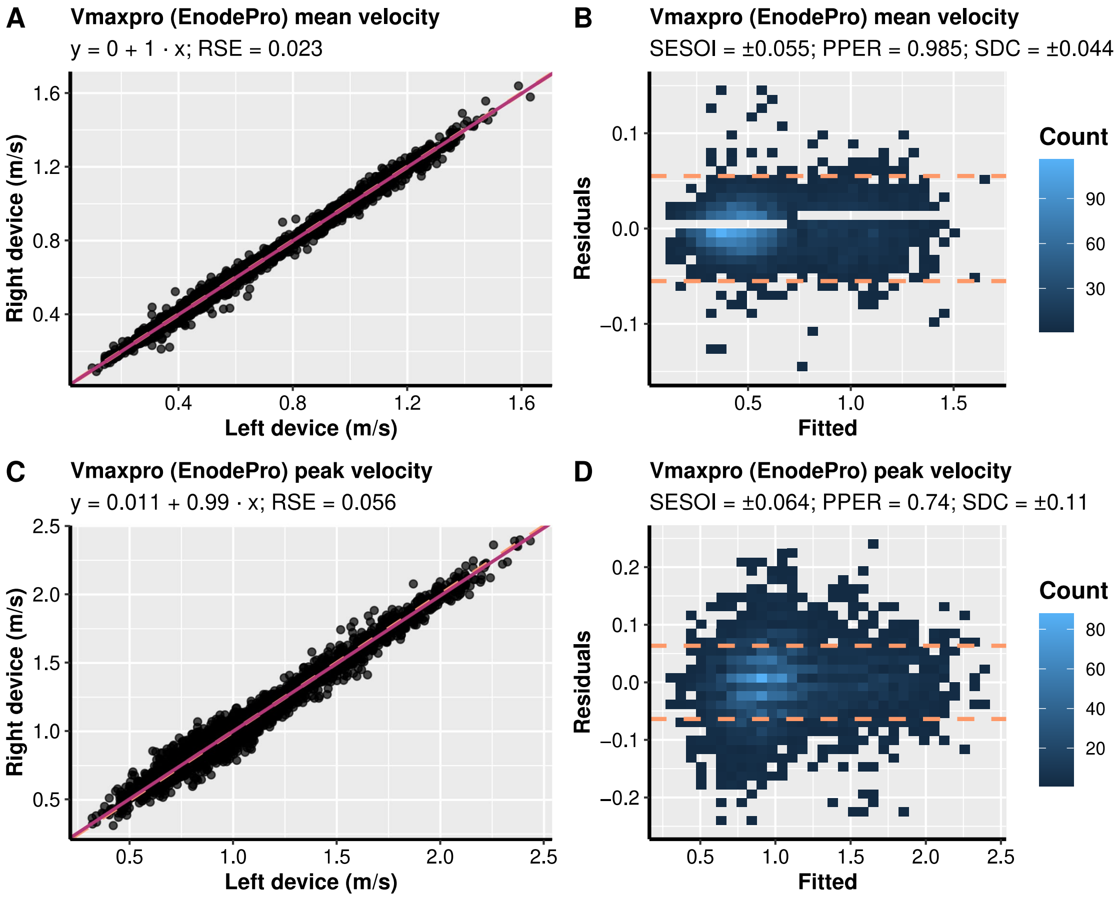
Note. SDC, smallest detectable change.

For the Vmaxpro devices, statistically significant fixed and proportional bias were observed for PV (intercept = 0.011 m/s, 95% CI [0.005, 0.017]; slope = 0.99, 95% CI

[0.986, 0.995]; Figure 3-4), but not MV (intercept = 0 m/s, 95% CI [-0.002, 0.001]; slope = 1, 95% CI [0.996, 1.003]; Figure 3-4). However, since the confidence intervals were within the SESOI limits (SESOI = ±0.062 m/s) for the PV intercept and considering that the confidence intervals were extremely narrow and very close to the value of 0 and 1 for intercept and slope, respectively, this difference could be considered practically irrelevant. SDC for MV was also within the SESOI limits for the Vmaxpro devices (SDC = 0.044 m/s). This was reflected by the SDC%1RM which was lower than the *a priori* selected load SESOI of 5% 1RM (SDC%1RM = 3.607%). In addition, SDC for PV was outside SESOI limits (SDC = 0.11 m/s) which resulted in SDC%1RM also being above SESOI of 5% (SDC%1RM = 6.907 %). Overall, both MV and PV of Vmaxpro devices do not seem to be affected by fixed and proportional bias. However, only MV showed perfect within-device agreement since PV displayed higher SDC than the *a priori* selected load SESOI of 5%.

The relative reliability (i.e., ICCs) of all devices, as well as their concordance (i.e., CCC), was good to excellent, whereas absolute reliability (i.e., CVs) was lower for PUSH2 compared to GymAware and Vmaxpro, and higher than the acceptable threshold of 5% (Table 3-1). The null hypothesis for the equivalence of MV of repetitions recorded by the left and right devices was rejected for GymAware and Vmaxpro, but not PUSH2 devices since the 1–2α confidence intervals of LoA were completely within the ± equivalent margin of 0.06 m/s (Figure 3-5; Table 3-1). For PV, the null hypothesis for the equivalence was only rejected for GymAware devices due to 1–2α confidence intervals of LoA being completely within the ± 0.11 m/s margin of equivalence, as opposed to the other two devices (Figure 3-6; Table 3-1).

Figure 3-4 Scatterplots between left and right units (A and C) and ordinary least product (OLP) model residuals plots (B and D) for Vmaxpro (alias, EnodePro) within-units comparisons. Left-hand panels show the identity line (orange dashed line) and OLP model prediction (magenta solid line). Ordinary least product model intercept (fixed bias), slope (proportional bias), and residual standard error (RSE) are listed in each panel. The residuals plot depicts a scatterplot between model fit on the x-axis and model residuals on the y-axis. The smallest effect size of interest (SESOI) area is surrounded by orange dashed lines. The proportion of practically equivalent residuals (PPER) represents the proportions of residuals that are within SESOI limits.



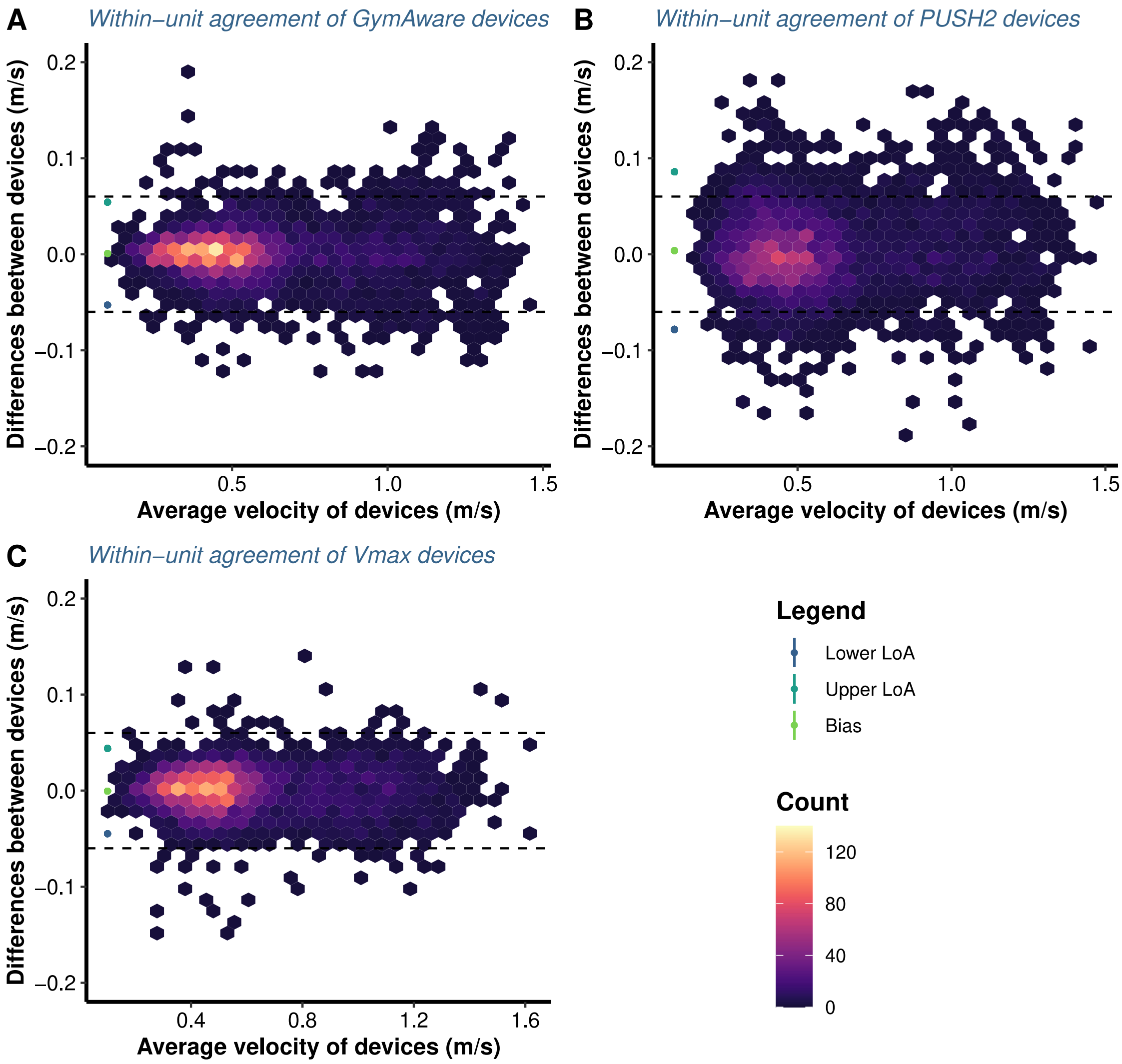
Note. SDC, smallest detectable change.

Table 3-1 Estimates of complementary statistical parameters and parameters estimated by Bland-Altman analysis with 95% confidence intervals.

Device	Variable	CV	ICC	CCC	Bias	Upper LoA	Lower LoA
GymAware	Mean Velocity	3.358 [3.286, 3.433]	0.995 [0.995, 0.995]	0.995 [0.995, 0.995]	0.001 [-0.002, 0.004]	0.054 [0.051, 0.576]	-0.053 [-0.056, 0.050]
	Peak Velocity	3.405 [3.333, 3.482]	0.989 [0.989, 0.990]	0.989 [0.989, 0.990]	0.001 [-0.006, 0.007]	0.102 [0.095, 0.109]	-0.100 [-0.108, -0.094]
PUSH2	Mean Velocity	5.141 [5.027, 5.261]	0.987 [0.987, 0.988]	0.987 [0.987, 0.988]	0.004 [0.001, 0.007]	0.086 [0.082, 0.089]	-0.078 [-0.081, -0.074]
	Peak Velocity	5.64 [5.522, 5.780]	0.979 [0.978, 0.980]	0.979 [0.978, 0.980]	0.005 [-0.002, 0.011]	0.150 [0.144, 0.157]	-0.141 [-0.147, -0.134]
Vmaxpro (EnodePro)	Mean Velocity	2.722 [2.663, 2.784]	0.997 [0.996, 0.997]	0.997 [0.996, 0.997]	-0.001 [-0.002, 0.002]	0.044 [0.042, 0.046]	-0.045 [-0.471, -0.042]
	Peak Velocity	3.763 [3.681, 3.848]	0.987 [0.987, 0.988]	0.988 [0.987, 0.988]	0.001 [-0.005, 0.006]	0.112 [0.106, 0.118]	-0.111 [-0.117, -0.106]

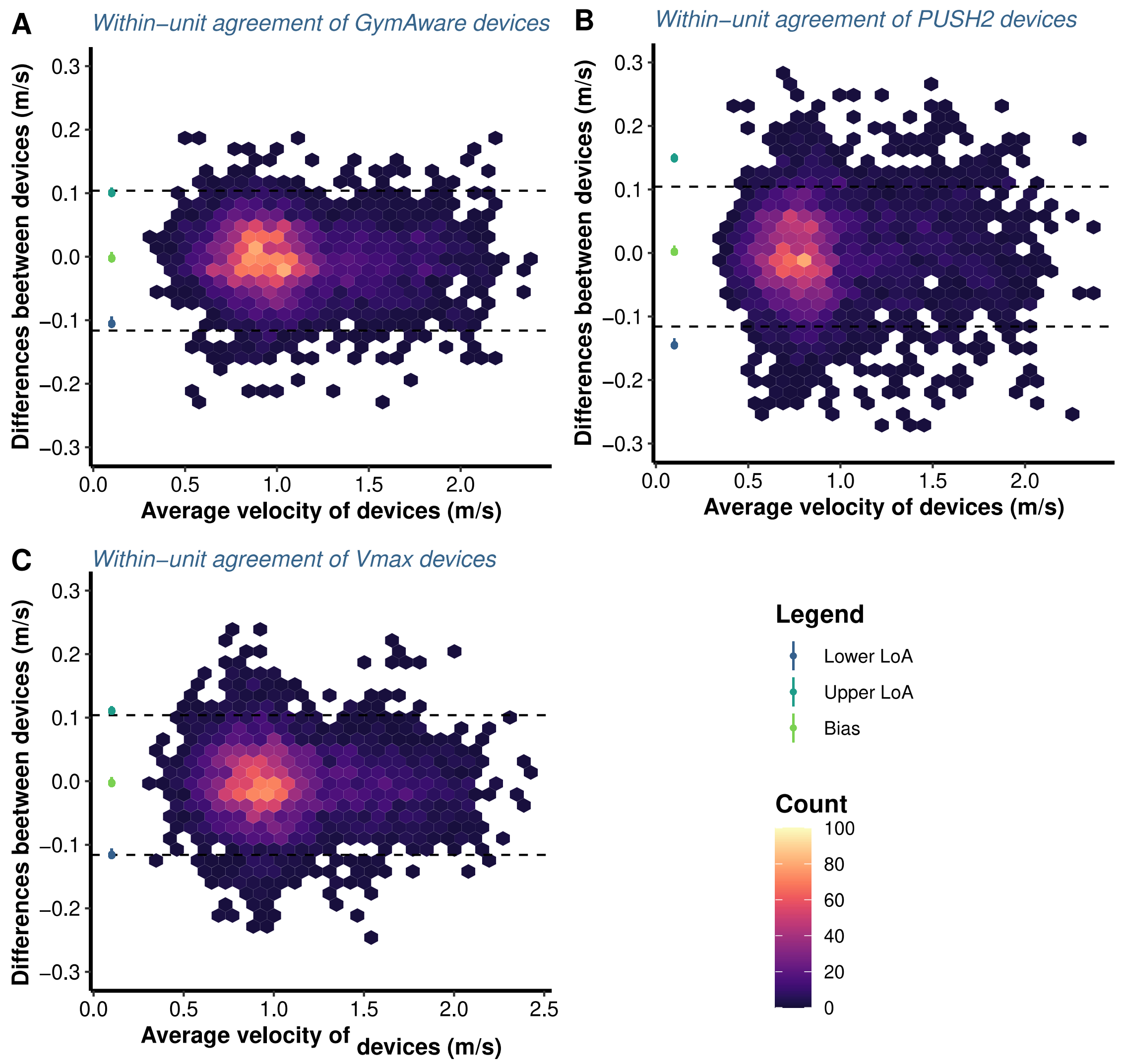
Note. [number, number], confidence interval; CV, coefficient of variation; ICC, intraclass correlation coefficient; CCC, Lin's concordance correlation coefficient; LoA, level of agreement.

Figure 3-5 Bland-Altman plots illustrating the agreement between the repetitions mean velocity for two GymAware (A), PUSH2 (B) and Vmaxpro (alias, EnodePro) devices (C). Dashed lines represent an equivalent margin of ± 0.06 m/s defined as the smallest detectable change in load-velocity profiles during the free-weight back squat exercise.



Note. LoA, limits of agreement

Figure 3-6 Bland-Altman plots illustrating the within-unit agreement between the repetitions peak velocity for two GymAware (A), PUSH2 (B) and Vmaxpro (alias, EnodePro) devices (C). Dashed lines represent an equivalent margin of ± 0.11 m/s defined as the smallest detectable change in load-velocity profiles during the free-weight back squat exercise.



Note. LoA, limits of agreement

3.4 Discussion

To our knowledge, this is the first study that examined the reproducibility of GymAware, PUSH2 and Vmaxpro velocity monitoring devices during the free-weight back squat exercise while also examining their sensitivity for detecting true changes in RT performance. The main findings of this study were 1) fixed and proportional bias was not observed for any of the devices and velocity metrics examined in this study; 2) only MV from GymAware and Vmaxpro, but not PUSH2 devices were sensitive enough to detect true changes in RT performance according to the *a priori* established criteria; 3)

GymAware (MV and PV) and Vmaxpro (MV), but not PUSH2 (neither MV nor PV) devices demonstrated high levels of within-unit agreement (i.e., equivalence) concerning SDC for load-velocity profiles in the free-weigh back squat exercise previously reported in the literature. Collectively, these findings support the use of MV and PV from GymAware LPT and MV from Vmaxpro devices for RT monitoring and prescription due to their low magnitudes of error; thus, allowing for sensible detection of meaningful changes in neuromuscular status and functional performance during RT.

Most of the available studies examining the reliability of velocity monitoring devices including PUSH2 and Vmaxpro have quantified inter-individual or intra-individual variability in movement velocity during the same testing condition (e.g., velocity against the same relative load for all individuals) or during the "same" testing condition separately by a specific amount of time (e.g., 48-72 hours; test-retest reliability), respectively. However, this study design fails to separate biological (i.e., human) and technological variation and, as such, does not reveal any information about the true source of measurement error [132]. When the calibration device is not available, an effective approach to examine devices' reproducibility (i.e., their true technological error) is to simultaneously use two or more devices of the same brand under the same testing conditions [136-138]. This approach was taken in the current study and revealed that GymAware devices possess almost perfect reliability for MV as evidenced by low RSE, high PPER and sensitivity to detect meaningful changes in performance (i.e., SDC%1RM), and the absence of fixed and proportional bias. In comparison, PV from GymAware devices demonstrated small, but practically non-significant fixed and proportional bias, and slightly lower PPER and SDC%1RM. These findings are in partial agreement with the only previous study [138] examining the reproducibility of GymAware while simultaneously using two devices under the same testing conditions. More specifically, Jovanovic & Jukic [138] found PV from GymAware to be a more sensitive metric compared to MV in detecting changes in performance during the hex-bar deadlift exercise, although both velocity metrics were found to be highly sensitive and reliable. It is important to highlight that although PV from GymAware was less sensitive than MV in the present study, it was still sensitive enough to detect meaningful changes in RT performance. Namely, when investigating the equivalence of PV recorded by two GymAware devices, upper and lower LoA were within the lowest SDC for the individualised load-velocity profiles reported by Banyard et al. [28] during the free-weight back squat exercise. Therefore, it can be concluded that both MV and PV from GymAware are reliable and sensitive to detecting meaningful changes in neuromuscular status and functional performance during the free-weight back squat exercise.

In the present study, fixed and proportional bias was not an issue for *body mode* PUSH2 devices. However, somewhat higher RSE, PPER and SDC%1RM compared to GymAware – especially for MV – and *a priori* established criteria, suggest that caution should be exercised when using PUSH2 devices in practical settings. In the previous study [138], where the reproducibility of *bar mode* PUSH2 devices was examined, the authors reported worse RSE, PPER, and SDC%1RM than those observed in the present study for the PUSH2 device. Therefore, although the reproducibility of *body mode* PUSH2 devices examined in the present study was unacceptable, reproducibility was greater than for previously reported *bar mode* PUSH2 devices. It is important to note that several software updates may have played a bigger role in the improved reproducibility of the PUSH2 devices observed in the present study compared to the differences between the *body* and *bar mode* of PUSH2 devices. Furthermore, we also observed a lack of agreement for both MV and PV between two PUSH2 devices concerning the SDC of the individualised load-velocity profiles in the free-weight back squat exercise. Therefore, while substantial fixed and proportional bias were not present for PUSH2 devices, they do seem to possess a considerable amount of random error which negatively affects their sensitivity in detecting practically relevant changes in performance regardless of the velocity metric used. Nevertheless, it should be noted that MV from PUSH2 had a reasonably high PPER and low SDC%1RM, suggesting that practitioners who are only interested in detecting changes in performance greater than ~ 7% 1RM could still benefit from using PUSH2 devices. Though, caution should again be exercised when using these devices for monitoring neuromuscular status or terminating training sets based on velocity loss.

For Vmaxpro devices, neither fixed nor proportional bias was observed in the present study. Importantly, very low RSE and SDC%1RM, and high PPER were observed for MV. Interestingly, these values for RSE, SDC%1RM, and PPER were superior in comparison to GymAware and PUSH2 devices. In addition, MV between the two Vmaxpro devices was highly equivalent concerning SDC in load-velocity profiles suggesting their sensitivity in detecting very small changes in performance. However, RSE and SDC%1RM for PV were twice as high compared to MV of this device, but still slightly superior to those of PUSH2, but not GymAware devices. This finding was further reflected by the equivalence analysis for PV of Vmaxpro where upper and lower LoA always sat just outside (~ 0.007 m/s) the practically equivalent margin of ±0.11 m/s which corresponds to a real change in daily readiness to train during the free-weight back squat exercise when assessed by PV [28]. Therefore, MV from Vmaxpro devices can be used for RT monitoring, prescription, and performance evaluation, whereas caution should be exercised when using PV from Vmaxpro as it does not seem to be sensitive enough to detect the smallest changes in performance that could be relevant in practical settings.

Traditional interpretations of correlations and linear relationship coefficients (i.e., values > 0.90 as very high) previously failed to confirm devices' reliability [136, 137]. Similarly, MV and PV between pairs of the same device in the present study all showed high *r* values (i.e., ~ 0.98). However, this just means that the faster the movement on the first device, the faster the movement on the second device, giving no information about the magnitude of errors in absolute values. Since velocity monitoring devices, among other purposes, are used to establish the load-velocity profiles for the individuals it is crucial to evaluate their magnitudes of error in both absolute (i.e., m/s) and relative, practical terms (i.e., %1RM), as done in the present study. Furthermore, for the assessment of technological variability stricter criteria than previously used should be adopted, as recently recommended by Courel et al. [136]. For instance, if one considers CV values of < 10% and ICC values > 0.90 to represent good reliability of a given device, then one also must accept the remaining 10% error in the measurement. While these criteria could be seen as more than rigorous in social sciences, it is not enough for the assessment of technological devices. In this regard, Courel et al. [136] suggested ICC > 0.99, CV < 3.5%, RSE < 0.03 m/s for velocity monitoring devices to be considered reliable and possess acceptable sensitivity. Following these recommendations, only MV and PV from GymAware and MV from Vmaxpro can be used for RT monitoring and prescription, as previously concluded based on other statistical parameters provided in the present study. Finally, future research should also consider evaluating a wide range of statistical parameters rather than relying on traditional correlation, CV, and ICC coefficients to provide more nuanced insights into the reliability and sensitivity of velocity monitoring devices.

The present study is the first to examine the reproducibility of GymAware, *body mode* PUSH2 and Vmapro devices during the free-weight back squat exercise while evaluating and interpreting the magnitudes of errors according to pre-established, practical criteria. A relatively large number of males and females with different training backgrounds and experience levels performed ecologically valid RT sets with a range of different loads and repetition ranges. However, it should be noted that the validity of these devices was not evaluated in the current study due to the absence of a gold standard (i.e., the MOCAP system). In addition, the validity of GymAware, PUSH2 and Vmaxpro devices has been examined in previous studies using different approaches with conflicting findings reported, especially for PUSH2 and Vmaxpro devices [134, 135]. Therefore, future research is required to comprehensively examine the validity of these devices. Nevertheless, if the reproducibility and sensitivity of a given device are proven sound, the practitioners can be confident that the measurements are sensitive enough to detect practically meaningful changes in barbell velocity. While we aimed to isolate technological error by simultaneously using two devices of the same brand under the same testing conditions, it must be noted that a biological source of error could still be introduced in this setting if any side-to-side differences in the displacement of the ends of the barbell occur during free-weight RT exercises. To our knowledge, no study has quantified the effects of the barbell dip on the magnitude of this error. Therefore, it cannot be determined whether this affected the reproducibility and sensitivity analyses of the devices examined in the present study. Nevertheless, to circumvent the potential limitation of simultaneously using two devices of the same brand under the same testing conditions to examine their reproducibility and sensitivity, we recommend future researchers change the devices' position to the opposite end of the barbell after each set. Finally, it should be noted that manufacturers of velocity monitoring devices are very frequently releasing new software updates for devices and increasing the accuracy and stability of the algorithms used. This further suggests that the reproducibility of devices should be examined regularly to ensure that the measurements obtained are reliable and sensitive enough for the intended purpose.

3.5 Conclusion

The findings of the present study suggest that GymAware is highly reproducible and sensitive in detecting the smallest changes in RT performance, regardless of the velocity metric used. Vmaxpro can be considered as an equivalent, cheaper alternative to GymAware, but only if the MV metric is used for RT monitoring and prescription since PV from Vmaxpro was found to be a slightly less sensitive metric compared to PV from GymAware. Caution should be exercised when using PUSH2 devices in practice due to their comparatively higher, unacceptable measurement error and generally low sensitivity to detecting meaningful changes in neuromuscular status and functional performance during a free-weight back squat exercise.

Chapter 4: One velocity loss threshold does not fit all: consideration of sex, training status, history, and personality traits when monitoring and controlling fatigue during resistance training

Preface

In Chapter 2, the disagreement was highlighted in the literature as to whether different velocity loss (VL) thresholds modulate resistance training-induced adaptations in a dose-response fashion, considering studies that matched training volume between different VL thresholds found no differences in training adaptations. This questions the idea that the amount of VL allowed during a set – and not the volume of work completed – is what matters the most for inducing neuromuscular adaptations, and therefore VL thresholds' utility for prescribing resistance training volume. To further confound matters, other factors such as sex, training status and history and psychological traits of individuals could also affect the individual responses to different VL thresholds but have not yet been examined to date. Given that VL thresholds are used to control intra-set fatigue and prescribe training volume, it may be that individuals with distinct characteristics might respond differently to the same VL threshold, potentially leading to divergent long-term neuromuscular adaptations. Therefore, the following chapter quantified the variability in the volume of work completed after reaching different VL thresholds on two testing sessions and determined the effects of sex, training status and history, as well as psychological traits on the amount of work completed after reaching different VL thresholds using different loads in the free-weight back squat exercise.

This Chapter is under review in *Sports Medicine – Open* journal.

4.1 Introduction

Resistance training (RT) is widely recognised as an effective and efficient mode of training for stimulating a vast array of neuromuscular adaptations. There are many variables that play a part in designing an efficacious RT program such as training load, volume and frequency, rest periods, exercise type, movement velocity, and set structure configuration, among others [2]. Of these, training volume has received more attention from the scientific community and it is often seen as one of the key drivers of RT-induced adaptations such as muscle strength and hypertrophy [3, 34]. Traditionally, RT set volume is prescribed according to a theoretical maximum number of repetitions that can be performed against a given percentage of one-repetition maximum (%1RM) until reaching muscular failure (e.g., 10 repetitions with 75% of 1RM). Based on this, a specific number of repetitions is often prescribed for a group of individuals using the same relative load for all exercises. However, this method of prescribing RT volume might not provide the planned training stimulus for all individuals since the number of repetitions that can be completed against a given %1RM is both individual- and exercise-specific [12, 15]. For instance, if all individuals perform the same number of repetitions per set against the same relative load, it is possible that they will experience different degrees of fatigue upon completing a set, as the number of repetitions left in reserve could be considerably different between individuals. To combat these issues, instead of performing a fixed, predetermined number of repetitions, researchers have suggested terminating each training set as soon as a predetermined percentage of velocity loss (VL) is reached [15, 14].

Several studies have shown that monitoring repetition velocity is an objective, practical and non-invasive indicator of the acute metabolic stress, hormonal response and mechanical fatigue induced by RT [141, 142]. In this regard, it has been suggested that monitoring VL across sets could serve as a precise method of quantifying the level of effort (i.e., repetitions performed with respect to the maximum number that can be completed) [15]. Indeed, recent studies have reported strong relationships between the VL experienced in a set and the percentage of performed repetitions with respect to the maximum number that can be completed in bench press and back squat exercises with different loads [14, 39]. In one study [14], it was also observed that the percentage of performed repetitions for a given magnitude of VL was very similar for all loads used, especially for those ranging between 50 and 70% 1RM, although the maximum number of repetitions completed against each relative load was significantly different. While this implies that VL should indeed be used to monitor and modify RT volume, it is important to acknowledge that the actual number of repetitions performed (i.e., volume of work) until reaching different VL thresholds was comparatively neglected as a consideration.

Many longitudinal studies compared the effectiveness of different VL thresholds on muscle strength, hypertrophy, and endurance as well as performance of athletic tasks. While the researchers generally concluded that the selected VL threshold can modulate these adaptations to training in a dose-response fashion [46, 47] , only two studies to date matched the training volume between different VL thresholds [49, 50]. More specifically, when the training volume was matched between different VL thresholds, researchers reported no significant differences in the effectiveness of lower and higher VL thresholds at inducing muscle strength and hypertrophy adaptations as well as improving performance of athletic tasks [50, 49]. This questions both the idea that the amount of VL allowed during a set – and not the volume of work completed – is what matters the most for inducing neuromuscular adaptations, and the usefulness of VL thresholds for prescribing RT volume. While the drawbacks of traditional methods of prescribing RT volume are often evidenced by the inter-individual variability in how many repetitions one can do until failure in each exercise and load, the VL method may suffer from the same problem. Furthermore, the relationship between VL and the number of repetitions performed might not be linear for all individuals. Specifically, some might perform multiple repetitions within a given VL threshold further contributing to the variability in the amount of work across individuals. In addition, it is likely that not all individuals can reach the same VL thresholds, especially higher ones (e.g., 50% VL), due to their characteristics, training status and history. Although plausible, this is purely speculative as it has not been thoroughly examined to date.

Previously, researchers have reported that sex, training status (e.g., strength levels) and history should all be considered when designing a RT program and monitoring changes in neuromuscular function [12, 20, 21]. Thus, it can be hypothesised that these factors could also affect the individual responses to different VL thresholds. Personality traits could be another influential factor when it comes to implementing VL thresholds in practice. For instance, emotional stability and conscientiousness have been associated with fatigue tolerance [143, 22]. Neuroticism – a trait on the opposite spectrum of emotional stability – represents the propensity to experience negative emotions and distress [144], and as such may lead to a decreased tolerance for fatigue during exercise. Conversely, conscientiousness represents the propensity to be persistent and self-controlled [144], and as such may enhance an individual's ability to tolerate fatigue during exercise. This could be particularly relevant during resistance training whereby repetitions are performed with maximal intent and to (or near) muscle failure. Hypothetically, individuals who score higher on neuroticism (or lower on emotional stability) could perform less work and quit sooner during a heavy RT set due to their reduced ability to cope with fatigue. Similarly, performing the concentric phase of the lift with maximal intent might be another hurdle for those individuals. In contrast, individuals high in conscientiousness could leverage their persistence to complete the task while giving their absolute best (e.g., doing more repetitions during a heavy RT set and lifting with maximal intent). Given that VL thresholds are used to control intra-set fatigue and prescribe training volume, it may be that individuals with distinct personality traits might respond differently to the same VL threshold, potentially leading to divergent long-term neuromuscular adaptations. Finally, the reliability of the amount of work completed after reaching different VL thresholds has not been thoroughly examined despite this method being widely used in practice. For example, knowing whether an individual who performs a given number of repetitions before reaching a given VL threshold in one training session will then perform the same number of repetitions before reaching that VL threshold a few days later, is critically important.

In light of these considerations and scarcity in the literature, an examination of the variability associated with different VL thresholds, and the influential factors associated with it is clearly needed. Therefore, the purpose of this study was to quantify the potential variability in the volume of work completed after reaching different VL thresholds and determine the effects of sex, training status and history, as well as personality traits on the reliability and magnitude of the amount of work completed after reaching different VL thresholds using different loads in the back squat exercise. Based on the findings from previous longitudinal studies on the topic that matched VL threshold for training volume [49, 50], it was hypothesised that there would be notable variability in the volume of work completed across VL thresholds, which could at least partially be explained by some of the above-mentioned factors.

4.2 Methods

4.2.1 Design

This study is a part of a larger project investigating the reliability of different velocity-based RT monitoring and prescription methodologies. Participants reported to the laboratory on four occasions with 48-72 hours of rest between the sessions. After familiarisation with the free-weight back squat movement, and all the equipment and instruments, instructions to move the barbell up as fast as they can, and feedback on the screen indicating the velocity of the barbell, participants performed an incremental loading (i.e., 1RM) test in the back squat exercise. In the next two sessions, participants completed repetitions to failure (RTF) tests in the same exercise with 90, 80, and 70% of their established 1RM. Importantly, each participant performed all sessions at the same time of the day (± 1 hour) to control for diurnal variation. In addition, the same researchers were always present throughout all testing sessions for each participant and laboratory environment was kept the same (e.g., temperature and humidity) to avoid potential effects of these factors on performance throughout testing sessions.

4.2.2 Participants

Fifty-one strength-trained people (15 females and 36 males; 18 to 40 years of age) participated in this study. Three male participants withdrew from the study due to injuries during their work or recreational sporting activity not related to the study, whereas two male participants dropped out of the study due to private reasons after completing one and three experimental sessions. Participants without a full data set were not analysed since the primary aim was to determine the reliability of the number of repetitions performed until reaching different VL. The relative strength – expressed as 1RM to body mass ratio – in the free-weight back squat exercise was 1.25 ± 0.30 and 1.79 ± 0.35 for females and males, respectively. To participate, participants had to confirm they 1) were willing to abstain from any additional lower-body training during the study; 2) were not currently taking medication that would alter metabolic or cardiovascular functions; 3) had no musculoskeletal limitations; 4) were not currently using anabolic steroids or had a history of use; and 5) had at least 6 months of RT experience training at least 2x/week including the back squat exercise at least 1x/week, with no longer than 2 weeks in a row off training during that period. Each participant gave written informed consent before starting the study. The protocol of this study was in accordance with the ethical requirements of the University Ethics Committee (approval number: 20/55), and The Code of Ethics of the World Medical Association.

4.2.3 Familiarisation session

Upon arriving to the laboratory, participants first completed a questionnaire to better understand their training history and usual practices when it comes to RT (Appendix F Ch. 4 File I). Next, participants' body mass and height were recorded using an electronic column scale and a wall mounted stadiometer (Seca Ltd., Hamburg, Germany). Participants then completed a standardised warm-up consisting of cycling at 100 rpm for 5 min, dynamic stretching for 2 min, 10 bodyweight lunges and squats, as well as 10 barbell squats. Thereafter, participants were familiarised with the instruction to lift the barbell up as fast as they can (during the concentric muscle action), feedback on the screen indicating velocity of the barbell, and the instruction to have at least a momentary pause at the top of the movement not lasting longer than 2 seconds between repetitions with feet maintaining contact with the floor (i.e., no jumping or lifting of the heels) at all times. To ensure familiarity with these instructions and general conditions in which they were required to perform 1RM and RTF tests, participants then completed 3 repetitions at 20, 40, and 60% of their estimated 1RM, and then 10 repetitions at 60% of their estimated 1RM. During these repetitions, participants were instructed to lift the barbell up as fast as they can and avoid pausing more than 2 seconds at the top of the movement (i.e., standing phase of the squat) while also receiving visual feedback indicating the velocity of the barbell. At the end of each session, all participants understood and felt comfortable with these conditions, and performed at least two sets with consistent repetition velocities (± 0.02 m/s). Participants were also asked to provide logs of their most recent (and heaviest) back squat sessions and to conservatively estimate their 1RM. This information was used to establish warm-up loads for the upcoming 1RM sessions.

4.2.4 One repetition maximum session: Day 2

Prior to the 1RM assessments, participants completed the same standardised warm-up as in the familiarisation session. The 1RM assessment was performed using a 20-kg barbell (Rogue, Columbus, Ohio, USA) and calibrated weight plates (Eleiko; Halmstad, Sweden, EU). The 1RM protocol consisted of 3 repetitions each at 20, 40, and 60%, and 1 repetition at 80, and 90% of an estimated 1RM, followed by 1RM attempts. After each successful attempt, the load was increased in consultation with the participant from 1 to 12.5 kg until no further weight could be lifted or until movement technique was compromised. In addition, a maximum of five 1RM attempts were allowed for each participant. Three and four minutes of passive rest were provided between each submaximal set and 1RM attempts, respectively. To ensure natural squatting patterns, each participant adopted a shoulder width stance and used a self-regulated eccentric velocity; immediately upon reaching the bottom of their squat, participants were instructed to perform the concentric (upward) portion of each repetition as fast as possible. Strong verbal encouragement and visual feedback were provided throughout all trials. Participants were required to reach a depth of the squat at which the top of the thighs was at least parallel to the floor, as determined by the investigators and a camera positioned perpendicularly to the participant, for a repetition to be considered successful.

4.2.5 Repetitions to failure sessions: Days 3 and 4

The same standardised warm-up as in the familiarisation and 1RM sessions was performed during the RTF sessions. Thereafter, participants completed four sets of 10, 5, 3, and 1 repetition of the free-weight back squat exercise against 30, 50, 70, and 90% of the 90% of their established 1RM (i.e., the heaviest load to be lifted that day). They were provided with 3 minutes of rest between warm-up sets, and 4 minutes between the last warm-up set and the first set to failure. After the general and specific warm-up, participants performed three sets with 90, 80 and 70% 1RM respectively, to failure with 10 minutes of rest between sets. Since the excessive fatigue from performing a high number of repetitions during RTF with lower loads (i.e., 70% 1RM) could have compromised the number of repetitions performed during subsequent RTF sets with greater loads (i.e., 80 and 90% of 1RM), the loads were not tested in a randomised fashion. Instead, participants always performed RTF with the highest load (i.e., 90%

1RM) first while the last RTF set was always performed with the lowest load (i.e., 70% 1RM). With regards to the exercise execution (including lifting instructions, encouragement, and visual feedback), the same conditions applied as during the 1RM session. The rest between two successive RTF sessions was 72 hours.

4.2.6 Data acquisition

The questionnaire pertaining to the training history and practices of participants is described in Appendix F Ch 4 File I. Briefly, the questions were related to the 1) number of repetitions participants perform during their own training, on average; 2) the intensity of load at which participants train, on average; 3) the number of repetitions left in reserve after completing their training sets, on average; and 4) the experience they have with RT, in years. These questions were multiple-choice; hence the responses were treated as categorical. After inspecting frequencies of responses for each category (both overall and within levels of outcome variables used in models), these variables were recoded by merging some response options to avoid having less than 5 responses in more than 20% of cells/categories [145]. In particular, the number of repetitions performed was transformed into a categorical variable with three levels (1–5, 5–8, >8), as well as was the intensity of load (<70, 70–80, 80–90), whereas the number of repetitions left in reserve and the experience with RT were transformed into categorical variables with two levels (0–2 and 2–4; ≤3 and >3, respectively).

Mean velocity of all the repetitions was recorded using the GymAware (manufacturer) linear position transducer (LPT). The GymAware is a commercially available LPT consisting of a power tool, made up of a steel cable that is wound on a cylindrical spool coupled to the shaft of an optical encoder. The power tool units were placed on both sides of the barbell perpendicular to the position between the hands and the loaded barbell sleeves, according to the manufacturer's instructions. The end of the cable was vertically attached to the barbell using a Velcro strap. The LPT of the current study measures the total displacement of its cable in response to changes in the barbell position and incorporates an angle sensor that accounts for motion in the horizontal direction during predominantly vertical displacement measurements. The software later accounts for the total distance and angle, and using basic trigonometry, provides a resultant vertical displacement. Instantaneous velocity was determined as the change in barbell position with respect to time, which is also provided by the LPT's software.

Data obtained from the LPT were transmitted via Bluetooth to a tablet (iPad, Apple Inc., California, USA) using the GymAware v2.8.0 app. The LPT attached to the right side of the barbell was connected to the TV and provided visual feedback indicating velocity of the barbell after each repetition. The data from this LPT was used for the analysis. Finally, to avoid any data loss due to issues with online clouds or the internet connection, mean velocity of all repetitions was manually recorded and organised in the Microsoft Excel spreadsheet (Microsoft Corporation, Redmond, Washington, USA) during each session. To ensure consistency and accuracy of this procedure, the same two researchers handled this task throughout the study.

The 50-item International Personality Item Pool (IPIP) Big Five Personality Inventory was used as a validated form of human personality assessment [146, 147]. The inventory contained 50 questions, 10 for each of the Big Five personality dimensions (Agreeableness, Conscientiousness, Extraversion, Neuroticism, and Openness). The IPIP items were administered with a 5-point, Likert-type scale ranging from 1 (*very inaccurate*) to 5 (*very accurate*) as in the original instrument using Qualtrics survey-building software. The scores for each item were averaged to obtain mean scores across personality dimensions. The participants received a personalised link to the online survey after completing the familiarisation session. For the purposes of the present study, only Conscientiousness and Neuroticism (or Emotional stability) were retained for the analysis.

4.2.7 Statistical Analysis

Individual repetitions and repetitions' velocity across VL thresholds are visualised in Figure 4-1 and Appendix F Ch. 4 File II. The agreement across days between the 1) number of repetitions performed until reaching a given VL threshold (i.e., from <5% to 60%> in 5% increments); and 2) velocity associated with the repetitions when a given threshold was first exceeded was examined. For this purpose, the modified true value varies method of the Bland-Altman analysis for multiple observations per participant [140] was used for each load separately. The bias and associated 95% limits of agreement (LoA) were evaluated and interpreted in the context of an *a priori* specified equivalent margin of ± 2 repetitions and ± 0.06 m/s, for repetitions and velocity of the repetitions, respectively. These criteria were selected since a more than two repetitions difference would not represent an improvement over more traditional RT prescription methods, whereas the smallest detectable change in velocity according to the load-velocity relationship in the free-weight back squat was reported as 0.06 m/s [28]. The confidence intervals for LoA were calculated according to the method of variance estimates recovery (MOVER) method, which considers the repeated measurements taken [148]. In addition, for LoA, equivalence tests were also performed via two one-sided tests (TOST). The TOST procedure was performed with an α-value of 0.1 and a 1—2α confidence interval. The null hypothesis of TOST was that the two values were not equivalent. If the 1–2α confidence interval was completely contained within the ± equivalent margin, the null hypothesis was rejected, and the two datasets (i.e., number of repetitions or velocities associated with a given threshold from day 1 and day 2) were considered equivalent [149]. All assumptions of the Bland-Altman analysis were satisfied.

Linear mixed-effects models with the Gaussian conditional distribution and identity link function were used to examine what affected the number of repetitions performed until reaching a given VL threshold and the velocity associated with the repetitions when a given VL threshold was exceeded for the first time (i.e., outcome measures). For this purpose, the load (3 levels), training experience (2 levels) and practices (2 or 3 levels), relative strength and conscientiousness and emotional stability were all considered as fixed effects.

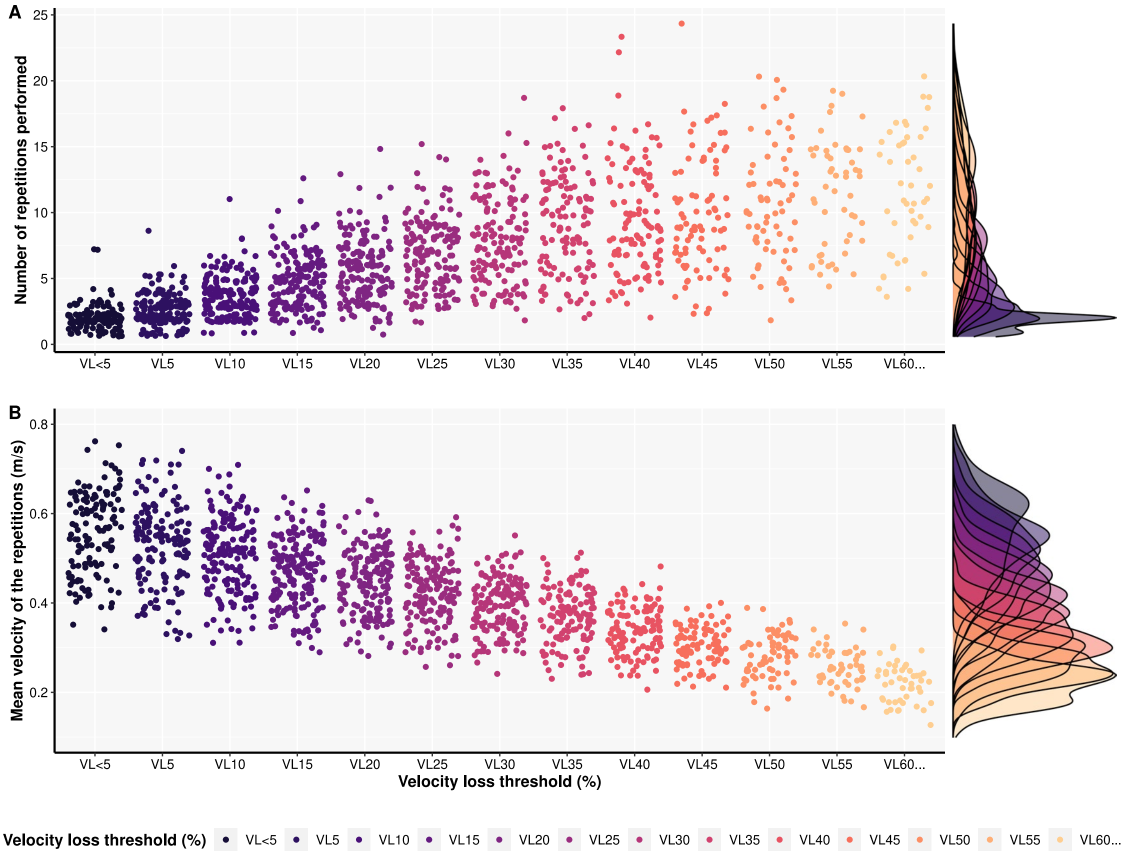
The same approach as described above was also used to investigate 1) factors affecting the probability of not reaching the same VL thresholds in both days among participants; 2) factors explaining whether a participant would perform multiple repetitions within a single VL threshold; and 3) factors affecting the probability of reaching a 50% VL in a set (i.e., the ability to endure low velocity repetitions). However, for all three analyses, generalised linear mixed effects models were used. A binomial conditional distribution was specified with a logit link function to predict the odds of reaching the same VL on both days, performing multiple repetitions within a single VL threshold, and being able to endure a 50% VL in a set.

For all models, participants (n = 46) and VL thresholds (n = 13) were treated as random effects giving rise to cross-classified random effects models, while their interaction was also introduced in the models when their addition did not result in a convergence error and when it improved the model fit. This was done to control for repeated measurements, and the general variation between participants, VL thresholds and participants' performance within certain VL thresholds. Since both fixed and random effects were used, restricted maximum likelihood estimation was used for evaluation of the linear-mixed effects models whereas maximum likelihood, with Laplace approximation, estimation was used for generalised linear mixed-effects models. The contribution of both fixed and random effects to the explanatory power of any of the explored models was examined using a likelihood ratio test, deviance statistic, and Akaike Information Criterion score, before selecting the final model to obtain the best-fit model while maintaining model parsimony. Importantly, the reduction of the model structure was always theoretically motivated and was done as a last resort. Statistical significance of fixed effects was examined by t-tests based on the Satterthwaite approximation or Wald Z-tests for linear mixed-effects and generalised mixed-effects models, respectively. For linear mixed-effects models, estimated marginal means and 95% confidence intervals (95%CI) were calculated and presented whereas for generalised mixed-effects models odds ratios as well as predicted probabilities with associated 95%CI were evaluated and presented to aid interpretation of the findings. For categorical predictors with more than 2 levels, post-hoc tests were performed with Holm-Bonferroni correction. More details on models' specification and diagnostics, as well as software packages used can be found in the Appendix F *Ch. 4 File III*.

To explore whether performing a higher number of repetitions until a given VL threshold results in a higher total number of repetitions performed in a set, Pearson product moment correlations were calculated for 10, 20, 30, and 40% VL across 70, 80, and 90% of 1RM. Prior to this, all data were examined and confirmed for normality via graphical inspection and the indicator value range for skewness and kurtosis [145].

All statistical analyses were conducted using the R language and environment for statistical computing (version 4.2.0, The R foundation for Statistical Computing, Vienna, Austria). Custom-written R script and associated dataset are available at the Open Science Framework repository (URL: https://osf.io/3cnw8/).

Figure 4-1 Visual representation of the number of repetitions (A) and velocity of repetitions associated with the first instance when a given velocity loss threshold was exceeded (B) performed across velocity loss thresholds, loads, and both testing sessions for all individuals.



4.3 Results

The null hypothesis for the equivalence of the number of repetitions performed until reaching a given VL threshold on day 1 and day 2 was not rejected for any of the examined loads since the 1–2α confidence interval of LoA either crossed or were completely outside the ± equivalent margin of 2 repetitions (Figure 4-2). Similarly, the null hypothesis for the equivalence of the mean velocity of repetitions associated with the first instance when a given VL threshold was exceeded on day 1 and day 2 was also not rejected for any of the loads examined due to 1–2α confidence intervals of LoA being completely outside the ± 0.06 m/s margin of equivalence (Figure 4-3).

Figure 4-2 Bland-Altman plots illustrating the agreement between the number of repetitions performed until reaching a given velocity loss threshold on two testing sessions for 70 (A), 80 (B) and 90% of 1RM load (C). Dashed lines represent equivalent margin of ± 2 repetitions whereas LoA represents limits of agreement.

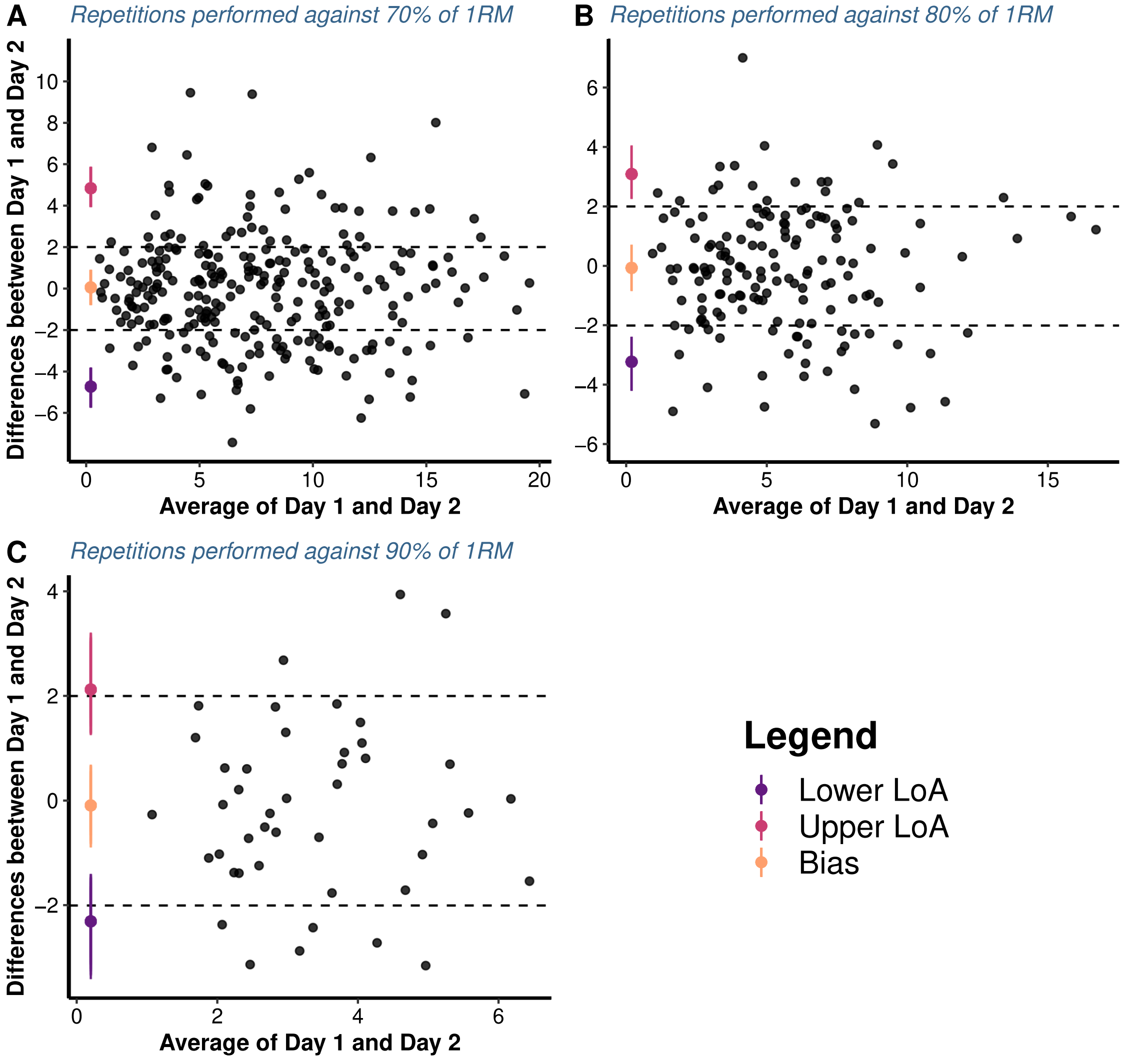
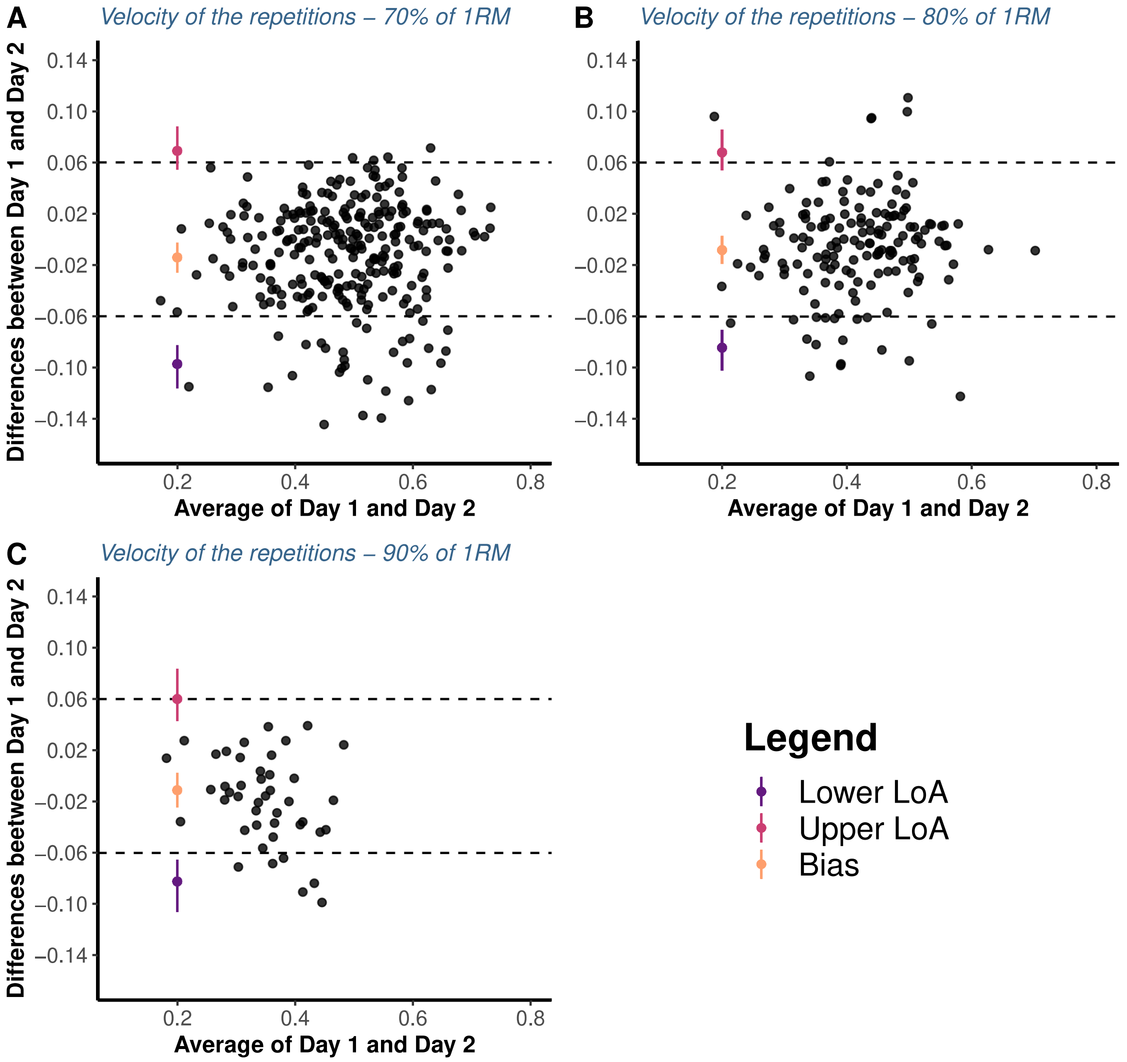
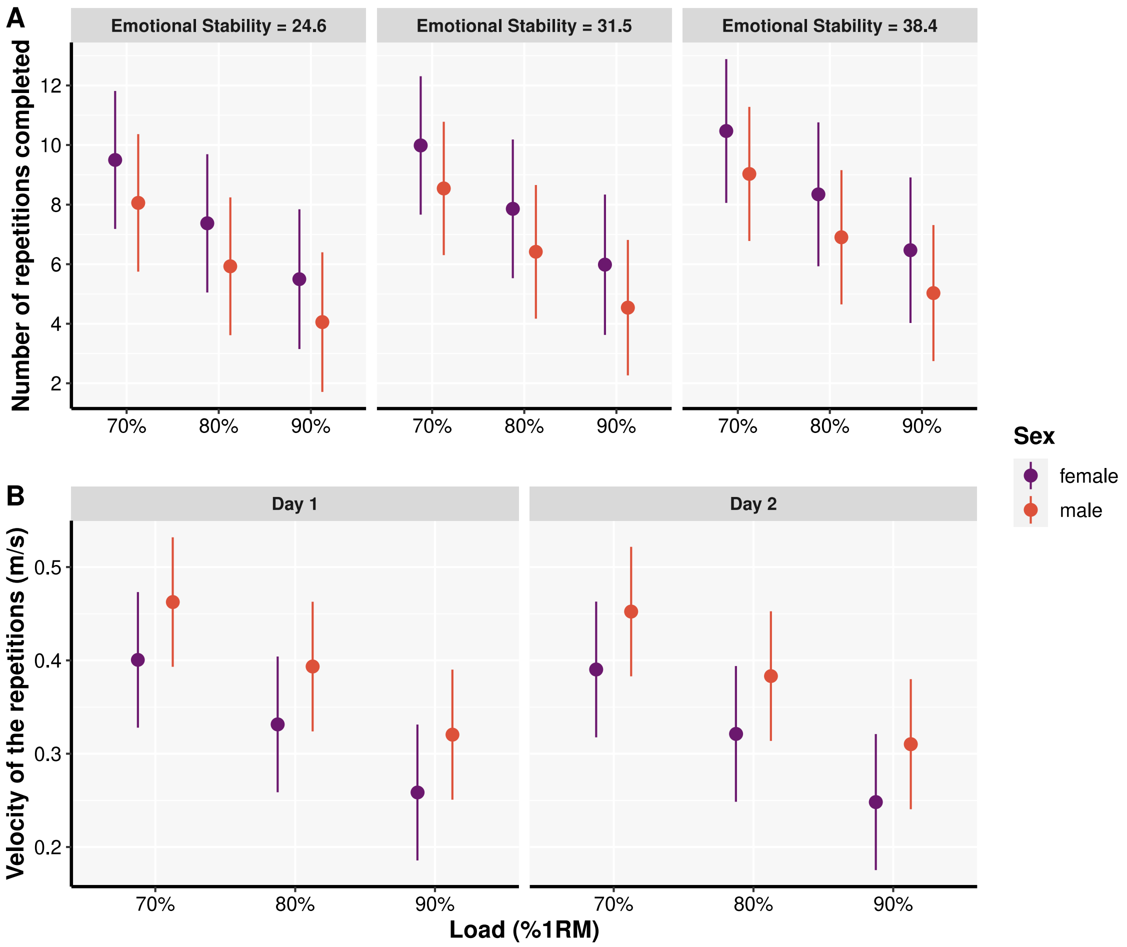


Figure 4-3 Bland-Altman plots illustrating the agreement between the repetitions velocity associated with the first instance a given velocity loss threshold was exceeded on two testing sessions for 70 (A), 80 (B) and 90% of 1RM load (C). Dashed lines represent equivalent margin of ± 0.06 m/s whereas LoA represents limits of agreement.



The number of repetitions performed until reaching a given VL threshold was affected by sex, load, and emotional stability (Table 4-1; Figure 4-4). Females performed more repetitions than males ($p = 0.011$), number of repetitions performed linearly decreased as the load increased ($p < 0.001$; Appendix F Ch. 4 File IV), and number of repetitions performed was higher among people with greater emotional stability. The mean velocity of repetitions associated with a first instance when a given VL threshold was exceeded was affected by day, sex, and load (Table 4-2; Figure 4-4). Males displayed greater mean velocities than females ($p = 0.005$), and mean velocity linearly decreased as the load increased ($p < 0.001$; Appendix F Ch. 4 File IV), and mean velocity of repetitions were generally greater on day 1 compared to day 2 ($p < 0.001$).

Figure 4-4 Estimated marginal means with 95% confidence intervals for the number of repetitions completed across velocity loss thresholds (A) and velocity of repetitions associated with the first instance a given velocity loss threshold was exceeded (B).



Note. For model estimates, please refer to Table 4-1 and Table 4-2, and for pairwise comparisons related to the loading condition please see Appendix F Ch. 4 File IV.

Table 4-1 Factors affecting: 1) number of repetitions performed until reaching a given velocity loss threshold; 2) the velocity of the repetitions associated with the first instance when a given velocity loss threshold was exceeded.

	N of repetitions until reaching velocity loss thresholds			Velocity when first exceeding velocity loss thresholds		
Predictors	Estimates	CI	p	Estimates	CI	p
(Intercept)	6.20	1.83 – 10.56	0.005	0.53	0.37 – 0.68	< 0.001
Day [Day 2]	-0.04	-0.26 – 0.17	0.683	-0.01	-0.01 – -0.01	< 0.001
Sex [male]	-1.44	-2.56 – -0.33	0.011	0.06	0.02 – 0.11	0.005
Load [80% 1RM]	-2.13	-2.39 – -1.86	< 0.001	-0.07	-0.07 – -0.07	< 0.001

Load [90% 1RM]	-4.00	-4.44 – -3.56	< 0.001	-0.14	-0.15 – -0.14	< 0.001
Emotional stability	0.07	0.01 – 0.13	0.027	-0.00	-0.00 – 0.00	0.190
Conscientiousness	-0.00	-0.07 – 0.07	0.925	-0.00	-0.00 – 0.00	0.898
Training experience [> 3 years]	-0.18	-1.05 – 0.70	0.692	-0.00	-0.04 – 0.03	0.872
Repetitions practices [8 – 12]	-0.13	-1.08 – 0.82	0.789	-0.00	-0.04 – 0.04	0.935
Repetitions practices [> 12]	0.26	-0.75 – 1.27	0.610	-0.00	-0.05 – 0.04	0.820
Relative strength (1RM/BM)	1.11	-0.18 – 2.39	0.091	-0.04	-0.09 – 0.01	0.083
Loads practices [70 – 80% 1RM]	-	-	-	0.00	-0.04 – 0.05	0.858
Loads practices [> 80% 1RM]	-	-	-	-0.01	-0.06 – 0.04	0.631
Repetitions in reserve practices [> 2 RIR]	-	-	-	0.01	-0.03 – 0.04	0.693
Random Effects						
σ^2	2.80			0.00		
$\tau_{00\ ID:VL}$	0.95			-		
$\tau_{00\ ID}$	1.34			0.00		
$\tau_{00\ VL}$	15.91			0.01		
ICC	0.87			0.96		
N_{ID}	46			46		
N_{VL}	13			13		
Observations	944			944		
Marginal R^2 / Conditional R^2	0.095 / 0.879			0.131 / 0.965		

Note. Reference groups were the following: Day [Day 1], Sex [female], Load [70% 1RM], Training experience [< 3 years], Repetitions practices [< 8], Loads practices [< 70% 1RM], Repetitions in reserve practices [< 2 RIR]. 1RM, one repetition maximum; BM, body mass; RIR, repetitions in reserve; ICC, interclass-correlation coefficient; R^2, pseudo coefficient of determination; CI, 95% confidence intervals; p, p value.

The model examining factors affecting the probability of not reaching the same VL thresholds on both days among participants revealed only load was an influential factor, with the probability of not reaching the same VL threshold across days linearly decreasing as the load increased ($p < 0.001$; Figure 4-5; Appendix F Ch. 4 File IV).

The model examining factors affecting the probability of doing multiple repetitions within a given VL threshold revealed the load, sex, emotional stability, strength level, repetitions in reserve training history, and number of repetitions typically performed per set were influential factors (Table 4-2; Figure 4-6). Females had a greater probability of doing multiple repetitions within a single VL threshold than males ($p < 0.001$), the probability of doing multiple repetitions linearly increased as load decreased ($p < 0.001$) and was greater for stronger ($p < 0.001$), more emotionally stable participants ($p < 0.001$), and among participants who generally performed a higher number of repetitions ($p = 0.002$) and left 2-4 repetitions left in reserve during their own training ($p < 0.001$).

Table 4-2 Factors affecting whether participants: 1) reached the same velocity loss threshold in two consecutive days; 2) performed multiple repetitions within a single velocity loss threshold; 3) were able to experience 50 % velocity loss within a training set.

	Reaching the same velocity loss threshold on both days			Multiple repetitions within a single velocity loss threshold			Experiencing 50% velocity loss within a set		
Predictors	Odds Ratios	CI	p	Odds Ratios	CI	p	Odds Ratios	CI	p
(Intercept)	0.66	0.11 – 3.83	0.645	0.09	0.03 – 0.31	< 0.001	0.24	0.00 – 59.06	0.609
Sex [male]	1.16	0.69 – 1.95	0.582	0.45	0.31 – 0.66	< 0.001	0.52	0.09 – 3.10	0.477
Load [80% 1RM]	2.43	1.82 – 3.24	< 0.001	0.42	0.33 – 0.54	< 0.001	0.55	0.15 – 1.94	0.351
Load [90% 1RM]	8.10	5.44 – 12.07	< 0.001	0.10	0.07 – 0.16	< 0.001	0.03	0.01 – 0.19	< 0.001
Emotional stability	1.00	0.97 – 1.02	0.751	1.04	1.02 – 1.06	< 0.001	1.17	1.02 – 1.34	0.029
Conscientiousness	1.00	0.97 – 1.03	0.971	1.00	0.98 – 1.02	0.794	0.99	0.87 – 1.13	0.900
Training experience [> 3 years]	0.85	0.57 – 1.28	0.449	0.82	0.61 – 1.09	0.168	-	-	-
Repetitions practices [8 – 12]	0.93	0.59 – 1.47	0.753	0.94	0.68 – 1.31	0.736	-	-	-
Repetitions practices [> 12]	1.14	0.69 – 1.89	0.604	1.78	1.25 – 2.55	0.002	-	-	-
Relative strength (1RM/BM)	1.30	0.73 – 2.33	0.376	2.23	1.47 – 3.40	< 0.001	-	-	-
Loads practices [70 – 80% 1RM]	0.94	0.56 – 1.59	0.824	0.81	0.56 – 1.18	0.273	-	-	-

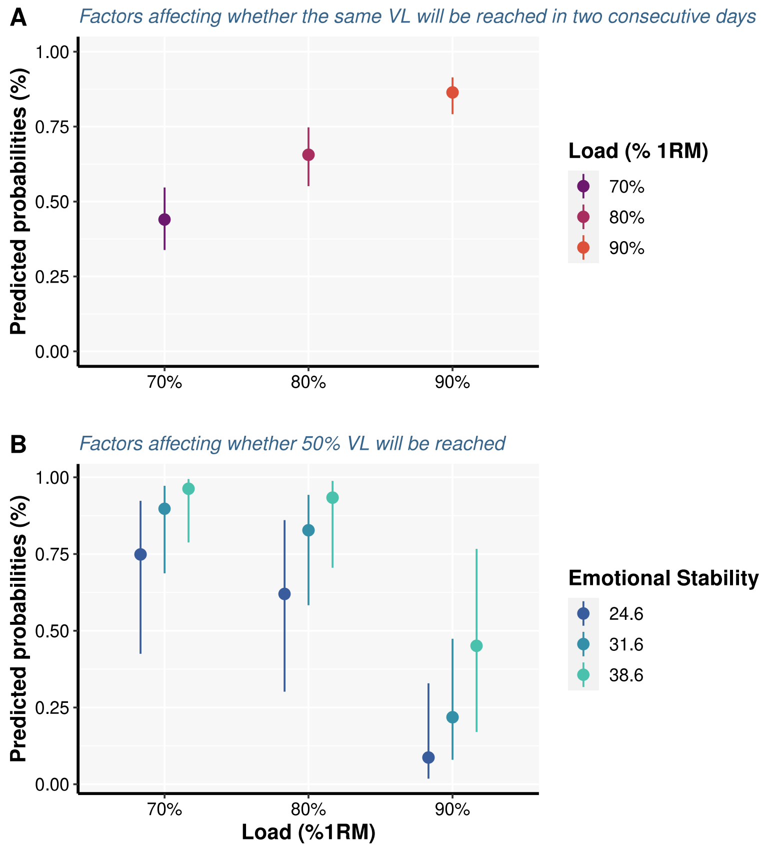
Loads practices [> 80% 1RM]	0.78	0.43 – 1.40	0.401	1.38	0.91 – 2.10	0.129	-	-	-
Repetitions in reserve practices [> 2 RIR]	0.93	0.62 – 1.40	0.734	1.67	1.25 – 2.23	0.001	0.28	0.05 – 1.69	0.165
Random Effects									
σ^2	3.29			3.29			3.29		
$\tau_{00\ ID}$	0.12			0.00			3.93		
$\tau_{00\ VL}$	0.38			0.19			-		
ICC	0.13			0.05			0.54		
N_{VL}	13			13			-		
N_{ID}	46			46			46		
Observations	1121			1593			138		
Marginal R^2 / Conditional R^2	0.155 / 0.267			0.199 / 0.242			0.333 / 0.696		

Note. Reference groups were the following: Load [70% 1RM], Sex [female], Training experience [< 3 years], Loads practices [< 70% 1RM], Repetitions practices [< 8], Repetitions in reserve practices [< 2 RIR]. 1RM, one repetition maximum; BM, body mass; RIR, repetitions in reserve; ICC, interclass-correlation coefficient; R^2, pseudo coefficient of determination; CI, 95% confidence intervals; p, p value.

The model examining factors affecting the probability of reaching 50% VL in a set (i.e., the ability to endure low velocity repetitions) revealed only load and emotional stability as influential factors with probability of reaching 50% VL in a set being higher for 70 ($p < 0.001$) and 80% ($p < 0.001$) compared to 90% of 1RM, and for participants who scored higher on emotional stability ($p = 0.029$).

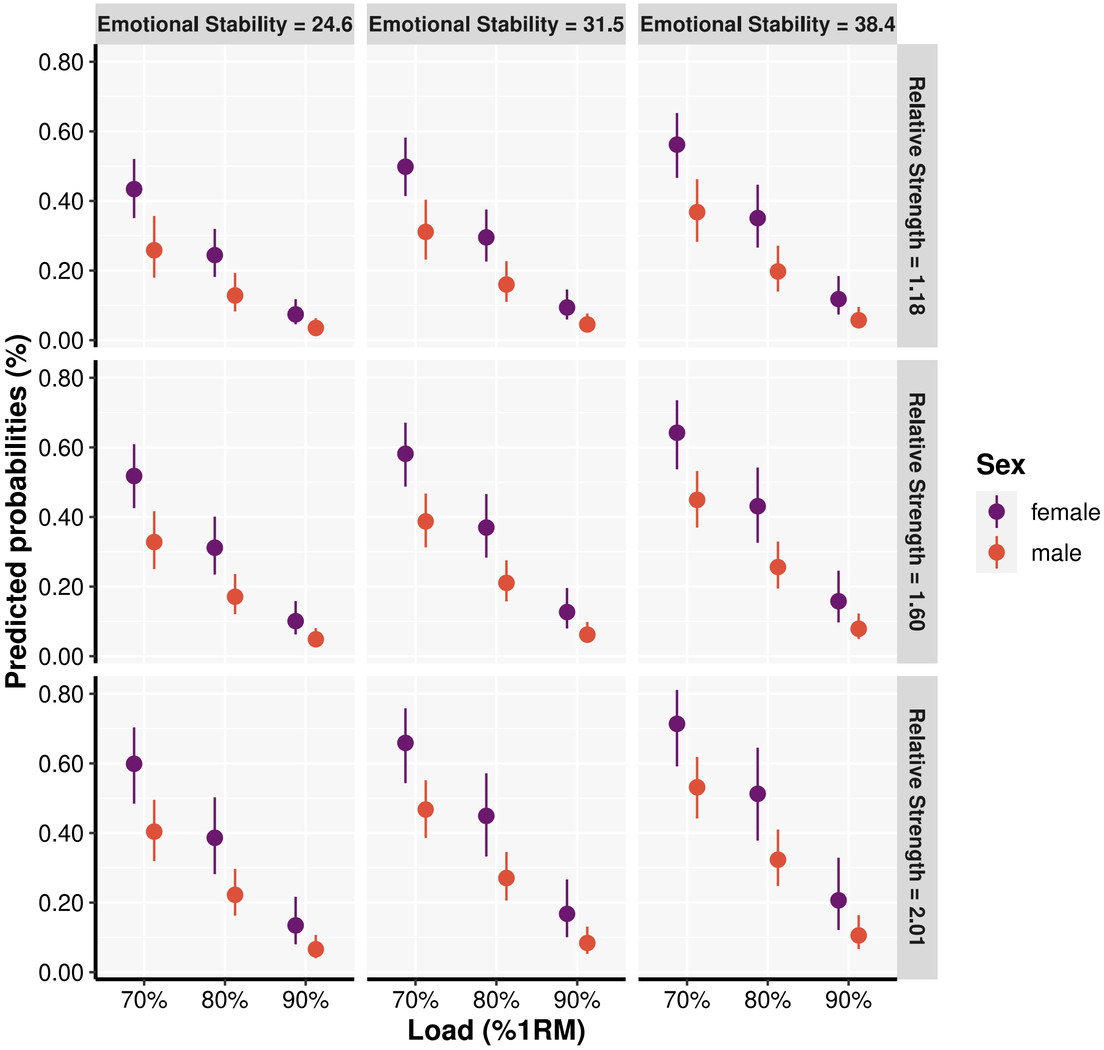
The relationship between the number of repetitions performed until reaching 10, 20, 30 and 40% VL and the total number of repetitions completed in a set was generally stronger for higher (i.e., 30 and 40% VL) compared to lower VL thresholds, regardless of the load (i.e., 70, 80 or 90% of 1RM) used (Appendix F Ch. 4 File IV).

Figure 4-5 Predicted probabilities with 95% confidence intervals for reaching the same velocity loss threshold on two testing sessions (A) and for reaching a 50% velocity loss in a set (B).



Note. For model estimates, please refer to Table 4-1 and Table 4-2, and for pairwise comparisons related to the loading condition please see Appendix F Ch. 4 File IV.

Figure 4-6 Predicted probabilities with 95% confidence intervals for performing multiple repetitions within a single velocity loss threshold. Columns make distinction between different levels of emotional stability whereas rows make a distinction between different strength levels of the participants.



Note. For model estimates, please refer to Table 4-1 and Table 4-2, and for pairwise comparisons related to the loading condition please see Appendix F Ch. 4 File IV.

4.4 Discussion

To our knowledge, this is the first study that comprehensively examined the reliability and magnitude of work completed across VL thresholds during RT while also exploring the effects of several factors potentially influencing the use of VL thresholds in practice. The main findings of this study were 1) the agreement of the number of repetitions performed across VL thresholds between two testing sessions was not acceptable, regardless of the load used; 2) the agreement of the velocities associated with the first instance when a given VL threshold was exceeded between two testing sessions was not acceptable, regardless of the load used; 3) the number of repetitions performed across VL thresholds was affected by sex, load, and emotional stability, whereas the magnitude of the velocity associated with the first instance a given VL threshold was exceeded was affected by sex, testing session, and load; 4) whether the same VL threshold was reached by the same person in two consecutive days was affected by load, whereas whether someone would experience a 50% VL in a set depended upon the load used and emotional stability of the person; and 5) whether someone would perform multiple repetitions within a given VL threshold was affected by sex, load, training history, strength, and emotional stability. Considering the above, it can be posited that 1) VL thresholds cannot be used to reliably control the amount of work completed during RT, but rather as a general variable quantifying the amount of fatigue experienced by an individual; and 2) VL thresholds should be highly individualised when used in practice since load, sex, training status, history, and psychological traits can all influence, at least to some extent, the variability in responses to different VL thresholds.

The agreement of the actual volume of work completed until reaching different VL thresholds between two consecutive testing sessions (72 hours apart) was not acceptable since the limits of agreement constantly sat outside the ± 2 repetitions margin, regardless of the load used. For instance, with 70% of 1RM, the upper CI of the upper LoA (estimate = 5.47) and lower CI of the lower LoA (estimate = -5.36) were higher and lower than 5 repetitions, respectively. This effectively means that, for the same threshold, individuals can be expected to perform anywhere between less than 5 and more than 5 repetitions on two consecutive testing sessions in a controlled environment (i.e., laboratory settings). While the extent to which this difference in work would affect longitudinal adaptations is not currently quantified, it is likely that the effect is profound. This contention is supported by the discrepancy in the literature regarding the effectiveness of various VL thresholds for inducing training adaptations. For instance, lower VL thresholds were equally effective and more beneficial for muscle strength and power adaptations, whereas higher VL thresholds were superior for muscle hypertrophy compared to lower ones [17]. However, when the volume of work was matched between different VL threshold groups, no differences were observed in muscle strength, hypertrophy or even gains in performance of athletic tasks [49, 50]. In addition, individuals might not reach the same VL threshold on two consecutive training sessions, as found in the present study (Figure 4-5), which compromises the ability of this method to control RT volume. This would only be exacerbated outside of controlled lab environments due to the complex interplay of different levels of fatigue, motivation, prior injury, and general readiness to train across individuals in common practical settings. Finally, the agreement of the velocities associated with the first instance when a given VL threshold was exceeded between two testing sessions was also not acceptable, regardless of the load used. Therefore, VL thresholds do not seem to be a reliable option for monitoring and prescribing RT volume.

The number of repetitions performed across VL thresholds was affected by sex, load and emotional stability, whereas the velocity associated with the first instance a given VL threshold was exceeded was affected by sex, load, and day. In this regard, both the number of repetitions and repetition velocity decreased as the load increased across VL thresholds. Although this finding may seem logical, it implies that the same amount of work cannot be completed just by selecting a given VL threshold, as the work completed is also load dependent. Thus, monitoring and performance evaluation (e.g., pre to post training cycle) should be done across the loading spectrum, while comparing performances for each load individually. Furthermore, regardless of the load used, females completed more repetitions than males across VL thresholds, while males performed repetitions at higher velocities. These findings align with the reported physiological and neuromuscular differences, often resulting in differences in exercise performance and recovery, between men and women.[150] Specifically, on average, men are stronger, and women are less fatigable; able to sustain force at the same relative intensity for a longer period [151, 152]. These sex differences in strength and fatigability were previously attributed to variation in muscle phenotype[153] insofar that women have smaller muscle fibres than men [153] and a higher proportion of type I fibres relative to type II [154], with greater muscle capillarisation [155], blood flow during exercise [156], and with distinct glycolytic and oxidative capacities [157, 158]. While relative strength did not influence the number of repetitions performed or repetition velocity across VL thresholds in the present study, sex differences in fatiguability could explain why females did more work, on average, compared to males across VL thresholds, and sex differences in the proportion of type I fibres relative to type II fibres, could explain why males performed repetitions at higher velocities, on average, across VL thresholds. Finally, individuals with higher levels of emotional stability tended to perform more repetitions across VL thresholds, on average. In general, high scorers on neuroticism – the trait on the opposite spectrum of emotional stability – tend towards heightened perception of fatigue symptoms [22]. Indeed, elevated neuroticism, by definition, is related to more frequent and intense experience of negative emotional states and elevated neuroticism is positively associated with fatigue [22, 143]. Furthermore, individuals with higher levels of neuroticism feel exhausted more frequently and report more severe fatigue than those with lower neuroticism.[159] It may be that individuals higher in emotional stability have in fact stronger fatigue tolerance (rather than propensity to experience less fatigue), thus enabling them to complete a greater amount of work across VL thresholds. Importantly, conscientiousness did not affect the number of repetitions performed or repetition velocity across VL thresholds in the present study, although this personality trait has been previously linked with fatigue [143]. Conscientiousness generally describes people who are task oriented. Since all participants who completed all the procedures were verbally encouraged and acknowledged for their efforts during the study, it may be that this was enough for people of all levels of conscientiousness to feel as though the task was successfully completed, thus preventing any influential effects of this personality trait that might have occurred if the experimental situation was less structured without clear instructions, encouragement and acknowledgments for completing the task (i.e., the testing session). The amount of VL experienced during RT has been repeatedly shown to be a useful, non-invasive indicator of the acute metabolic stress, hormonal response and mechanical fatigue during RT, and as such could be used to quantify fatigue induced by the training set [141, 142]. However, it seems that this monitoring practice could be drastically improved by considering individual trainee characteristics and training conditions since sex, the choice of load, and emotional stability all affected responses to different VL thresholds during RT.

There are several considerations when implementing velocity-based approaches to RT. For instance, the repetition-velocity relationship might not be linear for all individuals [45], and sets can be terminated after one or two repetitions exceed a predetermined threshold [160]. It seems logical that these considerations also apply to using VL thresholds during RT. It may be that whether individuals 1) can perform multiple repetitions within a single VL threshold; and 2) have the capacity to experience a 50% VL in a set are additional factors worth considering when implementing VL thresholds in practice, since both will likely affect the repetition-velocity relationship, as well as when sets are terminated. Indeed, whether individuals can do multiple repetitions within a single VL threshold is further influenced by sex, load, strength, emotional stability, and prior training practices. In this regard, females, stronger individuals, individuals higher in emotional stability, and those who generally perform higher repetitions in training (> 12) and leave 2-4 repetitions in reserve, are more likely to perform multiple repetitions within a single VL threshold. The effects of sex may be attributed to differences in fatiguability and muscle phenotype between males and females, whereas those with higher emotional stability had greater fatigue tolerance, allowing them to complete more work within the same VL threshold. It is not surprising that stronger individuals, and those who perform higher number of repetitions during their own training were more likely to perform multiple repetitions within a single VL threshold. Namely, stronger individuals would generally possess greater neural drive [161], myofibrillar cross-sectional area [162], and superior intermuscular coordination [163], all likely enhancing the ability to complete more work. In addition, generally performing a high number of repetitions during RT increased the odds of doing multiple repetitions within a single VL threshold likely due to these participants having greater muscle endurance (i.e., training specificity principle). Interestingly, those who usually left 2-4, compared to 0-2 reps in reserve in their own training were more likely to perform multiple repetitions within a single VL threshold. Furthermore, only load and emotional stability explained the ability of the individuals to experience a 50% VL during RT. Indeed, experiencing 50% VL with higher loads is unlikely given that repetition velocity sharply decreases as the load increases, thus not giving the opportunity to reach high VL. However, individuals higher in emotional stability were more likely to experience high VL during RT, probably due to their ability to cope with fatigue, as previously alluded to. At least some of these findings could also be explained by the fact that individuals have their own “pattern” of experiencing VL (Appendix F Ch. 4 File V) For instance, some people experience a gradual decline in velocity as the number of repetitions increase, whereas others maintain high velocity in the beginning and then experience a sudden drop in velocity, while others experience an early drop in velocity and then maintain velocity near the end of a set. The exploratory correlations between the number of repetitions performed until reaching 10, 20, 30, and 40% VL and the maximum number of repetitions completed in a set across loads support the concept that individuals have unique VL patterns. If there was indeed a general pattern of VL, one would assume very high correlations ($r > 0.9$) between the number of repetitions performed until reaching any of the VL thresholds and the maximum number of repetitions performed in that set (until failure). However, this was not the case, especially not with the loads (e.g., 70-80% 1RM) and VL thresholds (0-20%) typically used to optimise neuromuscular adaptations during RT, as the correlations never surpassed $r = 0.63$ (Appendix F Ch. 4 File VI). While this insight is entirely exploratory, it seems reasonable to hypothesise that individuals possess their own patterns of VL, which limits the generalisability of specific VL threshold stimuli across individuals. Considering all the above, it seems prudent to consider the choice of load and individual trainee characteristics (i.e., training status, history, and psychological traits) when implementing VL thresholds in practice as each affects the variability of responses.

The present study took a unique approach to examine a range of factors related to the use of VL thresholds during RT, and there are several considerations when interpreting the data. Firstly, the reliability and magnitude of the work completed until reaching different VL thresholds may not necessarily transfer to other exercises. However, the effects of trainee characteristics are likely applicable to a variety of exercises. Secondly, while attempts were made to represent a broad range of participants (e.g., training experience, strength levels, sex etc.) these findings may not generalise to sedentary populations since the participants had at least 6 months of RT experience. This at least partially explains why training experience did not influence any of the outcomes in the present study. Thirdly, since not every set in the present study was performed in a completely fresh state, some residual fatigue may have affected performance in subsequent sets and perhaps between day agreement for the amount of work completed across VL thresholds. However, 72 hours of rest between sessions and long rest intervals between sets, with participants performing sets with loads in a descending order should have ensured that the potential effects of fatigue were minimised. Fourthly, while efforts were made to balance the numbers of female and male participants, the number of females in the present study was considerably lower compared to males (due to COVID-related issues with recruitment). However, the females had a wide range of strength levels, training experience, and different training practices, improving this sample's generalisability. Nevertheless, future studies should aim to balance the number of male and female participants when making comparisons, where possible. Finally, the present study could not determine variability in metabolic, neuromuscular, and biomechanical responses to different VL thresholds. Therefore, future studies should quantify the extent that the demonstrated variability in the amount of work completed until reaching different VL thresholds affects the variability in acute metabolic, neuromuscular, and biomechanical responses to VL thresholds, as well as in longitudinal adaptations.

4.5 Conclusion

The present study expands on the previous velocity-based RT literature while providing several novel findings. The results question the utility of using VL thresholds to prescribe RT volume as the agreement in the amount of work completed across two consecutive testing sessions was not acceptable. Furthermore, while monitoring VL during RT is often used as a non-invasive indicator of the acute metabolic stress, hormonal response, and mechanical fatigue during RT, findings of the present study suggest that VL monitoring practices could be further improved by considering sex, training status, history, and psychological traits of individuals due to their effects on the variability in responses to different VL thresholds. In addition, it is also worth considering individual patterns of experiencing VL in a set as trainee's characteristics (e.g., emotional stability) and training conditions (i.e., the choice of load) can determine the relationship between VL and the number of repetitions completed. Therefore, using the same VL thresholds for all individuals, while assuming generalisability of the stimuli applied, would likely lead to variable acute physiological responses to RT and divergent neuromuscular adaptations over the long term.

Chapter 5: Velocity loss is a flawed method for monitoring and prescribing resistance training volume with a free-weight back squat exercise

Preface

Despite the observed variability in the volume completed before reaching different VL thresholds in the previous Chapter, recent studies have reported strong relationships between the velocity loss (VL) experienced in a set and the percentage of performed repetitions with respect to the maximum number that can be completed ($\%_{repetitions}$) in various exercises with different loads. While this implies that VL-$\%_{repetitions}$ should be used to monitor and modify resistance training (RT) volume, this concept has not been examined with free-weight exercises utilising the stretch-shortening cycle in the literature to date. This is important to consider given the popularity of free-weight exercises among trainees, especially athletes, and their greater transfer to sports performance compared with concentric-only actions, particularly in more complex multi-joint exercises. Finally, while this VL-$\%_{repetitions}$ relationship is often used in practice by strength and conditioning, physiotherapy and sport science professionals, its predictive validity has not yet been examined. To confirm the usefulness of the VL-%repetitions relationship, one would ideally want to know whether the established VL-$\%_{repetitions}$ relationship for a given individual during an initial testing session predicts future data reasonably well, in this case, the $\%_{repetitions}$ completed in subsequent training sessions. To further confound matters, other factors such as sex, training status and history and psychological traits could also affect the stability of VL-$\%_{repetitions}$ relationships but have not yet been examined. Therefore, the following Chapter expands on Chapter 4 and examines the goodness of fit, prediction accuracy, and reliability of general and individual VL-$\%_{repetitions}$ relationships in the free-weight back squat exercise. The effects of sex, training status and history, as well as personality traits, on the goodness of fit and the accuracy of these relationships were also investigated.

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5.1 Introduction

Resistance training (RT) is recognised as an effective mode of training for inducing muscle strength, power, and hypertrophy adaptations. In addition, RT is often used for injury prevention and rehabilitation purposes and is also generally recommended due to its positive effects on general health and quality of life [1, 30]. There are numerous variables within a RT program (e.g., volume, frequency, intensity of load, exercise selection, movement velocity) that can be manipulated for the purpose of affecting acute responses, and subsequent adaptation, to RT. Of note, RT volume is considered a critical variable for driving neural and structural adaptations [34, 3]. In traditional RT programs, set-volume is prescribed using a fixed, predetermined number of repetitions within the set based on the theoretical relationship between a maximum number of repetitions individuals can do with a given percentage of one-repetition maximum (%1RM). Indeed, this way of monitoring and prescribing RT set-volume is relatively simple and practical and can be managed with relative ease with large groups of people. However, large inter-individual variability exists for the maximal number of repetitions that can be completed to failure with different exercises and loads [12, 15]. This variability is problematic as it implies that prescribing the same relative load with a fixed number of repetitions will lead to heterogeneous training stimuli across individuals due to the potential differences in the level of effort experienced (i.e., number of repetitions left in reserve with respect to the maximum number of repetitions possible). Therefore, there is a need for alternative methods of monitoring and prescribing RT volume that take into account individuals' performance capacities and provide a more homogeneous level of effort across individuals.

During an exercise set, as the number of repetitions performed with maximal voluntary effort increases, movement velocity progressively decreases due to fatigue accumulation. Indeed, findings of several studies indicate that monitoring velocity loss (VL) experienced during a set is an objective, practical and non-invasive indicator of the acute metabolic stress, hormonal response and mechanical fatigue induced by RT [141, 142, 164]. Moreover, a very close relationship between VL and the percentage of performed repetitions out of the maximum possible in a set ($\%_{repetitions}$) was observed for paused bench press and back squat exercises performed in a Smith machine with loads ranging from 50% to 85% of 1RM [14, 39]. In addition, Gonzalez-Badillo et al. [14]

reported a low inter-individual variability (coefficient of variation ranging from 2.2% to 6.6%) in $\%_{repetitions}$ for a given magnitude of VL with 60% of 1RM. While these findings imply that this general VL-$\%_{repetitions}$ relationship can be used to monitor and prescribe RT set-volume, Sanchez-Moreno et al. [165] recently reported higher goodness of fit for individual compared to general VL-$\%_{repetitions}$ relationship during the paused bench press exercise performed in a Smith machine and thus recommended the use of individual relationships which allow for a more homogeneous level of effort between individuals. Although these findings are useful, it is not clear whether the results are ecologically valid to free-weight exercises utilising the stretch-shortening cycle that involve vertical and horizontal barbell movements [166]. Free-weight exercises utilising the stretch-shortening cycle are more popular among trainees, especially athletes, and have been shown to have a greater transfer of training effects to sports performance compared with concentric-only contractions, particularly in more complex multi-joint exercises [167, 168]. Therefore, it is necessary to examine the general and individual VL-$\%_{repetitions}$ relationships for free-weight exercises such as the barbell back squat and to determine the agreement between the $\%_{repetitions}$ on two consecutive testing sessions to ascertain the utility of such relationships for monitoring and prescribing RT using free weights.

When designing a RT program, sex, training status (e.g., strength levels), and history are typically considered due to their potential effects on adaptations to RT [150, 12, 20]. However, the effects of these factors on the stability of the VL-$\%_{repetitions}$ relationship have not been comprehensively examined. In addition, since VL is used to monitor RT-induced fatigue and prescribe RT, personality traits such as emotional stability and conscientiousness could also affect the stability of VL-$\%_{repetitions}$ relationships due to their association with how individuals cope with fatigue [143, 22]. Additionally, only second-order polynomial regression was previously used to model both general and individual VL-$\%_{repetitions}$ relationships. Thus, it is currently unknown whether simpler linear models could fit the data equally well and reduce the complexity of data analysis for practitioners seeking to establish these relationships. Finally, and most importantly, the predictive validity of both general and individual VL-$\%_{repetitions}$ relationships has not been examined to date. Evaluating those relationships on two different testing sessions and comparing goodness of fit is not enough when determining models' utility in real-world settings. To consider a general or individual VL-$\%_{repetitions}$ relationship useful, they should demonstrate acceptable predictive validity first which could then be revaluated with individuals only sporadically, but not during every RT session.

Considering the above-mentioned scarcity in the literature, further examination of VL-$\%_{repetitions}$ relationships is clearly needed. Therefore, the purpose of this study was to 1) examine the goodness of fit of general and individual VL-$\%_{repetitions}$ relationships in a free-weight back squat exercise and determine the effects of sex, training status and history, as well as personality traits on the models' fit; 2) quantify the agreement between the $\%_{repetitions}$ completed until reaching a given VL threshold on two testing sessions; and 3) determine the ability of general and individual VL-$\%_{repetitions}$ relationships to predict data in a subsequent testing session while also examining which factors affected the accuracy of the predictions. Such evidence is important to guide the VL approach to monitoring and prescribing RT with free-weight exercises.

5.2 Methods

5.2.1 Design

This study employed a test-retest study design and is a part of a larger project investigating the validity of different velocity-based RT monitoring and prescription methods. Participants visited the laboratory on four separate occasions, separated by 48 – 72 hours of rest between sessions. Participants first completed a familiarisation session that covered the free-weight back squat movement, the equipment and instruments used, an instruction to move the barbell up as fast as possible, and visual feedback on a screen indicating the velocity of the barbell. In the second session, participants completed an incremental loading test (i.e., 1RM) in the back squat exercise. In the last two sessions, participants completed a repetition to failure (RTF) test in the back squat, with 70, 80, and 90% of their pre-determined 1RM. All participants completed the experimental 1RM and RTF sessions at the same time of day (± 1 hour) to avoid diurnal variation in exercise performance.

5.2.2 Participants

Fifty-one strength-trained men and women (36 males and 15 females; 18 to 40 years of age) volunteered to participate in this study. However, five male participants withdrew from the study due to injury incurred at their work or recreational sporting activity not related to the study (n = 3) or for personal reasons (n = 2). Participants without a full data set were excluded from the analysis as the primary aim of the study was to determine the stability of the number of repetitions performed until a given VL threshold was met. Female and male participants recorded a 1RM relative to body mass in the free weight back squat of 1.25 ± 0.30 (range: 0.86 – 2.12) and 1.79 ± 0.35 (range: 1.18, 2.61), respectively. To be eligible for inclusion, participants confirmed that they (1) were willing to abstain from lower-body training during their participation in the study, (2) were not currently taking metabolic or cardiovascular function-altering medications, (3) were free of musculoskeletal injury, (4) were not actively taking anabolic steroids or had a history of anabolic steroid use, (5) had at least six months of RT experience training at least 2x/week, performing the back squat exercise at least 1x/week, with no more than two weeks in a row without RT during that period. Participants gave informed, written consent before commencing the study. The protocol of the current study was approved by the University Ethics Committee (approval number: 20/55).

5.2.3 Familiarisation session

Participants arrived at the laboratory and completed a training history questionnaire regarding their habitual RT practices. Participants' body mass and height were then recorded using an electronic column scale and wall mounted stadiometer (Seca Ltd, Hamburg, Germany), respectively. Participants then completed a standardised warm-up, which consisted of cycling at 100 rpm for 5 mins; dynamic stretching for 2 mins; 10 bodyweight lunges and squats; and 10 squats with barbell only. Participants were familiarised with the instruction to lift the barbell up as fast as they can during the concentric muscle action and the provided visual feedback on a screen indicating the mean velocity of the barbell. Participants were also instructed to take at least a momentary pause between repetitions, but not to take more than 2 seconds between repetitions, with the feet remaining in contact with the floor for all repetitions (i.e., no jumping or lifting of the heels). Participants were asked to provide training logs for their most recent, heaviest back squat session and to conservatively estimate their 1RM. This information was used to inform the warm-up loads for the subsequent 1RM session. Participants then completed 3 repetitions at 20, 40, and 60% of their estimated 1RM, and then 10 repetitions at 60% of their estimated 1RM, to ensure familiarity with the instructions. Participants received visual feedback of barbell velocity during these practice repetitions and practiced the instruction to move the barbell up as fast as possible and avoid pausing for more than two seconds between repetitions (i.e., standing phase of the squat). At the end of the session, participants confirmed they understood and felt comfortable with the study instructions and performed at least two sets with consistent repetition velocities (± 0.02 m/s).

5.2.4 One repetition maximum session: Day 2

Participants arrived at the laboratory and completed the same standardised warm-up as in the familiarisation session. A 20-kg barbell (Rogue, Columbus, Ohio, USA) and calibrated weight plates (Eleiko, Halmstad, Sweden, EU) were used for the 1RM assessment. The protocol for the 1RM session consisted of 3 repetitions at 20, 40, and 60%; and 1 repetition at 80% and 90% of the estimated 1RM, followed by 1RM attempts [169, 170]. If a 1RM attempt was completed successfully, the load was increased 1 to 12.5 kg in consultation with the participant, until they could not complete an attempt or until the movement technique was compromised. A maximum of five 1RM attempts per participant were completed to establish the 1RM. Three- and four-minutes rest were provided for participants between submaximal sets and 1RM attempts, respectively [169, 170]. To facilitate a habitual squatting technique, participants adopted a self-selected foot stance and eccentric tempo. Upon reaching the bottom of the squat, participants received instruction to lift the barbell up as fast as possible. Verbal encouragement was provided by researchers and visual feedback on barbell velocity was provided on a screen, for all trials. Participants were required to squat to a depth where the top of the thighs were at least parallel to the floor, as determined by the researchers, and a camera positioned perpendicularly to the participant, for a repetition to be considered successful.

5.2.5 Repetitions to failure sessions: Days 3 and 4

The standardised warm-up that was completed in the familiarisation and 1RM sessions was completed by participants at the RTF sessions. Participants then completed 10, 5, 3, and 1 repetitions of the free-weight back squat exercise against 30, 50, 70, and 90% of the heaviest load that is going to be lifted that day (i.e., 90% of the established 1RM load), respectively. Participants were provided 3 minutes of rest between warm-up sets, and 4 minutes prior to the first set to failure. To minimise fatigue from the high-repetition 70% test from influencing the repetitions completed in the subsequent 80 and 90% tests, the RTF loads were not tested in a randomised order. Instead, participants performed RTF from highest to lowest load (i.e., 90% 1RM first, 80% 1RM second, and 70% 1RM third). The lifting instructions, verbal encouragement, and visual feedback standardisation used in the 1RM session were also used for all sets completed during the RTF sessions. RTF sessions were separated by at least 72 hours.

5.2.6 Data Acquisition

The training history questionnaire is presented in Appendix F Ch. 5 File I. Briefly, the questionnaire asked participants about (1) the number of repetitions they typically performed in training; (2) the loading intensity at which they usually train, (3) the number of repetitions left in reserve they usually have at the end of training sets, and (4) their RT experience in years. These questions were multi-choice; therefore, the responses were treated as categorical. The frequency of responses was inspected for each category (overall and within levels of outcome variables used in models) and these variables were recoded by merging several response options to avoid having less than 5 responses in more than 20% of cells [145]. Specifically, the number of repetitions performed containing three levels (1-5, 5-8, and >8) and the intensity of load (<70, 70-80, 80-90) were transformed into categorical variables containing three levels. The number of repetitions left in reserve (0-2 and 2-4) and RT experience (≤3 and >3) were transformed into categorical variables containing two levels.

The mean velocity of all repetitions was recorded using a GymAware linear position transducer (LPT). This validated LPT [171] was placed on either side of the barbell and perpendicular to the position between the hands and the loaded barbell sleeves, per the manufacturer's instructions. The end of the LPT cable was vertically attached to the barbell by a Velcro strap. This LPT measures the total displacement of its cable in response to changes in the barbell position. Changes in barbell position with respect to time is used to determine instantaneous velocity, which is also provided by the LPT's software. The GymAware v2.8.0 app was used on a tablet (iPad, Apple Inc., California, USA) to transmit the data obtained from the LPT via Bluetooth. The LPT attached to the right side of the barbell was connected to a TV screen, which provided visual feedback indicating the mean velocity of the barbell after each completed repetition. The analysis in the current study was completed using data from this LPT. Additionally, the mean velocity of all completed repetitions was manually recorded and organised in a Microsoft Excel spreadsheet (Microsoft Corporation, Redmond, Washington, USA) during each session, to avoid issues with online cloud data storage or internet connection. The same two researchers completed this task throughout data collection to ensure consistency and accuracy. Using the mean velocity data, the magnitude of VL was calculated as a relative difference between the fastest and the last repetition performed in a set.

The 50-item International Personality Item Pool (IPIP) Big Five Personality Inventory was used as a validated assessment of the human personality [146, 147]. This inventory contains 50 questions, 10 of each assessing the Big Five personality dimensions (Agreeableness, Conscientiousness, Extraversion, Neuroticism, and Openness). A 5-point, Likert-type scale ranging from 1 (very inaccurate) to 5 (very accurate) was used to administer the IPIP items. Mean scores across personality dimensions were obtained by averaging the scores for each item. Only conscientiousness and emotional stability were retained for the analysis in the present study.

5.2.7 Statistical analysis

Linear and second-order polynomial regression models were used to determine the individual and general VL-$\%_{repetitions}$ relationships. General relationships were determined separately for each load and testing session while pooling together the data from all participants, whereas individual relationships were obtained for each participant separately, on both testing sessions and with each load. The goodness of fit of general relationships was examined through the coefficient of determination (R^2) and residual standard error (RSE) of the models, whereas medians and ranges of R^2 and RSE were evaluated for individual VL-$\%_{repetitions}$ relationships.

Linear mixed-effects models with the Gaussian conditional distribution and identity link function were used to examine the influential factors on individual relationships' R^2 and RSE (i.e., model fits and model errors). For this purpose, the load (3 levels), training experience (2 levels) and practices (2 or 3 levels), relative strength, conscientiousness and emotional stability were all considered as fixed effects.

To assess the agreement across days between $\%_{repetitions}$ until reaching a given VL threshold (i.e., from 5% to 60%> in 5% increments), the true modified value varies method of the Bland-Altman analysis for multiple measures per participant [140] was used for each load separately. An *a priori* equivalent margin of ± 10% of the repetitions completed until reaching a given VL threshold was used in the interpretation and evaluation of bias and the associated 95% limits of agreement (LoA). This criterion was chosen since more than a 10% difference would not be considered an improvement over traditional RT prescription methods such as stopping sets at a predetermined perceived number of repetitions in reserve. The method of variance estimates recovery (MOVER) was used to calculate the confidence intervals (CI) for LoA, as this considers the multiple, repeated measurements taken [148]. For LoA, two one-sided tests (TOST) were performed as the equivalence test, with an α-value of 0.1 and a 1–2α CI. The null hypothesis of TOST was that the two values were not equal. The null hypothesis was rejected where the 1–2α CI was contained in full of the ± equivalent margin, and in this instance, the two datasets (i.e., data from the two testing sessions) were considered equivalent [149]. All assumptions of the Bland-Altman analysis were met.

The predictive validity of the general and individual VL-$\%_{repetitions}$ relationships was examined by using the models from the first testing session (i.e., general model with all participants' data pooled and individual models of each participant) and fitting them to the data of the second testing session. Thereafter, general, and individual models' errors were evaluated by calculating an absolute difference between the observed and predicted data in the second testing session. Models' absolute error of less than 5% was deemed excellent, 5-10% acceptable, and more than 10% error not useful for monitoring and prescribing RT. An error of 10% or more was not considered acceptable as a difference in 10% VL could represent different qualitative classifications of the threshold (e.g., low vs moderate vs large) that is often used in research and practice. Additionally, a difference in 10% VL could lead to different RT-induced adaptations [164]. To examine factors which influenced the absolute differences between observed and predicted data, linear mixed-effects models were used, as previously described. Finally, to confirm the robustness of these findings, generalised linear mixed-effects models, with a binomial conditional distribution and logit link function, were also used to examine factors affecting the probability of not exceeding an absolute prediction error of 10%.

For all mixed models, participants (n = 46) were treated as random effects to control for repeated measurements and the general variation between participants. Since both fixed and random effects were used, restricted maximum likelihood estimation was used for the evaluation of the linear mixed-effects models whereas maximum likelihood, with Laplace approximation, estimation was used for generalised linear mixed-effects models. The contribution of both fixed and random effects to the explanatory power of any of the explored models was examined using a likelihood ratio test, deviance statistic, and Akaike Information Criterion score, before selecting the final model to obtain the best fit while maintaining model parsimony. Importantly, the reduction of the model structure was always theoretically motivated and was done as a last resort. The statistical significance of fixed effects was examined by t-tests based on the Satterthwaite approximation or Wald Z-tests for linear mixed-effects and generalised linear mixed-effects models, respectively. For linear mixed-effects models, predictors' estimates and 95% CI were calculated and presented whereas for generalised mixed-effects models odds ratios with associated 95%CI were evaluated and presented to aid the interpretation of the findings. For categorical predictors with more than 2 levels, post-hoc tests were performed with Holm-Bonferroni correction. More details on models' specifications and diagnostics can be found in the Appendix F Ch. 5 File II.

All statistical analyses were performed in R language and environment for statistical computing (version 4.2.0, The R foundation for Statistical Computing, Vienna, Austria) using the *SimplyAgree* [172], *lme4* [173], and *emmeans* [174] packages, models' performance using the *performance* [175] and *DHARMa* [176] packages, and preparation and visualisation of data using the *tidyverse* [177] and *sjPlot* [178] packages. Custom-written R script and associated dataset are available at the Open Science Framework repository (URL: https://osf.io/3yuvr/).

5.3 Results

The goodness of fit for the general VL-$\%_{repetitions}$ relationship across loads and testing sessions was generally strong and comparable for both linear and second-order polynomial regression models (Figure 5-1; Table 5-1). However, the goodness of fit of the individual relationships was always stronger (Figure 5-2; Table 5-2), regardless of the load, testing session and regression model.

Figure 5-1 A general relationship between velocity loss and the percentage of the repetitions completed out of maximum possible fitted with linear (red line) and second-order polynomial regression (light blue line) models. Coefficient of determination (R^2), as well as residual standard errors (RSE), are also presented for both linear (in red) and second-order polynomial regression (in light blue) models.

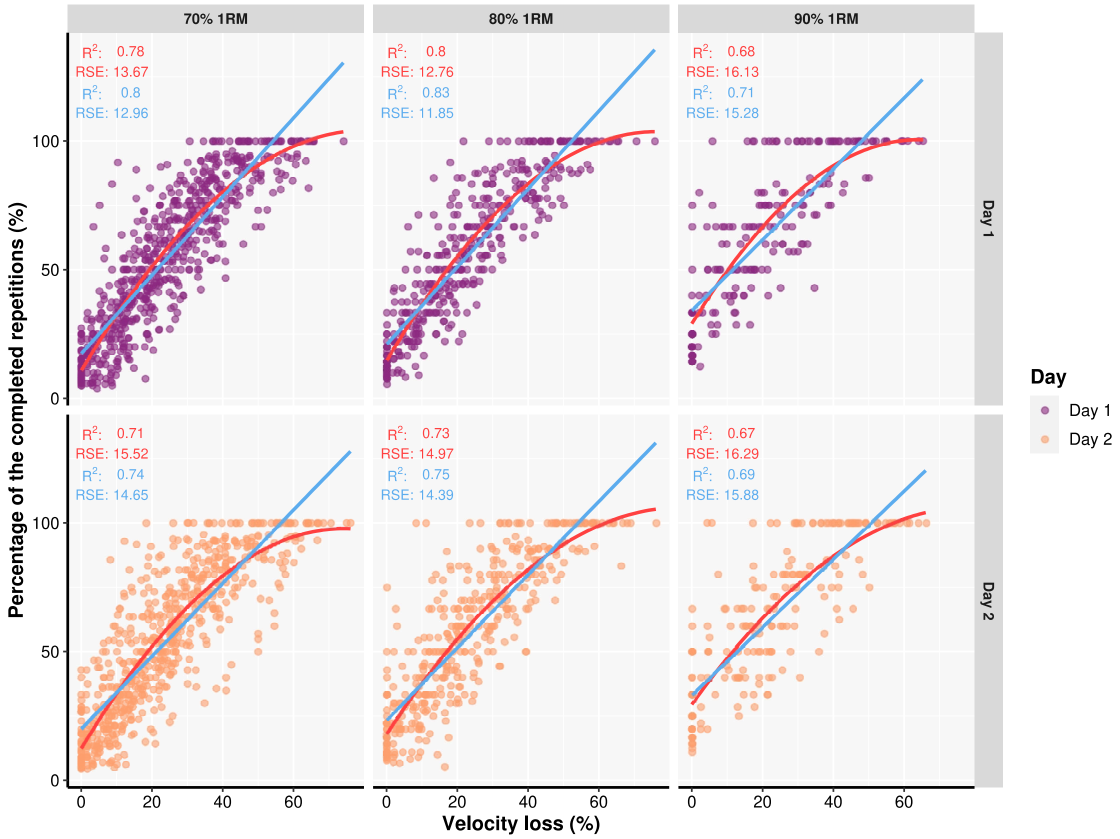
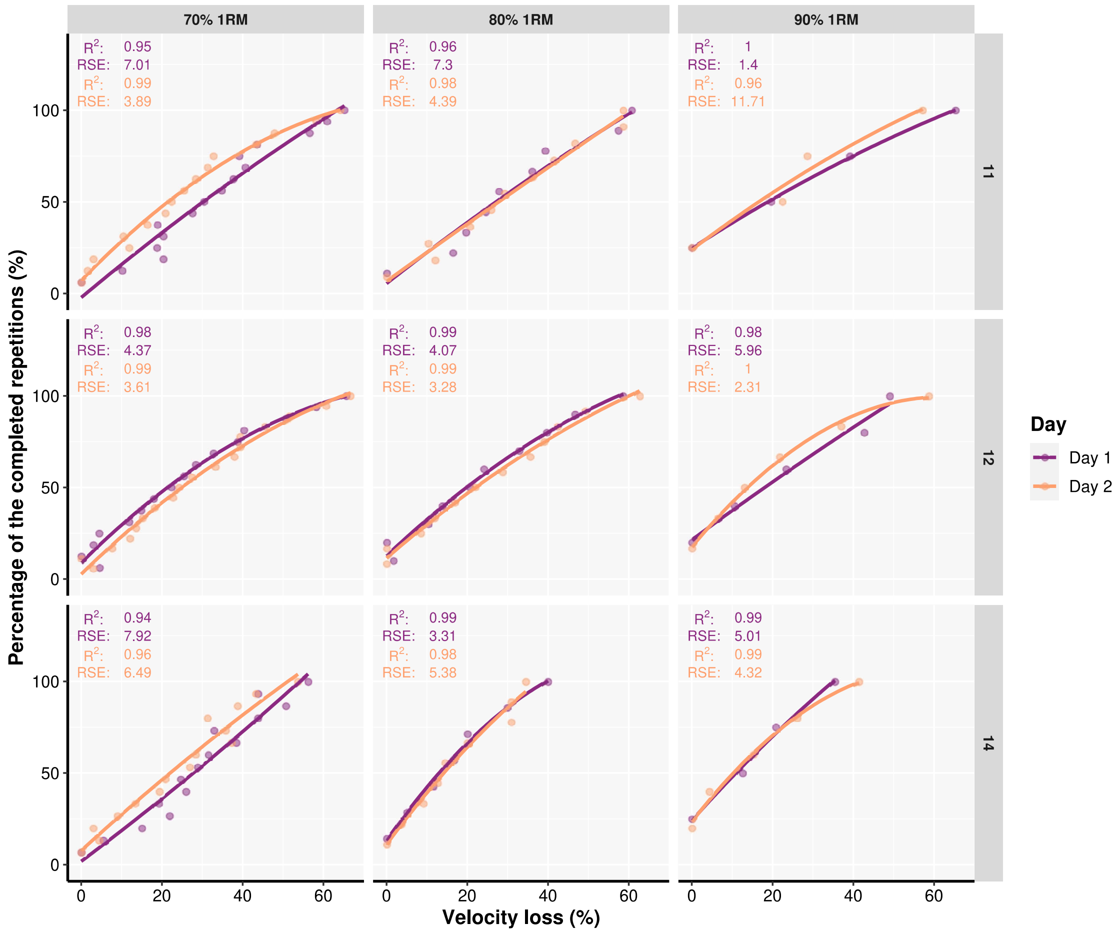


Figure 5-2 Individual relationships between velocity loss and the percentage of the repetitions completed out of maximum possible fitted with second-order polynomial regression models for representative participants. Coefficient of determination (R^2), as well as residual standard errors (RSE), are also presented for both testing sessions.



Note. ID, the participants' identification number.

The goodness of fit of individual VL-%$_{repetitions}$ relationships was affected by testing session, model type, and load (Table 5-3). R^2 was higher in the second testing session ($p < 0.001$), when the second-order polynomial regression model was used ($p < 0.001$), and with 90% ($p = 0.030$) and 80% ($p = 0.030$) compared to 70% of 1RM load (Appendix F Ch. 5 File III). Therefore, second-order polynomial regression models were used for later evaluation of the predictive validity of the VL-%$_{repetitions}$ relationships.

Table 5-1 Percentages of the completed repetitions with respect to the maximum possible until reaching a given velocity loss threshold.

	70% 1RM		80% 1RM		90% 1RM	
VL	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
VL5	19.05 ± 9.16	21.19 ± 11.73	27.72 ± 11.39	29.3 ± 18.25	49.05 ± 19.91	60.14 ± 22.51
VL10	30.47 ± 14.06	31.04 ± 13.59	41.83 ± 13.97	39.04 ± 17.29	45.5 ± 10.89	46.66 ± 14.1
VL15	40.96 ± 13.78	43.94 ± 14.39	45.75 ± 13.3	47.07 ± 17.56	62.41 ± 18.68	56.74 ± 17.53
VL20	51 ± 14.71	48.28 ± 15.5	56.61 ± 16.77	55.19 ± 17.6	74.83 ± 18.17	58.69 ± 17.98
VL25	58.28 ± 15.71	57.54 ± 14.19	66.27 ± 14.98	65.35 ± 14.77	71.26 ± 18.15	73.47 ± 15.87
VL30	69.83 ± 15.09	69.12 ± 17.3	73.85 ± 12.19	70.93 ± 14.06	77.86 ± 18.12	83.61 ± 16.66
VL35	77.96 ± 13.43	75.3 ± 14.61	82.71 ± 10.6	76.06 ± 15.92	88.89 ± 10.88	82.61 ± 18.41
VL40	82.77 ± 12.24	82.55 ± 14.22	85.04 ± 12.1	82.98 ± 7.87	95.41 ± 8.54	87.95 ± 14.91
VL45	90.12 ± 9.56	89.08 ± 7.08	89.5 ± 9.08	90.03 ± 9.15	98.21 ± 5.06	93.85 ± 11.39
VL50	90.34 ± 11.26	86.47 ± 15.52	95.74 ± 7.71	96.12 ± 5.88	97.96 ± 5.4	93.75 ± 12.5
VL55	91.87 ± 6.78	94.14 ± 8.95	96.63 ± 5.25	98.16 ± 4.11	100 ± 0	100 ± 0
VL60≥	96.63 ± 5.73	96.38 ± 4.92	100 ± 0	97.91 ± 5.9	100 ± 0	100 ± 0

Note. VL, velocity loss; 1RM, one-repetition maximum.

Table 5-2 Goodness of fit for individual VL-%repetitions relationships established using linear and polynomial regression models on two testing sessions with different loads.

		Day 1						Day 2					
Load	Model type	Median R^2	Min R^2	Max R^2	Median RSE	Min RSE	Max RSE	Median R^2	Min R^2	Max R^2	Median RSE	Min RSE	Max RSE
70% 1RM	linear	0.93	0.35	0.98	8.32	4.79	25.33	0.90	0.52	0.99	9.73	2.89	21.46
70% 1RM	polynomial	0.94	0.42	0.99	8.06	3.93	25.20	0.93	0.53	0.99	9.03	2.99	22.36
80% 1RM	linear	0.93	0.60	0.99	8.41	2.37	21.48	0.92	0.43	0.99	9.35	3.23	26.24
80% 1RM	polynomial	0.95	0.73	1.00	7.48	1.06	17.75	0.96	0.47	0.99	7.37	3.26	29.43
90% 1RM	linear	0.96	0.24	1.00	7.58	0.12	41.10	0.92	0.49	1.00	10.81	1.85	33.71
90% 1RM	polynomial	0.97	0.57	1.00	8.09	0.41	35.36	0.94	0.57	1.00	10.92	2.31	29.34

Note. 1RM, one-repetition maximum; R^2, coefficient of determination; RSE, residual standard error.

Table 5-3 Factors affecting 1) the goodness of fit of individual VL-%repetitions relationships; 2) absolute differences between predicted and observed %repetitions in a subsequent testing session based on individual VL-%repetitions relationships; and 3) the probability of individual VL-%repetitions relationships exceeding a 10% prediction error

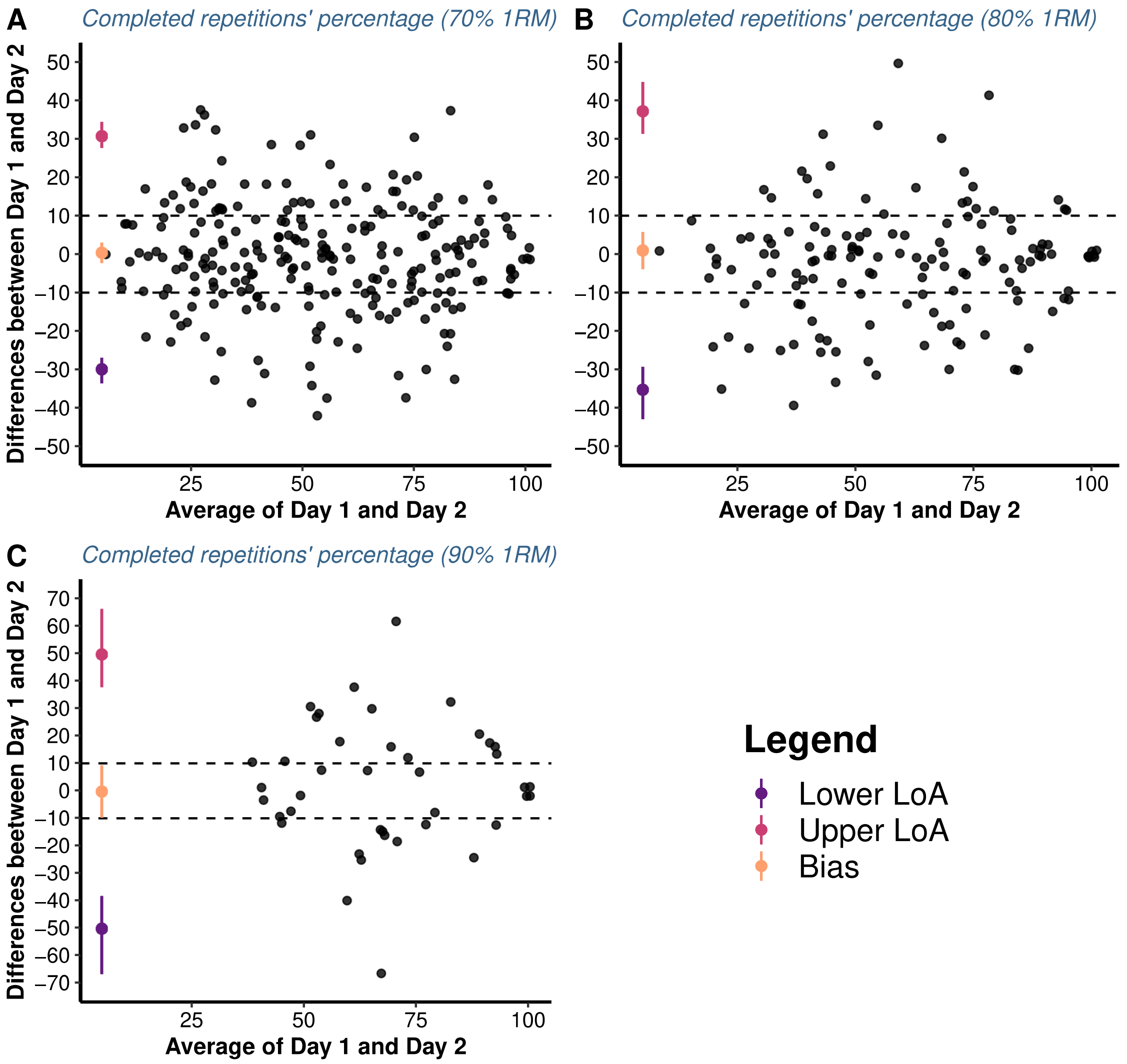
	Factors affecting R^2			Factors affecting absolute differences			Factors affecting probability of exceeding 10% error		
Predictors	Estimates	CI	p	Estimates	CI	p	OR	CI	p
(Intercept)	0.97	0.77 – 1.16	<0.001	10.95	-2.18 – 24.08	0.102	0.30	0.05 – 1.95	0.208
Day [Day 2]	-0.02	-0.04 – -0.01	0.006	-	-	-	-	-	-
Model [polynomial]	0.03	0.02 – 0.05	<0.001	-	-	-	-	-	-
Sex [male]	0.04	-0.02 – 0.10	0.235	-0.24	-4.24 – 3.75	0.905	0.98	0.76 – 1.27	0.885
Load [80% 1RM]	0.02	0.00 – 0.04	0.017	0.72	-0.49 – 1.93	0.245	1.90	1.36 – 2.64	<0.001
Load [90% 1RM]	0.03	0.01 – 0.04	0.009	6.11	4.54 – 7.68	<0.001	1.00	0.97 – 1.03	0.945
Emotional Stability	-0.00	-0.00 – 0.00	0.433	-0.05	-0.27 – 0.17	0.643	1.02	0.98 – 1.05	0.370
Conscientiousness	-0.00	-0.01 – 0.00	0.316	0.11	-0.13 – 0.34	0.365	0.98	0.76 – 1.27	0.885
Training experience [> 3 years]	0.04	-0.00 – 0.09	0.070	-0.09	-3.22 – 3.04	0.955	0.79	0.51 – 1.23	0.296
Loads practices [70 – 80% 1RM]	0.02	-0.04 – 0.07	0.616	-3.09	-7.10 – 0.91	0.130	0.72	0.44 – 1.20	0.209
Loads practices [> 80% 1RM]	0.04	-0.03 – 0.11	0.235	-5.48	-10.03 – -0.93	0.018	0.89	0.51 – 1.54	0.667
Repetitions practices	0.02	-0.03 – 0.08	0.404	-1.10	-4.64 – 2.44	0.542	0.80	0.46 – 1.42	0.452

[8 – 12 repetitions]									
Repetitions practices [> 12 repetitions]	-0.00	-0.06 – 0.06	0.984	-0.12	-4.02 – 3.78	0.953	0.51	0.27 – 0.98	0.043
Repetitions in reserve practices [> 2 RIR]	0.02	-0.03 – 0.06	0.490	-1.82	-4.96 – 1.32	0.256	0.85	0.54 – 1.33	0.477
Relative strength (1RM/BM)	-0.04	-0.10 – 0.03	0.255	1.17	-3.27 – 5.62	0.605	1.87	1.00 – 3.51	0.051
Random Effects									
σ^2	0.01			97.68			3.29		
$\tau_{00\ ID}$	0.00			15.53			0.22		
ICC	0.30			0.14			0.06		
N_{ID}	46			46			46		
Observations	552			1295			1295		
Marginal R^2 / Conditional R^2	0.139 / 0.393			0.072 / 0.200			0.049 / 0.106		

Note. Reference groups were the following: Load [70% 1RM], Sex [female], Training experience [< 3 years], Loads practices [< 70% 1RM], Repetitions practices [< 8 repetitions], Repetitions in reserve practices [< 2 RIR]. 1RM, one repetition maximum; BM, body mass; RIR, repetitions in reserve; OR, odds ratio; ICC, interclass-correlation coefficient; R^2, coefficient of determination; CI, 95% confidence intervals; p, p value; VL-$\%_{repetitions}$, relationships between velocity loss and the percentage of the completed repetitions with respect to the maximum possible.

The null hypothesis for the equivalence of the $\%_{repetitions}$ until reaching a given VL threshold on day 1 and day 2 was not rejected for any of the examined loads since the 1–2α CI of LoA were always completely outside the ± equivalent margin of 10% (Figure 5-3).

Figure 5-3 Bland-Altman plots illustrating the agreement between the percentages of the repetitions completed – out of maximum possible – until reaching a given velocity loss threshold on two testing sessions for 70 (A), 80 (B) and 90% of 1RM load (C).



Note. Dashed lines represent an equivalent margin of ± 10% whereas LoA represents limits of agreement.

The predictive validity of the VL-$\%_{repetitions}$ relationship was not acceptable, regardless of whether general or individual relationships were fitted to the data since the absolute error between observed and predicted data on the second testing session – while using the data of the first testing session to make predictions – was always higher than 10%, regardless of the load used (Appendix F Ch. 5 File IV). The linear mixed-effects model investigating factors affecting absolute differences between observed and predicted data on the second testing session revealed only load and training load practices were influential factors (Table 5-3), with absolute errors being lower with 90% compared to 80% and 70% of 1RM ($p < 0.001$). After a multiple comparison correction was applied, there were no differences between participants who often use very high (i.e., 90%) compared to those who use lower loads (i.e., 80 or 70% of 1RM) during their own training ($p \geq 0.071$). Similarly, the generalised linear mixed-effects model examining factors affecting the probability of not exceeding an absolute prediction error of 10% also revealed only load and training load practices were influential factors (Table 5-3), with the probability of exceeding the 10% prediction error increasing with 90% compared to 70% ($p < 0.001$) and 80% of 1RM ($p < 0.001$) loads. There were no differences between participants who have different training load practices when multiple comparison correction was applied ($p \geq 0.130$).

5.4 Discussion

To our knowledge, this is the first study that examined the goodness of fit, prediction accuracy, and stability of general and individual VL-$\%_{repetitions}$ relationships in a free-weight back squat exercise while also exploring the effects of sex, training status and history, as well as personality traits on the goodness of fit and accuracy of those relationships. The main findings of this study were 1) individual rather than general VL-$\%_{repetitions}$ relationships yielded a higher goodness of fit for all loads and on both testing sessions; 2) goodness of fit for both individual and general relationships was higher on the second testing session compared to the first and with higher (i.e., 90 and 80% 1RM) compared to the lower loads (i.e., 70% 1RM), but was not affected by sex, training status and history nor personality traits; 3) for individual VL-$\%_{repetitions}$ relationships, second order polynomial regression models yielded a better goodness of fit compared to linear models whereas both regression models fit the data equally well for the general VL-$\%_{repetitions}$ relationship; 4) individual, but not general, VL-$\%_{repetitions}$ relationships displayed acceptable *RSE* apart with 90% 1RM in the second testing session; 5) the agreement between the $\%_{repetitions}$ performed across VL thresholds on two testing sessions was not acceptable, regardless of the load used; and 6) both general and individual VL-$\%_{repetitions}$ relationships established in the first testing session did not provide acceptable predictions of $\%_{repetitions}$ (due to high absolute errors) in the second testing session, and this prediction accuracy was not affected by sex, training status, history, or personality traits. Therefore, the findings of the present study question the utility of the VL-$\%_{repetitions}$ relationship to monitor and prescribe RT volume with a free-weight back squat exercise.

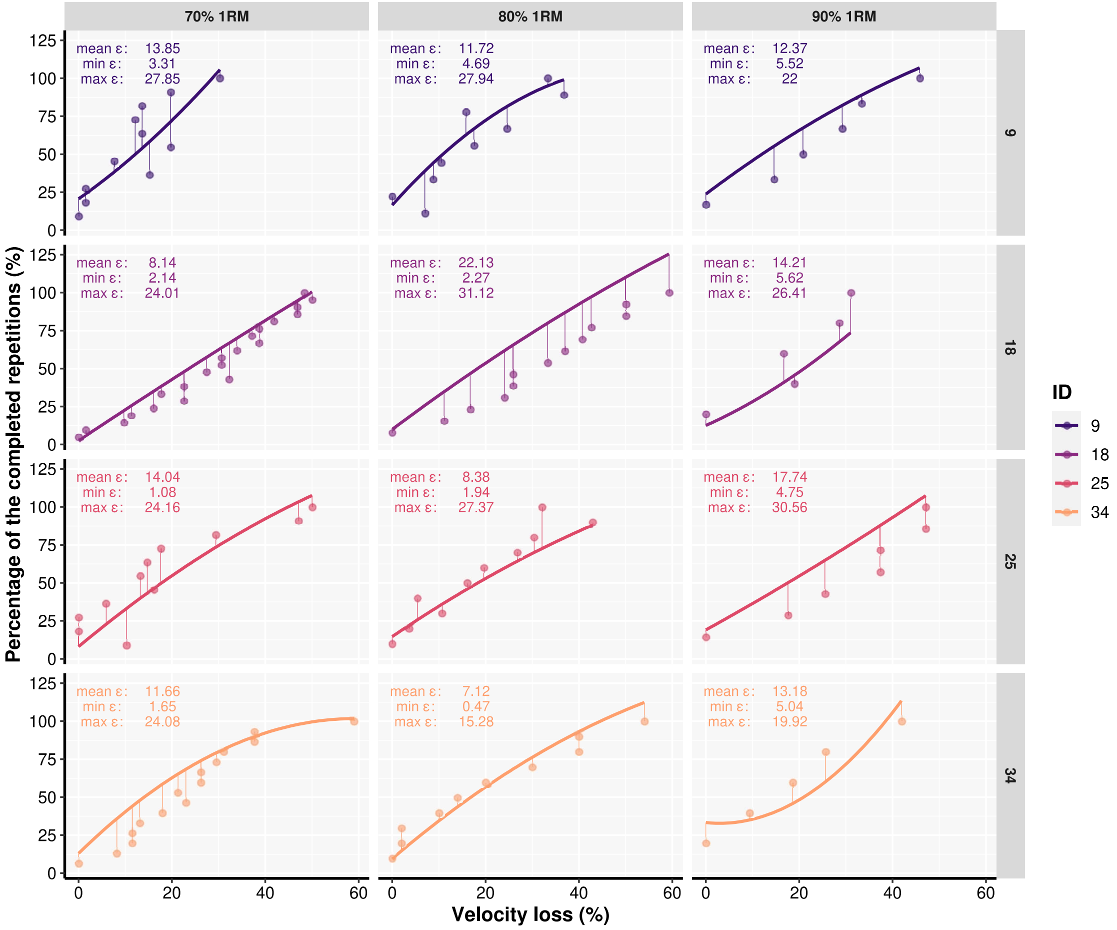
Researchers have previously reported high goodness of fit for the general VL-$\%_{repetitions}$ relationships with a wide range of exercises such as bench press ($R^2 \geq 0.8$), back squat ($R^2 \geq 0.93$), and shoulder press ($R^2 \geq 0.99$) [179, 39]. In the present study, much lower values of R^2 were observed ($R^2 = 0.67 – 0.80$). This discrepancy between the findings could partially be explained by the mode of the exercise used. Previously reported data on the goodness of fit of general VL-$\%_{repetitions}$ relationships came from exercises performed in a Smith machine whereas participants in the present study performed a free-weight back squat exercise. Therefore, it seems that there is a higher variability between the individuals in $\%_{repetitions}$ completed until reaching a given VL threshold when free-weights are used compared to Smith machines. More importantly, individual VL-$\%_{repetitions}$ relationships always provided better goodness of fit compared to general VL-$\%_{repetitions}$ relationships. This finding agrees with the study by Sanchez-Moreno et al. [165] who also recently reported higher goodness of fit for individual (R^2 = 0.97-0.99) compared to general VL-$\%_{repetitions}$ relationships (R^2 = 0.80-0.94) for the Smith machine bench exercise. Furthermore, second-order polynomial regression models always yielded a better fit to the VL-$\%_{repetitions}$ data compared to linear models, suggesting they should be used in practice. While these results are useful, it should also be noted that the RSE for both general (RSE ≥ 12.76) and individual (median RSE ≥ 7.37) VL-$\%_{repetitions}$ relationships always exceeded the 5% mark. This is important to consider as such an error – although being in an acceptable range for individual VL-$\%_{repetitions}$ relationships – may indicate that this prescription method does not provide any additional benefits for practitioners compared to more traditional RT prescription methods. These findings may also imply the instability of VL-$\%_{repetitions}$ relationships in providing accurate estimations of $\%_{repetitions}$ in practice. Finally, sex, training status and history as well as personality traits did not affect the goodness of fit of general and individual VL-$\%_{repetitions}$ relationships, indicating the potential generalisability of these findings.

Researchers previously recommended that each training set should be terminated as soon as a given VL is reached instead of prescribing a given, fixed, number of repetitions per set to be performed for each participant [15, 14]. The rationale behind this recommendation was the strong VL-$\%_{repetitions}$ relationship for back squat and bench press exercises performed in a Smith machine. Indeed, descriptive data reported by Gonzalez-Badilo et al. [14] indicate low inter-individual variability for the $\%_{repetitions}$ until reaching a given VL. However, Rodriguez Rosell et al. [39] recently suggested that the prescription of RT volume by using VL should be specific for each exercise and load. Careful inspection of the $\%_{repetitions}$ until reaching a given VL data in the present study suggests that the variability between individuals may indeed be very high (i.e., high standard deviations), despite similar mean $\%_{repetitions}$ values for a given VL threshold between the two testing sessions. Furthermore, this variability remained when the descriptive data of the present study were broken down by sex, training experience, and relative strength (Appendix F Ch. 5 File V). In fact, some differences could be observed, depending on the load and VL threshold, between sexes, participants with different levels of training experience, and relative strength. Nevertheless, it is important to highlight that the agreement between the $\%_{repetitions}$ until reaching a given VL on two testing sessions has not been examined to date. This is crucial as it directly assesses the practical utility of the VL-$\%_{repetitions}$ relationship for monitoring and prescribing RT set-volume. In this regard, the findings of the present study indicate substantial disagreement between $\%_{repetitions}$ performed until reaching a given VL threshold on two consecutive testing sessions (72 hours apart), regardless of the load used. Collectively, due to considerable variability in the $\%_{repetitions}$ performed until reaching a given VL threshold across participants and the observed disagreement between $\%_{repetitions}$ for a given VL threshold on two consecutive testing sessions, VL-$\%_{repetitions}$ relationship does not appear to be stable enough for monitoring and prescribing RT volume with a free-weight back squat exercise.

Although many studies have been recently published on the VL-$\%_{repetitions}$ relationship, the predictive validity of this relationship has not yet been examined. Researchers have previously examined the goodness of fit of VL-$\%_{repetitions}$ relationships on two separate days [14, 165]. Since this goodness of fit was generally very high for bench press and back squat exercises performed in a Smith machine, the conclusion would be that VL-$\%_{repetitions}$ relationship can safely be used to reliably, and with high precision, prescribe and monitor RT set-volume. Unfortunately, these findings are of limited ecological validity for free-weight exercises and provide limited empirical support for the use of VL-$\%_{repetitions}$ relationships to monitor and prescribe RT set-volume. This is because practitioners cannot establish a VL-$\%_{repetitions}$ relationship in every single training session with their athletes, patients, or clients. Therefore, to confirm the usefulness of the VL-$\%_{repetitions}$ relationship, one would ideally want to know whether the established VL-$\%_{repetitions}$ relationship for a given individual during an initial testing session predicts future data, in this case, the $\%_{repetitions}$ completed in subsequent training sessions reasonably well. The findings of the present study indicate that the predictive validity of both general and individual VL-$\%_{repetitions}$ relationships was unacceptable since the mean absolute differences between the predicted and observed $\%_{repetitions}$ in the subsequent testing session always exceeded the 10% mark, regardless of the load used (Appendix F Ch. 5 File V).

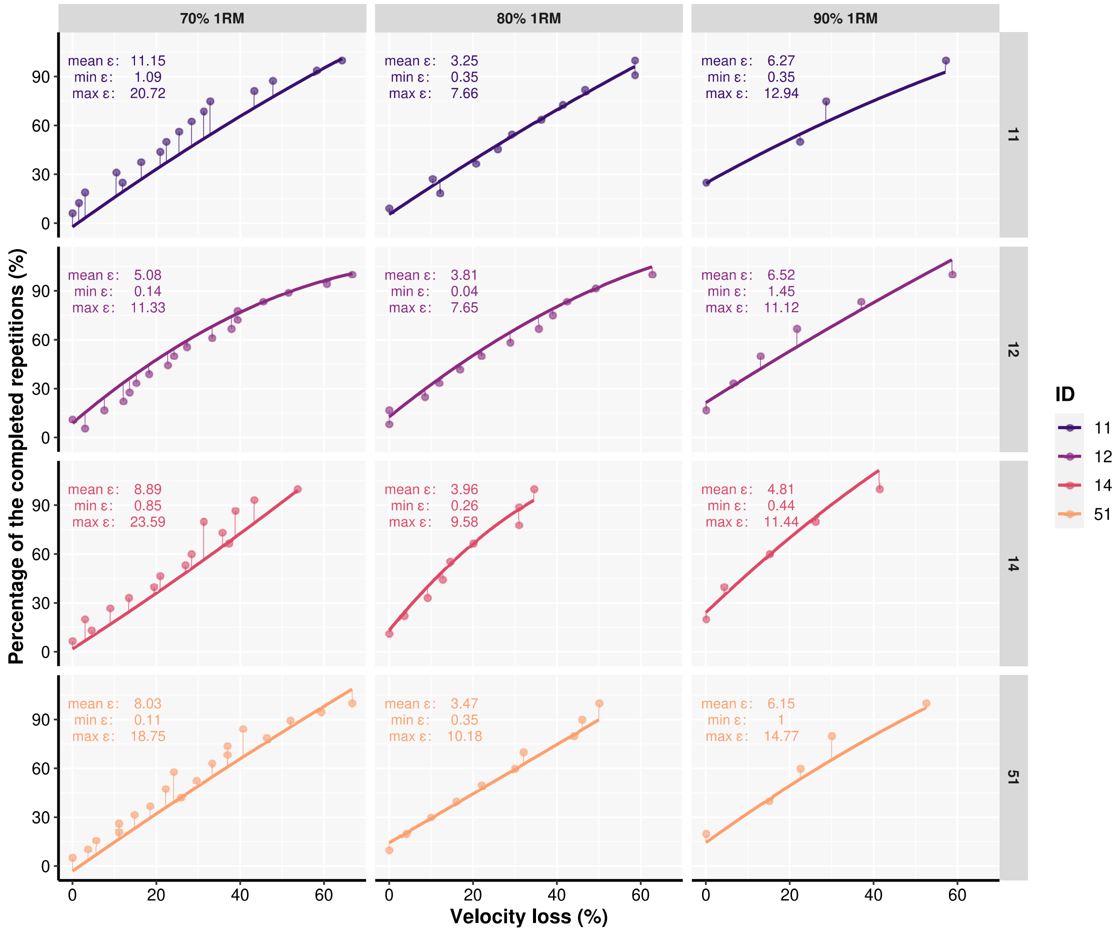
On an individual basis, there may be some circumstances where VL could provide utility for volume prescription, but the model prediction error is often very high for some individuals, at least for some loads. For instance, Figure 5-4 visualises representative participants' data where models' prediction errors always exceeded a 5% mark and frequently exceeded errors of 10% or more, as it was very often the case among the participants in the present study. In contrast, Figure 5-5 demonstrates representative participants' data where models' prediction errors were often lower than 5% but still exceeded that or even the 10% threshold for at least one of the loads for every participant. A more nuanced look at these figures allows for an appreciation of the maximal prediction error for individual $\%_{repetitions}$ with a given VL threshold and load. This is important as only focusing on mean error across the $\%_{repetitions}$ can hide the inability of the model to accurately predict the entire VL-$\%_{repetitions}$ spectrum. This indicates that problems can arise when prescribing a specific VL with a specific load for an individual whose model's prediction error was very high for that particular VL and its associated $\%_{repetitions}$.

Figure 5-4 Individual relationships between velocity loss and the percentage of the repetitions completed out of maximum possible established with the second-order polynomial regression in the first testing session (line) and fitted to the data of the second testing session (dots).



Note. Thin vertical lines connecting thick lines and dots across participants represent distances (or residual errors) between predicted and observed data. Mean (mean ε), minimal (min ε), and maximal (max ε) errors are also presented for each participant and load. This data is from representative participants where models' prediction errors always exceeded a 5% error mark and frequently exceeded errors of 10% or more.

Figure 5-5 Individual relationships between velocity loss and the percentage of the repetitions completed out of maximum possible established with the second-order polynomial regression in the first testing session (line) and fitted to the data of the second testing session (dots).



Note. Thin vertical lines connecting thick lines and dots across participants represent distances (or residual errors) between predicted and observed data. Mean (mean ε), minimal (min ε), and maximal (max ε) errors are also presented for each participant and load. This data is from representative participants where models' prediction errors did not always exceed the 5% error mark but still exceeded that or even the 10% threshold for at least one of the loads for every participant.

The present study also aimed to investigate what factors are associated with the observed prediction errors and the probability of exceeding a 10% prediction error. Based on the results of both models, only the choice of load (i.e., 90% of 1RM) inflated the prediction error compared to lower loads. In addition, the loads participants used during their own training appeared to affect prediction errors, with those usually training with higher loads (i.e., > 80% of 1RM, on average) having lower prediction errors and thus lower probability of exceeding a 5% prediction error. However, training with higher loads, on average, could still imply somewhat higher confidence and motivation to increase muscle strength in general, which may or may not be related to the training experience. Finally, other training history factors, relative strength, sex, and personality traits did not affect prediction errors of VL-$\%_{repetitions}$ relationships. Thus, these findings could probably be generalised within the resistance-trained population with a free-weight back squat exercise.

The present study comprehensively examined the predictive validity of the VL-$\%_{repetitions}$ relationship for monitoring and prescribing RT while also exploring the effects of a range of factors related to RT. However, there are several limitations that should be considered when interpreting the results. Firstly, it is unknown whether the findings of the present study transfer to other free-weight exercises. However, it seems reasonable to posit that the effects of training history, and status, sex, and personality traits are likely applicable to a variety of exercises. Secondly, the participants in the present study had at least 6 months of RT experience; thus, it is unclear whether the current findings generalise to those without RT experience (e.g., sedentary populations, trainees completing other exercise modalities). This may partially explain why in the present study, training experience did not influence the outcomes of interest. Thirdly, since the loads were not performed in a randomised order, residual fatigue incurred from the heavier loads (i.e., 90 and 80% of 1RM) could have influenced performance in subsequent sets (i.e., 80 and 70% of 1RM) and the between-day agreement for the $\%_{repetitions}$ completed across VL thresholds. However, this potential influence was mitigated by at least 72 hrs rest between trials, long inter-set rest periods (i.e., 10 mins), and the descending order of the load (i.e., higher to lower) in which participants completed the RTF sets. Fourthly, while efforts were made to recruit an equal sample of male and female participants, the number of females included in the analysis was substantially lower than males. However, it should be noted that the females in the present study had a wide range of strength levels, training experience, and different training practices, improving the sample's generalisability, and perhaps explaining the lack of sex differences [180] in this study. Finally, it should be acknowledged that the choice of the threshold for acceptable agreement and predictive validity could influence findings and interpretation thereof. However, the LoA for $\%_{repetitions}$ across testing sessions were much higher than 10% (even higher than 30%) and prediction errors rarely approached excellent or even acceptable levels. To conclude, a RT monitoring and prescription method with a higher than 10% error may not be justified in practical settings, given the existence of other well established, cost-free methods of monitoring and prescribing RT set-volume, such as stopping sets at a predetermined perceived number of repetitions in reserve [181].

5.5 Conclusions

The present study expands on the previous velocity-based RT literature while providing several novel findings, specifically for free-weight exercises. While individual VL-$\%_{repetitions}$ relationships always provided greater goodness of fit compared to general relationships, both displayed high variability. Specifically, the results of the present study question the utility of using either general or individual VL-$\%_{repetitions}$ relationships to prescribe RT volume with a free-weight back squat exercise as 1) the agreement in the $\%_{repetitions}$ completed until reaching a given VL threshold across two consecutive testing sessions was not acceptable, regardless of the load used; and 2) the ability of both general and individual VL-$\%_{repetitions}$ relationships to predict $\%_{repetitions}$ in a subsequent testing session was poor and always led to prediction errors higher than 10%. Sex, training status, and history as well as personality traits did not affect the goodness of fit of general and individual VL-$\%_{repetitions}$ relationships as well as their prediction accuracy, thus suggesting potential generalisability of those findings among the resistance-trained population. Therefore, VL-$\%_{repetitions}$ relationships do not seem to provide any additional benefits compared to more traditional, free methods and hence should not be used for the purposes of monitoring and prescribing RT with a free-weight back squat exercise.

Chapter 6: The fastest repetition in a set predicts the number of repetitions completed during resistance training the impact of individual characteristics

Preface

Considering the findings of Chapter 5, alternative means of monitoring and prescribing resistance training (RT) set volume are clearly needed. Traditionally, RT loads are prescribed as a percentage of one-repetition maximum (1RM; e.g., 85% of 1RM) or load that allows the performance of a certain number of repetitions before reaching muscle failure (XRM; e.g., 12RM is the load that can be lifted exactly 12 times). Unfortunately, establishing 1RM or XRM for the purposes of RT monitoring and prescription can be physically and psychologically demanding and time-consuming (e.g., compromised safety and frequent testing for different exercises). Moreover, if 1RM and XRM are not re-evaluated frequently, they become outdated as training adaptations occur. Further, both RT prescription methods can also under- or over-estimate individuals' abilities on a given day even when re-evaluated periodically due to individuals' normal fluctuations in readiness caused by environmental, lifestyle, and other training factors. Despite efforts to establish %1RM-velocity relationships with different exercises, little attention has been given to the potential XRM-velocity relationship which could, if proven valid, effectively allow for more accurate RT intensity and set-volume prescription. This chapter expands on previous chapters and explores the predictive validity of individual and general XRM-velocity relationships during the free-weight back squat while taking into account sex, training history and status as well as personality traits of the individuals.

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6.1 Introduction

Resistance training (RT) is performed by athletes to optimise strength, power and hypertrophy [1]. Additionally, it is recommended by national health organisations for improving health in the wider population [123, 32]. Designing efficient, individualised RT programs requires considering many variables such as exercise selection, order, intensity, volume, and others. However, intensity and volume are considered critical in program design due to their profound effects on the magnitude of RT-induced adaptations [3, 4].

Traditionally, RT intensity is prescribed via percentage of one-repetition maximum (1RM; e.g., 85% of 1RM) or a load that allows a given number of repetitions before reaching muscle failure (XRM; e.g., 12RM is the load that can be lifted exactly 12 times). Unfortunately, establishing 1RM or XRM for the purposes of RT monitoring and prescription can be physically and psychologically demanding and time consuming (e.g., compromised safety, frequent testing for different exercises) [5]. Moreover, if 1RM and XRM are not re-evaluated frequently, they become outdated as training adaptations occur. Both RT prescription methods can also under- or over-estimate individuals' abilities on a given day, even when re-evaluated periodically, due to normal fluctuations in readiness to train caused by environmental, lifestyle, and other training factors. Thus, researchers search for alternatives to 1RM and XRM prescription methods.

One of the proposed alternatives for prescribing RT intensity consists of recording barbell velocity during incremental loading tests to establish a load-velocity profile [182, 169]. Indeed, many researchers report an inverse, linear relationship between barbell velocity and %1RM [183, 182], although a minority of their studies use free-weight exercises [28, 169]. One rationale for monitoring repetition velocity relies upon its stability at a given load [28], meaning any fluctuation in velocity beyond the normal variation observed between training sessions likely reflects fatigue or strength gains [28]. Thus, monitoring velocity may help individualise training prescription. Further, researchers suggest individual- rather than general load-velocity profiles be established because %1RM-velocity relationships are highly individual [169, 184, 185].

Despite the benefits of establishing an individual load-velocity profile for monitoring and prescribing RT, some professionals still prefer the use of the XRM-based method as it guarantees the knowledge of the number of repetitions left in reserve by individuals with a given load. Additionally, compared to other RT prescription methods, knowing an individual's XRM provides insight into the training volume completed. While there are different ways of monitoring volume, it is usually defined as the number of sets and repetitions in a training session. Thus, if sets are fixed, volume is largely determined by repetitions per set (i.e., set volume). Set volume can be monitored by prescribing the XRM of a given load for an individual. However, it must be noted that researchers previously reported the number of repetitions completed to failure (RTF) is highly individual depending on training background and the %1RM used [12]; though individual load-velocity relationships may reduce this variability [179, 165]. Despite efforts to establish %1RM-velocity relationships with different exercises, little attention has been given to the potential XRM-velocity relationship.

Only two previous studies [120, 131] attempted to establish XRM-velocity relationships using maximal velocity of each set to failure to predict different XRMs. The authors reported that individual, rather than general (i.e., pooling the data from all individuals) XRM-velocity relationships provided a better goodness of fit for both Smith machine bench press and bench-pull exercises, allowing better XRM prediction accuracy [131, 120]. However, the XRM-velocity relationship for free-weight exercises such as the back squat is unexplored, which is important given the popularity of free-weight exercises among trainees, especially athletes. Other methodological factors should also be considered with the XRM-velocity relationship. Notably, the predictive validity of such relationships has not been examined in free-weight exercises with multiple loads. Unless an initially established XRM-velocity relationship can predict a subsequent XRM with acceptable accuracy, it suffers the same drawbacks as traditional, non-velocity-based RT prescriptions (e.g., normal daily fluctuations affect the relationship's accuracy). Moreover, it is unknown whether sex, training status and history affect the XRM-velocity relationship's stability. Personality traits such as emotional stability and conscientiousness can influence how individuals cope with fatigue [22], thus potentially affecting the XRM-velocity relationship's accuracy. Therefore, many factors related to the XRM-velocity relationship are yet unexplored.

To address the above-mentioned scarcity in the literature, this study 1) examined the goodness of fit of general and individual XRM-velocity relationships during free-weight back squats; 2) determined the effects of sex, training status and history, and personality traits on the models' fit; and 3) determined whether general and individual XRM-velocity relationships accurately predicted subsequent testing session data and examined factors potentially affecting this accuracy. Based on previous studies [120, 131], we hypothesised a greater goodness of fit for individual XRM-velocity relationships, whereas no other hypotheses were formulated given the dearth of literature on the topic.

6.2 Methods

6.2.1 Design

A repeated-measures, crossover design was used to investigate the predictive ability of the maximal velocities of three sets to failure with different loads in the free-weight back squat exercise for determining XRM. Before RTF sessions, two preliminary sessions occurred including a familiarisation session with all procedures and conditions, and a 1RM free-weight back squat assessment. Thereafter, participants reported to the laboratory on two separate occasions and performed a single set with 90, 80, and 70% of their pre-determined 1RM with 10 minutes rest between sets, and 72 hours rest between sessions. To control for environmental and diurnal factors, the same researchers were always present, and all sessions occurred at the same time (± 1 hour) under similar (∼20°C and ∼60% humidity) conditions.

6.2.2 Participants

Fifty-one resistance-trained people (15 females and 36 males; 18-40 years old) were initially recruited. Unfortunately, five males withdrew due to injury outside the study (n = 3) or for undisclosed personal reasons (n = 2). These participants' data were not analysed as the purpose of this study was to determine the prediction accuracy of the XRM-velocity relationship. 1RM relative to body mass ranged from 0.86 – 2.12 and 1.18 – 2.61 for females and males, respectively. More participant data are reported in Appendix F Ch. 6 File I. Participants had to confirm they (1) were willing to cease additional lower-body training during the study; (2) were not taking any medications related to metabolic or cardiovascular functioning; (3) were not injured; (4) were not taking anabolic steroids and did not have a history of their use; and (5) had a least 6 months of RT experience, training at least twice per week, performing back squats at least once a week, without more than two weeks off during that period. Before commencing, participants gave informed, written consent. The University Ethics Committee approved the study protocol (approval number: 20/55).

6.2.3 Familiarisation session

Upon arrival, participants completed a training history questionnaire, then provided training logs for their most recent, heaviest back squat session, and conservatively estimated their 1RM to inform warm-up loads for the subsequent 1RM session. Their body mass and height were then recorded using an electronic scale and wall mounted stadiometer (Seca Ltd, Hamburg, Germany). Thereafter, participants completed a standardised warm-up of cycling at 100 rpm for 5 mins and dynamic stretching for 2 mins; 10 bodyweight lunges and squats; and 10 barbell-only squats. Participants were then familiarised with the visual feedback on a screen showing mean barbell velocity and instructions (1) to descend into a squat at a controlled velocity, to then lift the barbell up as fast as they can, and (2) to take at least a momentary pause between repetitions, not lasting more than 2 seconds, while remaining in contact with the floor (i.e., no jumping or lifting the heels). To ensure familiarity with the instructions and visual feedback, participants then completed 3 repetitions at 20, 40, and 60%, then 10 repetitions at 60% of estimated 1RM under those conditions. All participants performed at least two sets with consistent repetition velocities (± 0.02 m/s) and reported they felt comfortable with the instructions and visual feedback.

6.2.4 One repetition maximum session

Participants performed the same standardised warm-up before the 1RM assessment. Thereafter, participants performed 3 repetitions at 20, 40, and 60%; and 1 repetition at 80 and 90% of estimated 1RM, followed by 1RM attempts using a 20-kg barbell (Rogue, Columbus, Ohio, USA) and calibrated weight plates (Eleiko, Halmstad, Sweden, EU) [186, 170, 169, 28]. After successful 1RM attempts, load increased 1-12.5kg in consultation with the participants. 1RM tests terminated when participants could not complete an attempt or when a completed attempt required compromised movement technique. A maximum of five 1RM attempts were allowed. Three- and four-minutes rest were provided between submaximal sets and 1RM attempts, respectively. Participants adopted self-selected foot stances and eccentric tempos. They received the same lifting instructions as during the familiarisation session and were verbally encouraged and had a screen in front of them providing visual barbell velocity feedback. For a repetition to be considered successful, the top of the participants' thighs had to be at least parallel to the floor, which was visually confirmed by the researchers, and a camera perpendicular to the participant.

6.2.5 Repetitions to failure sessions

Before RTF tests, participants performed the same standardised warm-up as during previous sessions. Thereafter, participants completed 10, 5, 3, and 1 repetitions of the free-weight back squat against 30, 50, 70, and 90% of their established 90% of 1RM (i.e., the heaviest load for the day), respectively. Three minutes rest between warm-up sets and 4 minutes prior to the first set to failure was provided. Participants performed RTF from the highest to lowest load (i.e., 90% first, 80% second, and 70% 1RM third) in a fixed sequence to prevent excessive fatigue accumulation – caused by the high-repetition test with 70% – from negatively affecting RTF with 80 and 90%. To ensure recovery, 10 minutes rest was provided between sets and 72 hours between sessions. The same lifting instructions, verbal encouragement, and visual feedback standardisation previously described also occurred during RTF sessions.

6.2.6 Data Acquisition

To examine habitual RT practices of the participants, they were asked about 1) the number of repetitions they perform in training, on average; 2) the intensity of load at which they usually train; 3) the usual number of repetitions they leave in reserve at the end of sets, and 4) their training experience. The full training history questionnaire is presented in Appendix F Ch. 6 File II. Questions were multi-choice, and thus responses were treated as categorical. Response frequency was inspected for each category (overall and within levels of outcome variables used in models) and these variables were recoded by merging several response options to avoid having less than 5 responses in more than 20% of cells.[145] Specifically, the number of repetitions performed (1-5, 5-8, and >8) and load (<70, 70-80, 80-90) were transformed into categorical variables containing three levels. The number of repetitions in reserve (0-2 and 2-4) and RT experience (≤3 and >3) were transformed into categorical variables containing two levels.

A GymAware (Kinetic Performance Technologies, Canberra, Australia) linear position transducer (LPT), was used to monitor velocity of all repetitions. Two LPTs were placed on either side of the barbell, perpendicular to the position between the hands and the loaded barbell sleeves, per the manufacturer's instructions. The reliability and validity of this LPT was previously confirmed and its characteristics described elsewhere [187, 171]. The GymAware v2.8.0 app was used on a tablet (iPad, Apple Inc., California, USA) to transmit data from the LPT via Bluetooth. The LPT attached to the right side of the barbell was connected to a TV providing visual feedback of mean barbell velocity for each repetition. Thus, all analyses are based on this LPT's data. To avoid issues with cloud data storage or internet connectivity, mean velocity of all repetitions was manually recorded and organised in an excel spreadsheet (Microsoft Corporation, Redmond, Washington, USA). Additionally, to ensure consistency and accuracy, this was always completed by the same two researchers.

To assess personality, the 50-item International Personality Item Pool (IPIP) Big Five Personality Inventory was used [146, 147]. This inventory contains 50 questions, 10 for each personality dimension (Agreeableness, Conscientiousness, Extraversion, Neuroticism, and Openness). IPIP items were administered via 5-point, Likert-type scales ranging from 1 (very inaccurate) to 5 (very accurate). Scores were obtained by averaging the scores for each item. Only conscientiousness and emotional stability were analysed.

6.2.7 Statistical analysis

Linear regression models – with maximal velocity of each set as a predictor and XRM as the outcome – were used to determine individual and general XRM-velocity relationships. General relationships were determined separately for each testing session by pooling data from all participants, whereas individual relationships were obtained for each participant separately, on both testing sessions. The goodness of fit of general relationships was examined though the coefficient of determination (R^2) and residual standard error (RSE) of the models, whereas medians and ranges of R^2 and RSE were evaluated for individual XRM-velocity relationships.

Multiple linear regression models were used to examine influential factors on individual XRM-velocity relationships' goodness of fit. Load (3 levels), training experience (2 levels) and practices (2 or 3 levels), relative strength and conscientiousness and emotional stability were all considered predictors.

The predictive validity of the general and individual XRM-velocity relationships was examined by using the models from the first testing session and fitting them to the second testing session data. The general and individual models' errors were then evaluated by calculating an absolute difference between the observed and predicted data in the second testing session. Models were deemed practically useful for monitoring and prescribing RT if the error rates were below 2 repetitions. To examine factors affecting the probability of exceeding a prediction error of more than 2 repetitions, multiple logistic regression models were used, specified with a binomial distribution and a logit link function.

For linear models, predictors' estimates and 95% confidence intervals (95%CI) were calculated and presented whereas for generalised models, odds ratios with associated 95%CI were evaluated and presented to aid interpretation. For categorical predictors with more than 2 levels, post-hoc Holm-Bonferroni corrections were performed. Additional models' specification and diagnostics details are in Appendix F Ch. 6 File III.

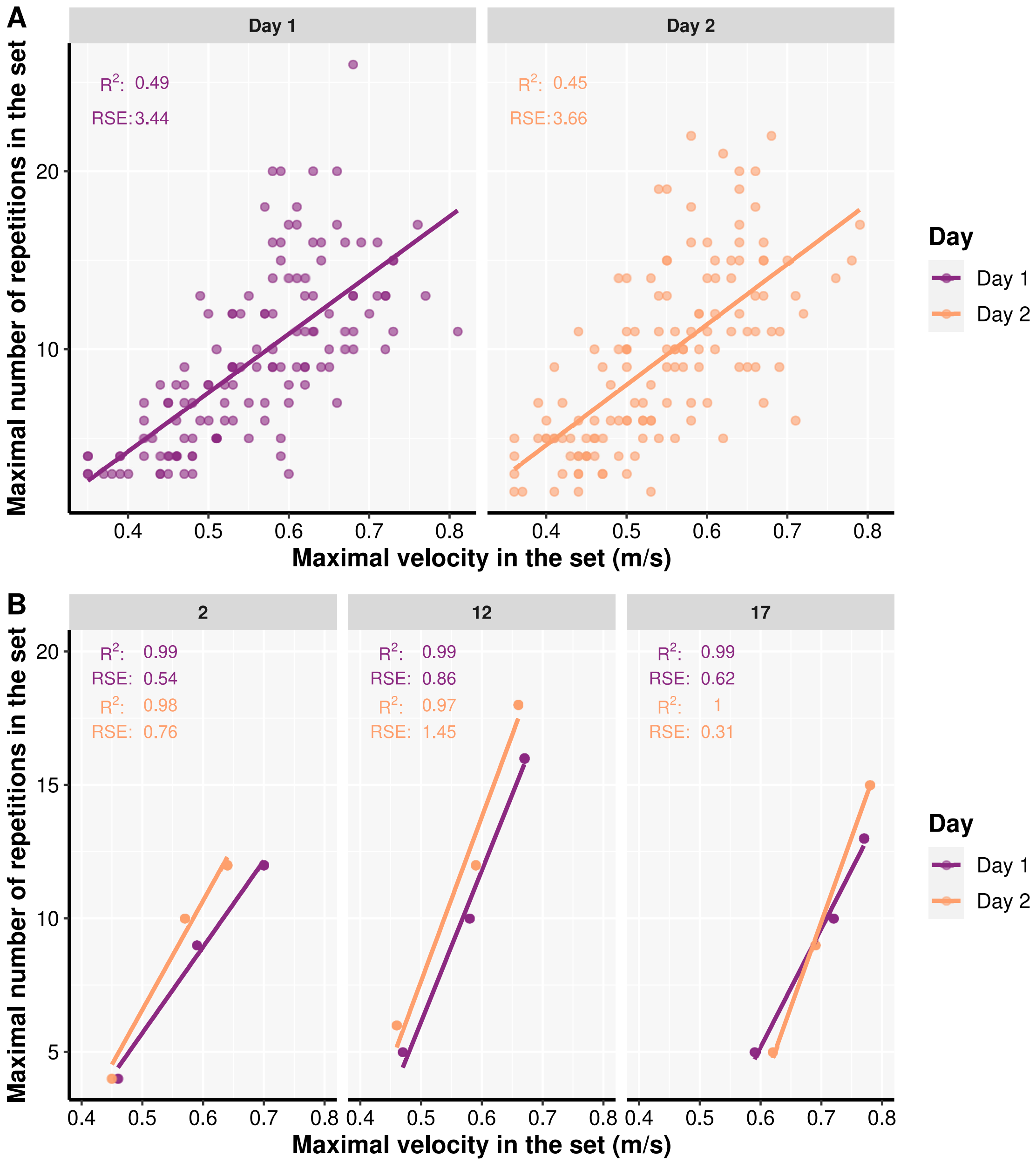
All statistical analyses were performed in R language and environment for statistical computing (version 4.2.0, The R foundation for Statistical Computing, Vienna, Austria) using the *stats* package, models' performance using the *performance* package [175], and preparation and visualisation of data using the *tidyverse [177]* and *sjPlot [178]* packages. Custom-written R script and associated dataset are available at the Open Science Framework repository (URL: https://osf.io/pqa3v/).

6.3 Results

Goodness of fit for the general XRM-velocity relationship was strong and comparable on the first (R^2 = 0.45; RSE = 3.44 repetitions; Figure 6-1) and second (R^2 = 0.49; RSE = 3.66 repetitions; Figure 6-1) testing sessions. However, the goodness of fit of the individual XRM-velocity relationships was always stronger on both the first (R^2 = 0.98 [0.58, 1.00]; RSE = 1.01 [0.07, 5.5] repetitions; Figure 6-1) and second (R^2 = 0.98 [0.50, 1.00]; RSE = 1.15 [0.12, 4.24] repetitions; Figure 6-1) testing sessions. R^2 of the individual XRM-velocity relationships was not affected by any of the examined factors ($p \geq 0.295$; Table

6-1). Individual models' RSE was only affected by sex, with males having lower RSE than females ($p = 0.033$; Table 6-1).

Figure 6-1 General (A) and individual (B) relationships between absolute velocity of the fastest repetition in a set and the maximum number of repetitions completed in a set



Note. Coefficient of determination (R^2) as well as residual standard errors (RSE) are also presented for general and individual relationships established on both testing sessions. The data for the individual relationships are from three representative participants.

Table 6-1 Factors affecting the goodness of fit of individual XRM-velocity relationships.

	R^2			RSE		
Predictors	Estimates	CI	p	Estimates	CI	p
(Intercept)	0.99	0.79 – 1.19	< 0.001	1.27	-0.83 – 3.36	0.232
Day [Day 2]	-0.00	-0.04 – 0.04	0.984	-0.07	-0.47 – 0.34	0.739
Sex [male]	0.03	-0.03 – 0.09	0.389	-0.70	-1.34 – -0.06	0.033
Emotional Stability	-0.00	-0.00 – 0.00	0.483	0.02	-0.01 – 0.06	0.225
Conscientiousness	-0.00	-0.01 – 0.00	0.295	-0.00	-0.04 – 0.03	0.866
Training experience [> 3 years]	0.02	-0.02 – 0.07	0.328	0.10	-0.40 – 0.60	0.686
Loads practices [70 – 80% 1RM]	0.03	-0.03 – 0.09	0.325	0.19	-0.44 – 0.82	0.553
Loads practices [> 80% 1RM]	0.04	-0.03 – 0.11	0.271	0.32	-0.40 – 1.04	0.380
Repetitions practices [8 – 12]	0.01	-0.04 – 0.06	0.734	-0.13	-0.69 – 0.43	0.648
Repetitions practices [> 12]	-0.01	-0.07 – 0.05	0.727	0.62	-0.00 – 1.24	0.051
Repetitions in reserve practices [> 2 RIR]	0.02	-0.03 – 0.06	0.476	0.22	-0.28 – 0.72	0.383
Relative strength (1RM/BM)	-0.01	-0.07 – 0.06	0.844	-0.27	-0.98 – 0.43	0.445
Observations	92			92		
R^2 / R^2 adjusted	0.131 / 0.012			0.220 / 0.112		

Note. Reference groups were the following: Load [70% 1RM], Sex [female], Training experience [< 3 years], Loads practices [< 70% 1RM], Repetitions practices [< 8 repetitions], Repetitions in reserve practices [< 2 RIR]. 1RM, one repetition maximum; BM, body mass; RIR, repetitions in reserve; OR, odds ratio; R^2, coefficient of determination; RSE, residual standard error; CI, 95% confidence intervals; p, p value; XRM-velocity relationship, relationships between the number of repetitions completed to failure and the maximum velocity in the set.

The predictive validity of the general XRM-velocity relationship was not acceptable since the absolute error between the observed and predicted data on the second testing session – using the model established in the first testing session – was higher than 2 repetitions on average (mean ε = 2.81 repetitions; Appendix F Ch. 7 File IV). Individual XRM-velocity relationships displayed acceptable predictive validity as the absolute error of 2 repetitions, although being close to it, was not exceeded on average (mean ε = 1.96 repetitions; Appendix F Ch. 6 File IV). Multiple linear regression models did not reveal any influential factors affecting absolute errors of the individual XRM-velocity relationships in predicting data on the second testing session. In addition, multiple logistic regression models did not reveal any influential factors affecting the probability of exceeding an absolute prediction error of 2 repetitions for individual XRM-velocity relationships (Table 6-2). A more detailed descriptive analysis of prediction errors broken down by sex, training experience, and relative strength is presented in Appendix F Ch. 6 File IV.

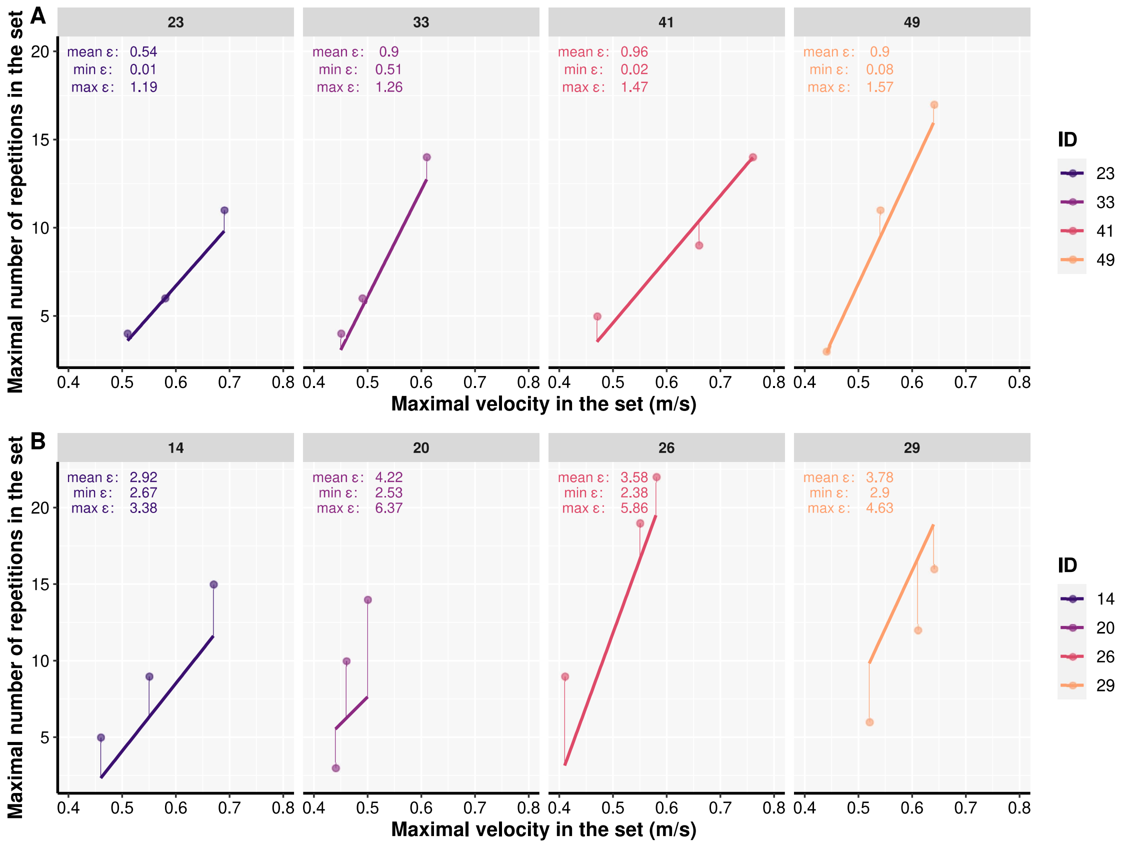
Table 6-2 Factors affecting the 1) the absolute differences between predicted and observed XRM in a subsequent testing session based on individual XRM-velocity relationships; and 2) the probability of individual XRM-velocity relationships exceeding a prediction error of 2 repetitions.

	Absolute differences			Exceeding the error		
Predictors	Estimates	CI	p	OR	CI	p
(Intercept)	1.40	-1.47 – 4.27	0.336	1.15	0.03 – 56.13	0.942
Sex [male]	0.10	-0.78 – 0.98	0.823	0.76	0.23 – 2.47	0.649
Relative strength (1RM/BM)	-0.35	-1.32 – 0.63	0.482	0.52	0.13 – 1.92	0.330
Emotional Stability	0.04	-0.01 – 0.09	0.092	1.04	0.98 – 1.11	0.228
Conscientiousness	0.00	-0.05 – 0.05	0.976	0.98	0.91 – 1.05	0.484
Training experience [> 3 years]	0.03	-0.66 – 0.71	0.935	1.14	0.46 – 2.93	0.774
Repetitions practices [8 – 12]	-0.23	-1.00 – 0.55	0.565	0.83	0.28 – 2.45	0.736
Repetitions practices [> 12]	0.78	-0.07 – 1.64	0.072	2.68	0.87 – 8.58	0.088
Loads practices [70 – 80% 1RM]	-0.46	-1.33 – 0.41	0.297	0.78	0.25 – 2.35	0.652
Loads practices [> 80% 1RM]	-0.72	-1.71 – 0.27	0.151	0.56	0.15 – 2.01	0.378
Repetitions in reserve practices [> 2 RIR]	-0.00	-0.69 – 0.68	0.990	1.42	0.55 – 3.73	0.465
Observations	138			Observations	138	

R^2 / R^2 adjusted	0.162 / 0.096	R^2 Tjur	0.121

Note: Reference groups were the following: Load [70% 1RM], Sex [female], Training experience [< 3 years], Loads practices [< 70% 1RM], Repetitions practices [< 8 repetitions], Repetitions in reserve practices [< 2 RIR]. 1RM, one repetition maximum; BM, body mass; RIR, repetitions in reserve; OR, odds ratio; R^2, coefficient of determination; R^2 Tjur, Tjur's pseudo coefficient of determination for generalised linear models with binary outcomes; RSE, residual standard error; CI, 95% confidence intervals; p, p value; XRM-velocity relationship, relationships between the number of repetitions completed to failure and the maximum velocity in the set.

Figure 6-2 Individual relationships between absolute velocity of the fastest repetition in a set and the maximum number of repetitions completed in a set. Thin vertical lines connecting thick lines and dots across participants represent distances (or residual errors) between predicted and observed data.



Note. Mean (mean ε), minimal (min ε), and maximal (max ε) errors are also presented for each participant and load. This data is from representative participants where models' prediction errors never (A) and always (B) exceeded (A) a 2 repetitions error mark.

6.4 Discussion

This is the first examination of the goodness of fit and prediction accuracy of general and individual XRM-velocity relationships during free-weight back squats while exploring the effects of sex, training status and history, as well as personality traits on goodness of fit and accuracy of those relationships. The main findings were 1) individual XRM-velocity relationships provided a higher goodness of fit compared to general relationships on both testing sessions; 2) the goodness of fit of individual XRM-velocity relationships was not affected by sex, training status and history or personality traits; 3) individual, but not general XRM-velocity relationships established on the first testing session provided acceptable predictions of XRM in the second testing session, on average; and 4) prediction accuracy of individual XRM-velocity relationships was not affected by sex, training status and history, or personality traits. Therefore, these findings expand on previous studies on XRM-velocity relationships in Smith machine exercises and support the utility of individual XRM-velocity relationships with free-weight exercises in practice, regardless of the sex, training status and history, or personality traits of trainees.

Velocity-based RT monitoring and prescription has many applications. The most researched applications are the use of 1) load-velocity profiles which allow for training load prescription that accounts for individuals' daily readiness to train, and 2) the concept of velocity loss (VL) to manage fatigue and set-volume with stipulations to perform repetitions until a pre-determined VL is exceeded [35]. Indeed, a strong relationship exists between VL magnitude and percentage of completed repetitions out of the maximum possible [14, 39]. Thus, researchers recommended each training set should be terminated when a given VL is reached instead of prescribing a given, fixed, number of repetitions per set. [14] However, authors of more recent studies outlined several methodological issues with using VL in practice.[45]. Specifically, these authors noted high inter-individual variability in the number of completed repetitions before reaching different VL thresholds, suggesting the inability of VL thresholds to control for set-volume across individuals with adequate prevision [45]. To address this issue, Garcia-Ramos et al. [120] and Miras-Moreno et al. [131] proposed the use of maximal velocities across sets to failure to predict XRM and control for set-volume in Smith machine exercises. In line with their findings [131, 120], the goodness of fit for individual XRM-velocity relationships was considerably greater in the present study, with R^2 values twice as high for individual compared to general XRM-velocity relationships in the free-weight back squat. Moreover, the current study also investigated factors affecting the goodness of fit of individual XRM-velocity relationships. Only sex affected the goodness of fit, with males' XRM-velocity relationships having a slightly lower RSE ($p = 0.033$) compared to females. However, the median *RSE* for females was still low and comparable to males (RSE = 1.42 vs 0.94), with almost identical R^2 values for the model's fit ($R^2 = 0.97$ vs 0.98). Importantly, participants in the present study performed only 3 sets to failure, compared to the previous studies [120, 131] where participants performed 4 sets to failure to establish the XRM-velocity relationship. Thus, the testing procedure for the XRM-velocity relationship could be further simplified by performing only 3 sets to failure with 90, 80, and 70% of 1RM, as in the present study. Since the XRM-velocity relationship seems to be linear, it is likely that this relationship can be further simplified by examining only two loads (i.e., the two-point method). Though, this is yet to be investigated.

Although high goodness of fit is important for judging the usefulness of any model, it does not guarantee its predictive validity. Researchers previously reported a high goodness of fit of XRM-velocity relationships on two separate days and concluded it could be used to reliably, and with high precision, estimate different XRMs in Smith machine exercises [120, 131]. However, such findings do not necessarily confirm the predictive validity of XRM-velocity relationships since they were established using the data from the respective sessions. Modelling XRM-velocity relationships would be useful for RT monitoring and prescription purposes, and more beneficial compared to no cost, traditional RT prescription methods, only if they can predict future XRM data reasonably well. Therefore, the present study investigated the ability of general and individual XRM-velocity relationships established on the first testing session to predict XRM in the subsequent testing session. We observed general XRM-velocity relationships had unacceptable prediction errors of 2.81 repetitions, on average. In contrast, individual XRM-velocity relationships demonstrated lower, acceptable (i.e., < 2 repetitions) prediction errors, on average. Neither sex, training status, history, or personality traits affected the accuracy of individual XRM-velocity relationships. Considering all the above, individual, but not general XRM-velocity relationships demonstrate acceptable accuracy and may be useful for RT monitoring and prescription.

Although the prediction errors of individual XRM-velocity relationships were acceptable, on average, caution should be exercised when implementing this concept in practice as models’ prediction errors for some individuals might still be unacceptable. For instance, Figure 6-2 illustrates 8 individuals’ data. For half of them, models’ prediction errors were on average almost perfect (< 1 repetition; Figure 6-2), but for the other half, prediction errors exceeded as many as 4 repetitions (Figure 6-2). Looking more closely at those individuals did not reveal any unique or explanatory factors differentiating them from one another. Namely, they had similar training practices and personality traits, and in both groups, there were 2 females and males. The only noticeable, albeit minor, difference was observed in relative strength, with the group of 4 individuals who had lower prediction errors being slightly stronger (relative strength = 1.56 vs 1.40 1RM/body mass). However, since multiple regression models did not reveal any effects of strength on XRM-velocity relationship prediction accuracy, it is more likely that relative strength does not affect prediction accuracy, rather some other unexplored factor(s) may. Interestingly, when the mean prediction accuracy of XRM-velocity relationships was broken down by sex, strength levels and training experience, models for less experienced individuals consistently yielded higher errors than for more experienced individuals (Appendix F Ch. 6 File IV). Additionally, this was exaggerated among less strong individuals, especially males. Therefore, practitioners should evaluate XRM-velocity relationships on case-by-case basis and especially among less experienced individuals, determine their usefulness to safeguard against potential, unwanted prediction errors which can lead to erroneous training decisions and suboptimal training adaptations.

In the present study, the goodness of fit and predictive validity of XRM-velocity relationships for monitoring and prescribing RT were examined while also exploring the effects of a range of factors on these relationships. Based on the findings reported in this study, practitioners can predict XRM daily without frequent RTF testing using only the fastest repetition in a set which allows them to prescribe RT loads (e.g., 8RM), and at the same time, to have an insight into the training volume completed and the number of repetitions left in reserve after the set is completed. However, there are several considerations when interpreting the results. First, whether these findings transfer to other free-weight exercises is unknown. However, the effects of training history, and status, sex, and personality traits are likely applicable to a variety of exercises. Second, all participants had ≥6 months of RT experience which may explain why training experience did not affect the stability or accuracy of the XRM-velocity relationships. However, it is unclear whether these findings can be extrapolated to those without RT experience. Third, there were fewer females in this study than males. However, the females had a wide range of strength levels, training experience, and training practices, improving the sample's generalisability. Finally, notably, the acceptable prediction error choice for the threshold of XRM-velocity relationships may have influenced our findings and interpretation thereof. However, any method with an error greater than 2 repetitions may not be justifiable in practical settings, given other well-established, cost-free methods of monitoring and prescribing RT set-volume exist, such as stopping sets at a predetermined perceived number of repetitions in reserve.

6.5 Conclusion

The present study expands on previous XRM-velocity relationship studies while providing several novel findings, specifically for free-weight exercises. Individualised XRM-velocity relationships provided twice as high goodness of fit and were able to predict XRM in a subsequent testing session with acceptable accuracy compared to general XRM-velocity relationships. Although sex, training status and history, and personality traits did not affect the goodness of fit of individual XRM-velocity relationships or their prediction accuracy, some individual XRM-velocity relationships might still yield unacceptable prediction errors. Therefore, XRM-velocity relationship accuracy should be evaluated on a case-by-case basis and future studies should explore additional factors which might cause prediction errors in some individuals. Nevertheless, an individual XRM-velocity relationship can be established with a simple linear regression model using the maximal velocity of three sets to failure with 90, 80 and 70% of 1RM and the corresponding number of repetitions performed to failure. This allows practitioners to prescribe RT loads matching an intended XRM by recording only the fastest velocity of the set (usually within the first 3 repetitions) with a given load and predicting, with reasonable accuracy, an individual's XRM.

Chapter 7: Modelling the repetitions-in-reserve-velocity relationship is a valid method for resistance training monitoring, prescription, and fatigue control

Preface

In Chapters 2 and 5, it was demonstrated how the relationship between velocity loss and the percentage of the completed repetitions suffers from several methodological issues. For instance, the exact number of repetitions performed, or left in reserve after completing a set remains unknown, and the percentage of the completed repetitions for a given velocity loss could vary across individuals, exercises, and loads. Perhaps, the simplest solution for this problem could be the use of repetitions in reserve-based rating of perceived exertion (RIR-based RPE) scale. Although this method is very practical and useful, it may be problematic since it is subjective, and its accuracy may be compromised among less experienced individuals. To address this problem, modelling the RIR-velocity relationship could be useful as it combines both velocity-based and RIR-based approaches to resistance training monitoring and prescription while relying only on the well-established velocity loss increase as the number of repetitions in a set increase. Therefore, this Chapter expands on Chapter 6 while exploring the validity of yet another potential alternative method to resistance training monitoring and prescription method using velocity loss.

This Chapter is under review in *Physiological Reports* journal.

7.1 Introduction

Resistance training (RT) is often performed by athletes to improve muscle strength, power, and hypertrophy as these adaptations often coincide with improvements in jumping, sprinting, change of direction, and sport-specific performance [1, 2]. In addition, RT is also recommended to the general population due to its profound, positive effects on physical and mental performance, health, and quality of life [30-32]. Many variables come into play when designing an efficacious RT program such as exercise selection, order, frequency, intensity, volume, velocity, and set structure, among others. However, training intensity and volume receive comparably more attention from the scientific literature as the manipulation of these training variables often determines the magnitude of RT-induced adaptations.

RT intensity is historically prescribed by selecting the load relative to the individual's one-repetition maximum (1RM). On the other hand, RT volume is often defined as the number of sets and repetitions performed in a training session. Thus, when the number of sets for a training session is fixed, volume is prescribed and largely determined by the number of repetitions performed per set (i.e., set-volume). Set-volume prescription is often based on the theoretical relationship between a maximum number of repetitions individuals can do with a given percentage of 1RM (%1RM); thus, presenting an inherent connection between traditional RT intensity and volume prescription. While this RT prescription approach is relatively simple and ideal for implementation in practice, there are several limitations to it. Firstly, the 1RM test can be physically and psychologically demanding and time consuming and can also compromise the safety of an individual doing the test [5]. Additionally, while 1RM tests are generally reliable [6], changes in other factors that are challenging to control such as mood state [10] and multimedia exposure immediately prior to [11] and poor sleep [7] the day prior to testing can impact strength performance. Thus, if a 1RM test happens to be reflective of abnormal performance, positive or negative, subsequently prescribed RT intensity would be lighter or heavier than needed to achieve desired training adaptations. Likewise, even if a 1RM test does accurately reflect current strength levels of an individual, using this test to continuously prescribe RT intensity can be erroneous as it does not account for inherent variation in human performance due to normal biological and psychological variability and factors such as sleep [188], nutrition [8], and life stress [9], all of which can affect RT performance. Secondly, the maximal number of repetitions that can be completed to failure with different exercises and loads varies substantially among individuals [12]. This suggests that prescribing the same relative load with a fixed number of repetitions will likely lead to heterogeneous training stimuli across individuals. To combat these fundamental issues with traditional RT intensity and volume prescription, sport scientists have proposed a velocity-based approach to monitoring and prescribing RT programs [35].

The rationale behind a velocity-based approach to RT intensity prescription relies on the strong, inverse relationships between barbell velocity and the %1RM observed in many multi-joint exercises [35]. Indeed, this relationship is reliable in both Smith machine and free-weight exercises [184, 185, 28], and thus useful for prescribing RT intensity by adjusting the absolute load to match the velocity associated with the intended %1RM intended for a given training session. For set-volume prescription, a velocity-based approach may also be beneficial as the barbell velocity decreases within a set when the exercise is performed with maximal concentric effort and fatigue ensues [15]. Indeed, a very close relationship between velocity loss (VL) and the percentage of performed repetitions out of the maximum possible in a set was observed for different exercises performed in a Smith Machine [14, 189]. According to these studies, when a 30% VL in a set is reached, the individuals have completed approximately 50% and 60% of the maximum number of repetitions in the bench press and pull-up exercises, respectively [14, 189]. Unlike the load-velocity relationship, the relationship between VL and the percentage of the completed repetitions suffer from several methodological issues [45]. For instance, the exact number of repetitions performed, or left in reserve after completing a set remains unknown, and the percentage of the completed repetitions for a given VL could vary across individuals, exercises, and loads [14, 39]. Thus, current velocity-based approaches offer advantages for RT intensity prescription but may be of limited use for RT volume prescription.

One of the most simplistic ways to terminate sets based on fatigue accumulation during RT is using the repetitions in reserve-based rating of perceived exertion (RIR-based RPE) scale [190]. More specifically, individuals could be instructed to terminate sets based on the number of additional repetitions they believe they could complete before reaching muscle failure. Thus, when the load and number of sets are fixed for a given session, individuals can perform repetitions until reaching a pre-determined RIR intended for inducing the desired training stimulus. Although this relatively novel method of autoregulation during RT is very practical and useful, it may be problematic since it is subjective, such that RIR accuracy is highest among those with sufficient RT experience when training closer to failure with moderate- to low-repetition sets [191, 192]. To address this problem, modelling the RIR-velocity relationship could be useful as it combines both velocity-based and RIR-based approaches to RT monitoring and prescription while relying only on the well-established VL increase as the number of repetitions in a set increase.

Only two studies [40, 120] attempted to establish the relationship between RIR and velocity. Morán-Navarro et al. [40] examined the within-individual variability for the velocity associated with a given number of RIR in the Smith machine bench press, shoulder press, bench pull, and back squat. Although the authors concluded that velocity at a given RIR is very similar and highly reliable for a given exercise, noteworthy within-individual variability was observed, especially for the bench press and shoulder press exercises and less experienced individuals. Similarly, Garcia Ramos et al. [120] also reported large between-individual variability for velocity at a given RIR (from 1 to 10). Based on these findings, it seems that a RIR-velocity relationship, like a load velocity relationship, is highly individual, though this is yet to be confirmed. However, it is important to note that RIR-velocity relationships have not been established for free-weight exercises, despite their popularity among trainees, especially athletes. Additionally, little is known how sex, modelling strategies (e.g., linear vs polynomial regression models), training history and strength levels affect the stability of RIR-velocity relationships. Personality traits such as emotional stability and conscientiousness could also potentially affect the stability of RIR-velocity relationships as these traits generally affect how people cope with fatigue [22]. Importantly, the predictive validity of RIR-velocity relationships – as well as factors affecting it – should also be examined to determine the usefulness of this method for RT monitoring and prescription in practice. Therefore, it is evident that many factors related to the RIR-velocity relationship are yet to be explored.

To consider the above-mentioned scarcity in the literature, this study aimed to 1) examine the goodness of fit of general and individual RIR-velocity relationships fitted with linear and polynomial regression models in a free-weight back squat exercise; 2) determine the effects of sex, training status and history, as well as personality traits on the models' fit; 3) determine the ability of general and individual RIR-velocity relationships to predict data in a subsequent testing session and examine the factors potentially affecting the accuracy of the predictions; and 4) determine whether the RIR-velocity relationship provides acceptable prediction accuracy by averaging velocities of repetitions associated with RIRs that participants achieved with more than a single load. Based on the high inter-individual variability of velocity at different RIR reported in the previous two studies [120, 40], we hypothesis a greater goodness of fit for individual RIR-velocity relationships, whereas no other hypotheses were formulated due to the dearth of literature on the topic.

7.2 Methods

7.2.1 Design

This study is a part of a larger project investigating the validity of different velocity-based RT monitoring and prescription methodologies. Participants reported to the laboratory on four occasions with 48-72 hours of rest between the sessions. In the first session, after participants' anthropometric measures were taken, participants were familiarised with the free-weight back squat movement, the equipment, instruments, verbal instructions to move the barbell up as fast as they can, and visual feedback on the screen of barbell velocity. In the second session, participants performed an incremental loading (i.e., 1RM) test in the back squat exercise. In the final two sessions, participants completed repetitions to failure (RTF) tests in the same exercise with 90, 80, and 70% of their established 1RM. All sessions were performed at the same time of the day for each participant (± 1 hour), with the same researchers present, and under similar environmental conditions (∼20°C and ∼60% humidity) to control for the potential effects of these factors on performance.

7.2.2 Participants

Fifty-one strength-trained people (15 females and 36 males; 18 to 40 years of age) participated in this study. Three male participants withdrew from the study due to injuries during their work or recreational sporting activity not related to the study, whereas two male participants dropped out of the study due to undisclosed personal reasons after completing one and three experimental sessions. Since the primary aim of this study was to determine the validity of general and individual RIR-velocity relationships, only data from participants who completed all sessions were retained for the analysis. The 1RM in the free-weight back squat exercise was 83.29 ± 19.91 (relative strength = 1.25 ± 0.30) and 149.30 ± 23.66 (relative strength = 1.79 ± 0.35) for females and males, respectively. To be eligible for this study, participants had to confirm they 1) were willing to abstain from any additional lower-body training during the study; 2) were not currently taking medication that would alter metabolic or cardiovascular functions; 3) had no musculoskeletal limitations; 4) were not currently using anabolic steroids or had a history of use; and 5) had at least 6 months of RT experience training at least 2x/week including the back squat exercise at least 1x/week, with no longer than 2 weeks in a row off training during that period. Each participant provided written informed consent prior to commencing the study. The protocol of this study was approved by and was in accordance with the ethical requirements of the University Ethics Board (approval number: 20/55).

7.2.3 Familiarisation session

Participants first completed a questionnaire related to their training history and usual RT practices upon arriving to the laboratory (Appendix F Ch. 7 File I). They were also asked to provide logs of their most recent (and heaviest) back squat sessions and to conservatively estimate their 1RM. This information was later used to prescribe the loads for familiarisation with the lifting instructions and for warm-ups during the upcoming 1RM session. Next, participants' body mass and height were measured using an electronic column scale and a wall mounted stadiometer (Seca Ltd., Hamburg, Germany). Participants then completed a standardised warm-up consisting of cycling at 100 rpm for 5 min, dynamic stretching for 2 min, 10 bodyweight lunges and squats, as well as 10 barbell-only squats. Thereafter, participants were familiarised with the instruction to lift the barbell up as fast as they can (during the concentric muscle action), feedback on the screen indicating velocity of the barbell, and the instruction to have at least a momentary pause at the top of the movement not lasting longer than 2 seconds between repetitions with feet maintaining contact with the floor (i.e., no jumping or lifting of the heels) at all times. To ensure familiarity with these instructions and general conditions for the 1RM and RTF tests, participants then completed 3 repetitions at 20, 40, and 60% of their estimated 1RM, and then 10 repetitions at 60% of their estimated 1RM. During these repetitions, participants were provided the abovementioned instructions as well as visual feedback indicating the velocity of the barbell. At the end of each session, all participants understood and felt comfortable with these conditions, and performed at least two sets with consistent repetition velocities (± 0.02 m/s).

7.2.4 One repetition maximum session: Day 2

During the 1RM session, participants completed the same standardised warm-up as in the familiarisation session. The 1RM assessment was performed using a 20-kg barbell (Rogue, Columbus, Ohio, USA) and calibrated weight plates (Eleiko; Halmstad, Sweden, EU). The 1RM protocol consisted of 3 repetitions each at 20, 40, and 60%, and 1 repetition at 80, and 90% of an estimated 1RM, followed by 1RM attempts [169]. After each successful attempt, the load was increased in consultation with the participant from 1 to 12.5 kg until no further weight could be lifted or until movement technique was compromised. In addition, a maximum of five 1RM attempts were allowed for each participant. Three and four minutes of passive rest were provided between each submaximal set and 1RM attempt, respectively. Participants always adopted a self-selected foot stance and eccentric tempo. Strong verbal encouragement and visual feedback were provided throughout all trials. Participants were required to reach a squat depth at which the tops of the thighs were at least parallel to the floor, as determined by the investigators and a camera positioned perpendicularly to the participant, for a repetition to be considered successful.

7.2.5 Repetitions to failure sessions: Days 3 and 4

The same standardised warm-up as in the familiarisation and 1RM sessions was performed during the RTF sessions. Participants then completed four sets of 10, 5, 3, and 1 repetition of the free-weight back squat exercise against 30, 50, 70, and 90% of the 90% of their established 1RM (i.e., the heaviest load to be lifted that day), respectively. They were provided with 3 minutes of rest between warm-up sets, and 4 minutes between the last warm-up set and the first set to failure. After the general and specific warm-up, participants performed three sets with 90, 80 and 70% 1RM respectively, to failure with 10 minutes of rest between sets. Since the excessive fatigue from performing a high number of repetitions during RTF with 70% 1RM could have compromised the number of repetitions performed during subsequent RTF sets with 80% and 90% of 1RM, the loads were not tested in a randomised fashion. Instead, participants always performed RTF with the highest load (i.e., 90% 1RM) first while the last RTF set was always performed with the lowest load (i.e., 70% 1RM). With regards to the exercise execution (including lifting instructions, encouragement, and visual feedback), the same conditions applied as during the 1RM session. The rest between two successive RTF sessions was 72 hours.

7.2.6 Data acquisition

The training history and RT practices questionnaire can be found in the Appendix F Ch. 7 File I. Briefly, the questions were related to the experience participants have with RT, in years, and the average 1) number of repetitions they perform during their own training; 2) intensity of load at which they train; and 3) number of RIR they have left after completing their training sets. As the questions were multiple-choice; participants' responses were treated as categorical. After inspecting frequencies of responses for each category (both overall and within levels of outcome variables used in models), these variables were recoded by merging some response options to avoid having less than 5 responses in more than 20% of cells/categories [145]. In particular, the number of repetitions performed was transformed into a categorical variable with three levels (1–5, 5–8, >8), as well as was the intensity of load (<70, 70–80, 80–90), whereas the number of RIR and the experience with RT were transformed into categorical variables with two levels (0–2 and 2–4; ≤3 and >3, respectively).

In this study, mean velocity of all repetitions was monitored using the GymAware (GymAware, Kinetic Performance Technologies, Canberra, Australia) linear position transducer (LPT). An LPT was placed on both sides of the barbell perpendicular to the position between the hands and the loaded barbell sleeves, according to the manufacturer's instructions. The reliability and validity of this LPT has been previously confirmed and its characteristics described elsewhere [171, 187]. Data obtained from the LPT were transmitted via Bluetooth to a tablet (iPad, Apple Inc., California, USA) using the GymAware v2.8.0 app. LPT attached to the right side of the barbell was connected to the TV and provided visual feedback indicating velocity of the barbel after each repetition. The data from this LPT was used for the analysis. Finally, to avoid any data loss due to issues with online clouds or the internet connection, mean velocity of all repetitions were manually recorded and organised in a Microsoft Excel spreadsheet (Microsoft Corporation, Redmond, Washington, USA) during each session. To ensure consistency and accuracy of this procedure, the same two researchers handled this task throughout the study.

International Personality Item Pool (IPIP) Big Five Personality Inventory was used to assess stable personality traits, namely, Agreeableness, Conscientiousness, Extraversion, Neuroticism, and Openness [146, 147]. The inventory contains 50 statements (items), 10 for each of the mentioned Big Five personality dimensions which was administered using the Qualtrics survey-building software. Participants had to estimate how well each statement describes them using a 5-point Likert-type scale ranging from 1 (*very inaccurate*) to 5 (*very accurate*). Scores were averaged across items to obtain total scores for each of the five personality dimensions. For the purposes of the present study, only conscientiousness and emotional stability were used in the analysis.

7.2.7 Statistical Analysis

Linear and second order polynomial regression models were used to fit the general and individual RIR-velocity relationships. General RIR-velocity relationships were established separately for each load and testing session by pooling together the data from all participants, whereas individual relationships were determined for each participant separately, on both testing sessions and with each load. The goodness of fit of general relationships were examined though the coefficient of determination (R^2) and residual standard error (RSE) of the models, whereas medians and ranges of R^2 and RSE were evaluated for individual RIR-velocity relationships.

Linear mixed-effects models with the Gaussian conditional distribution and identity link function were used to examine factors influencing the goodness of fit of individual RIR-velocity relationships. For this purpose, the load (3 levels), training experience (2 levels) and practices (2 or 3 levels), relative strength and conscientiousness and emotional stability were all considered as fixed effects.

Predictive validity of the general and individual VL-$\%_{repetitions}$ relationships was examined by using the models from the first testing session (i.e., general model with all participants' data pooled and individual models of each participant) and fitting them to the data of the second testing session. Thereafter, general, and individual models' errors were evaluated by calculating an absolute difference between the observed and predicted data in the second testing session. Models' absolute error of less than 1 repetition was deemed excellent, 1-2 repetitions acceptable, and more than 2 repetitions error not useful for monitoring and prescribing RT. This decision was made given the existence of other well established, cost-free methods of monitoring and prescribing RT, such as stopping sets at a predetermined perceived number of RIR [193]. To examine factors which influenced the absolute differences between observed and predicted data, linear mixed-effects models were used, as previously described. Finally, to confirm the robustness of these findings, generalised linear mixed-effects models, with a binomial conditional distribution and logit link function, were also used to examine factors affecting the probability of not exceeding an absolute prediction error of 2 repetitions.

For all mixed models, participants (n = 46) were treated as random effects to control for repeated measurements, and the general variation between participants. Since both fixed and random effects were used, restricted maximum likelihood estimation was used for evaluation of the linear-mixed effects models whereas maximum likelihood, with Laplace approximation, estimation was used for generalised linear mixed-effects models. The contribution of both fixed and random effects to the explanatory power of any of the explored models was examined using a likelihood ratio test, deviance statistic, and Akaike Information Criterion score, before selecting the final model to obtain the best-fit while maintaining model parsimony. Importantly, the reduction of the model structure was always theoretically motivated and was done as a last resort. Statistical significance of fixed effects was examined by t-tests based on the Satterthwaite approximation or Wald Z-tests for linear mixed-effects and generalised linear mixed-effects models, respectively. For linear mixed-effects models, predictors' estimates and 95% confidence intervals (95%CI) were calculated and presented whereas for generalised mixed-effects models odds ratios with associated 95%CI were evaluated and presented to aid interpretation of the findings. For categorical predictors with more than 2 levels, post-hoc tests were performed with Holm-Bonferroni correction. More details on models' specification and diagnostics can be found in Appendix F Ch. 7 File II.

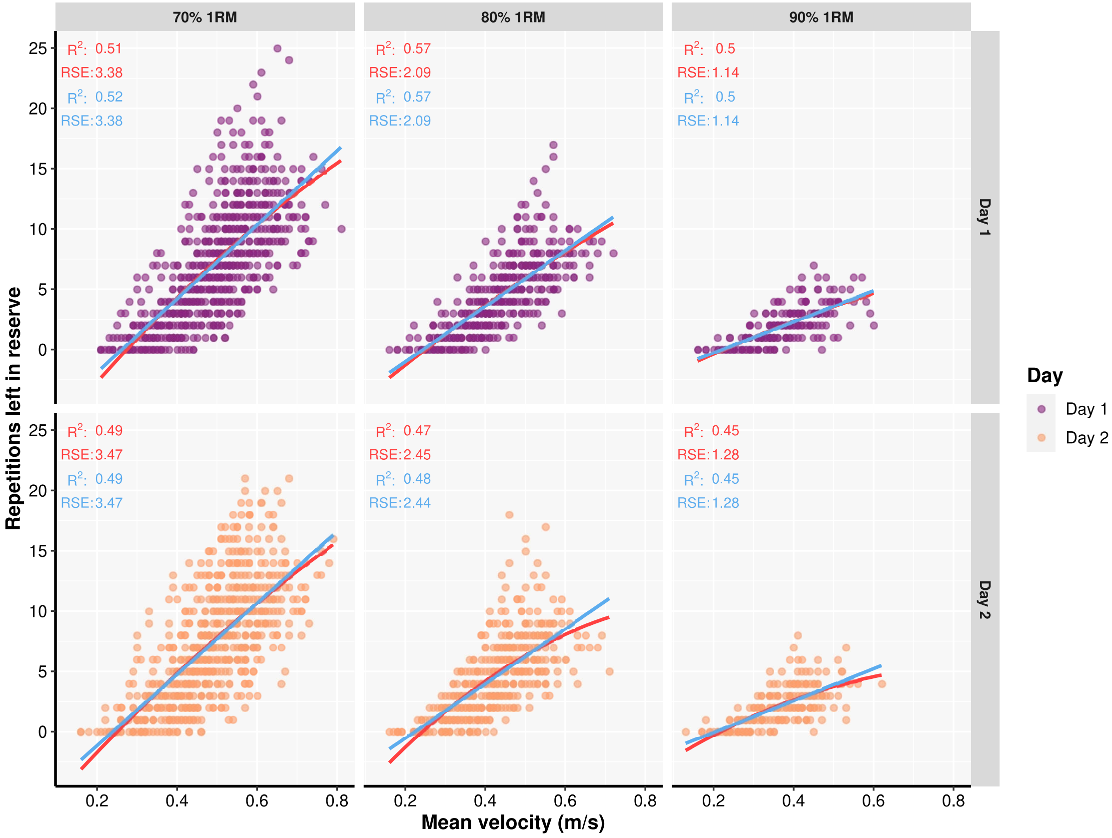
To explore whether RIR-velocity relationships could be further simplified, both general and individual RIR-velocity relationships were also established by averaging velocities of repetitions associated with RIRs that participants achieved with more than a single load. For instance, if an individual performed 5, 10, and 15 repetitions with 90, 80, and 70% of 1RM, respectively, velocities of RIRs from 1 to 5 and 6 to 10 were averaged across three and two loads, respectively. Thereafter, their goodness of fit and prediction validity was assessed as previously described for RIR-velocity relationships for each load separately.

All statistical analyses were performed in R language and environment for statistical computing (version 4.2.0, The R foundation for Statistical Computing, Vienna, Austria) using the *lme4 [173]* and *ggeffects [194]* packages, models' performance using the *performance* and *DHARMa [176]* packages, and preparation and visualisation of data using the *tidyverse [177]* and *sjPlot [178]* packages. Custom-written R script and associated dataset are available at the Open Science Framework repository.

7.3 Results

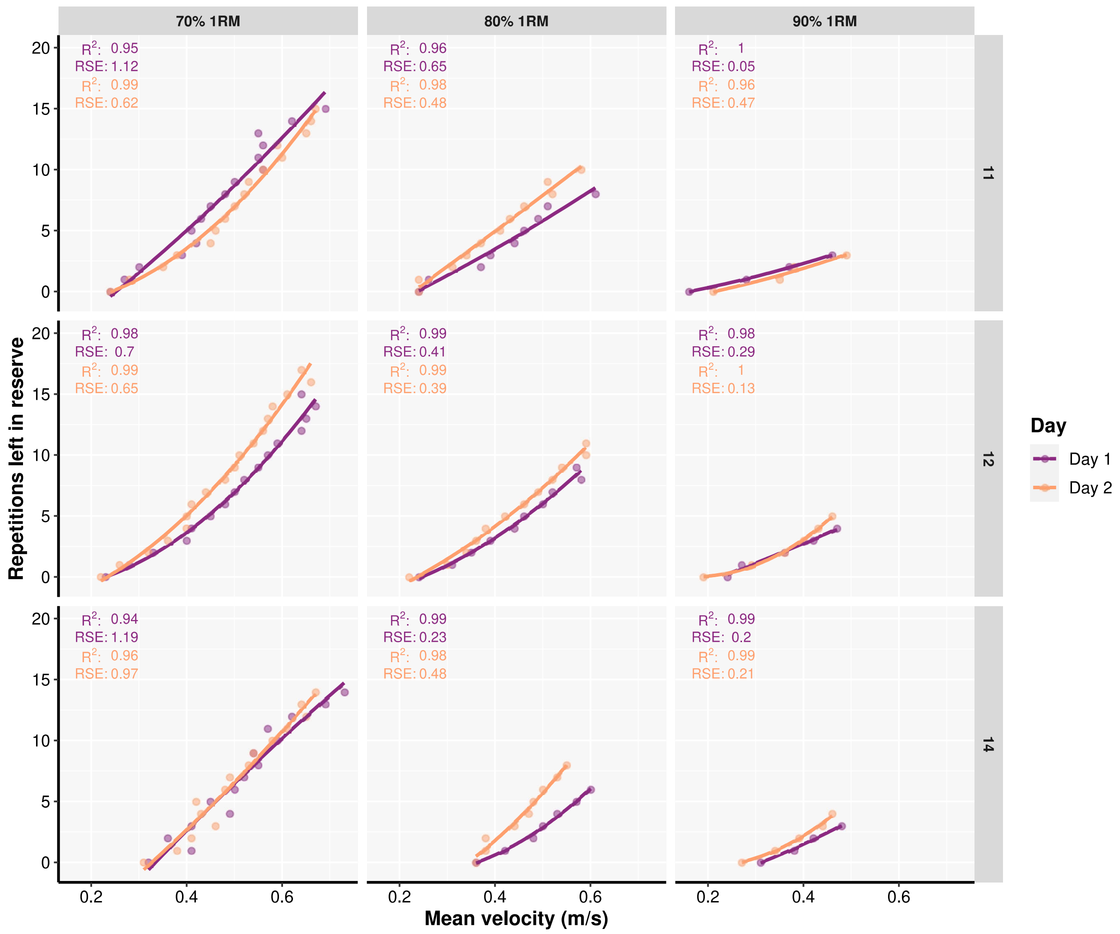
The goodness of fit for the general RIR-velocity relationship across loads and testing sessions was generally strong and almost identical for both linear and second order polynomial regression models (Figure 7-1). However, the goodness of fit of the individual relationships was always stronger (Figure 7-2), regardless of the load, testing session and regression model.

Figure 7-1 General relationship between repetitions left in reserve and mean absolute velocity fitted with linear (red line) and second order polynomial regression (light blue line) models.



Note. Coefficient of determination (R^2) as well as residual standard errors (RSE) are also presented for both linear (in red) and second order polynomial regression (in light blue) models.

Figure 7-2 Individual relationships between repetitions left in reserve and mean absolute velocity fitted with second order polynomial regression models for representative participants.



Note. Coefficient of determination (R^2) as well as residual standard errors (RSE) are also presented for both testing sessions.

The goodness of fit of individual RIR-velocity relationships was affected by testing session, model type, and training experience (Table 7-1). R^2 was higher in the second testing session ($p < 0.001$), when the second order polynomial regression model was used ($p < 0.001$), and with 90% ($p = 0.030$) and 80% ($p = 0.030$) compared to 70% of 1RM load (Appendix F Ch. 7 File III). RSE was higher in the second testing session ($p < 0.001$), as the load decreased from 90% to 70% 1RM ($p < 0.001$) and among less experienced individuals ($p = 0.035$).

Table 7-1 Factors affecting the goodness of fit of individual RIR-velocity relationships.

	R^2			RSE		
Predictors	Estimates	CI	p	Estimates	CI	p
(Intercept)	0.97	0.77 – 1.16	<0.001	0.91	-0.02 – 1.85	0.056
Day [Day 2]	-0.02	-0.04 – -0.01	0.007	0.11	0.05 – 0.17	<0.001
Polynomial model	0.03	0.02 – 0.05	<0.001	-0.06	-0.12 – 0.00	0.056
Sex [male]	0.04	-0.02 – 0.10	0.234	-0.26	-0.55 – 0.03	0.076
Load [80% 1RM]	0.02	0.00 – 0.04	0.017	-0.58	-0.65 – -0.51	<0.001
Load [90% 1RM]	0.03	0.01 – 0.04	0.009	-0.86	-0.93 – -0.78	<0.001
Emotional Stability	-0.00	-0.00 – 0.00	0.432	0.01	-0.00 – 0.03	0.130
Conscientiousness	-0.00	-0.01 – 0.00	0.315	0.00	-0.01 – 0.02	0.730
Training experience [> 3 years]	0.04	-0.00 – 0.09	0.071	-0.24	-0.46 – -0.02	0.035
Habitual loads [70 – 80% 1RM]	0.02	-0.04 – 0.07	0.613	-0.07	-0.36 – 0.21	0.627
Habitual loads [> 80% 1RM]	0.04	-0.03 – 0.11	0.234	-0.07	-0.39 – 0.25	0.679
Habitual repetitions [8 – 12]	0.02	-0.03 – 0.08	0.403	-0.05	-0.30 – 0.20	0.691
Habitual repetitions [> 12]	-0.00	-0.06 – 0.06	0.987	0.14	-0.14 – 0.42	0.328
Habitual repetitions in reserve [> 2 RIR]	0.02	-0.03 – 0.06	0.490	0.04	-0.19 – 0.26	0.728
Relative strength (1RM/BM)	-0.04	-0.10 – 0.03	0.253	0.17	-0.14 – 0.49	0.284
Random Effects						
σ^2		0.01			0.12	
$\tau_{00\ ID}$		0.00			0.09	
ICC		0.30			0.42	
N_{ID}		46			46	
Observations		552			524	
Marginal R^2 / Conditional R^2		0.139 / 0.393			0.458 / 0.686	

Note. Reference groups were the following: Load [70% 1RM], Sex [female], Training experience [< 3 years], Habitual loads [< 70% 1RM], Habitual repetitions [< 8 repetitions], Habitual repetitions in reserve [< 2 RIR]. 1RM, one repetition maximum; BM, body mass; RIR, repetitions in reserve; R^2, coefficient of determination; RSE, residual standard error; ICC, intra-class correlation coefficient; CI, 95% confidence intervals; p, p value. Number of observations for the RSE model is lower than for the R^2 model as some polynomial model with 90% of 1RM resulted in no error (i.e., perfect fit due to the minimum number of data points, ~ 3). These observations were automatically discarded by the model.

Predictive validity of the general RIR-velocity relationship was acceptable for 80% and 90% but not for 70% of 1RM (Appendix F Ch. 7 File IV). Regardless of the load used and whether linear or polynomial models were fitted to the data, predictive validity of individual RIR-velocity relationships was always acceptable since the absolute error between observed and predicted data on the second testing session – while using the data of the first testing session to make predictions – was always lower than 2 repetitions (Appendix F Ch. 7 File III). The linear mixed-effects model investigating factors affecting absolute differences between observed and predicted data on the second testing session revealed only load was an influential factor (Table 7-2), with absolute errors linearly decreasing as the load increased ($p < 0.001$). Similarly, the generalised linear mixed-effects model examining factors affecting the probability of not exceeding an absolute prediction error of 2 repetitions revealed load, sex and number of repetitions typically performed per set were influential factors (Table 7-2). Specifically, the probability of exceeding the 2 repetitions prediction error linearly decreased as the load increased ($p < 0.001$), was greater for females than males ($p = 0.003$), and greater among participants who usually completed more than 12 repetitions compared to those who usually performed less than 8 repetitions during their own training ($p = 0.04$; Appendix F Ch. 7 File III).

Table 7-2 Factors affecting the 1) the absolute differences between predicted and observed RIR in a subsequent testing session based on individual RIR-velocity relationships; and 2) the probability of individual RIR-velocity relationships exceeding a prediction error of 2 repetitions.

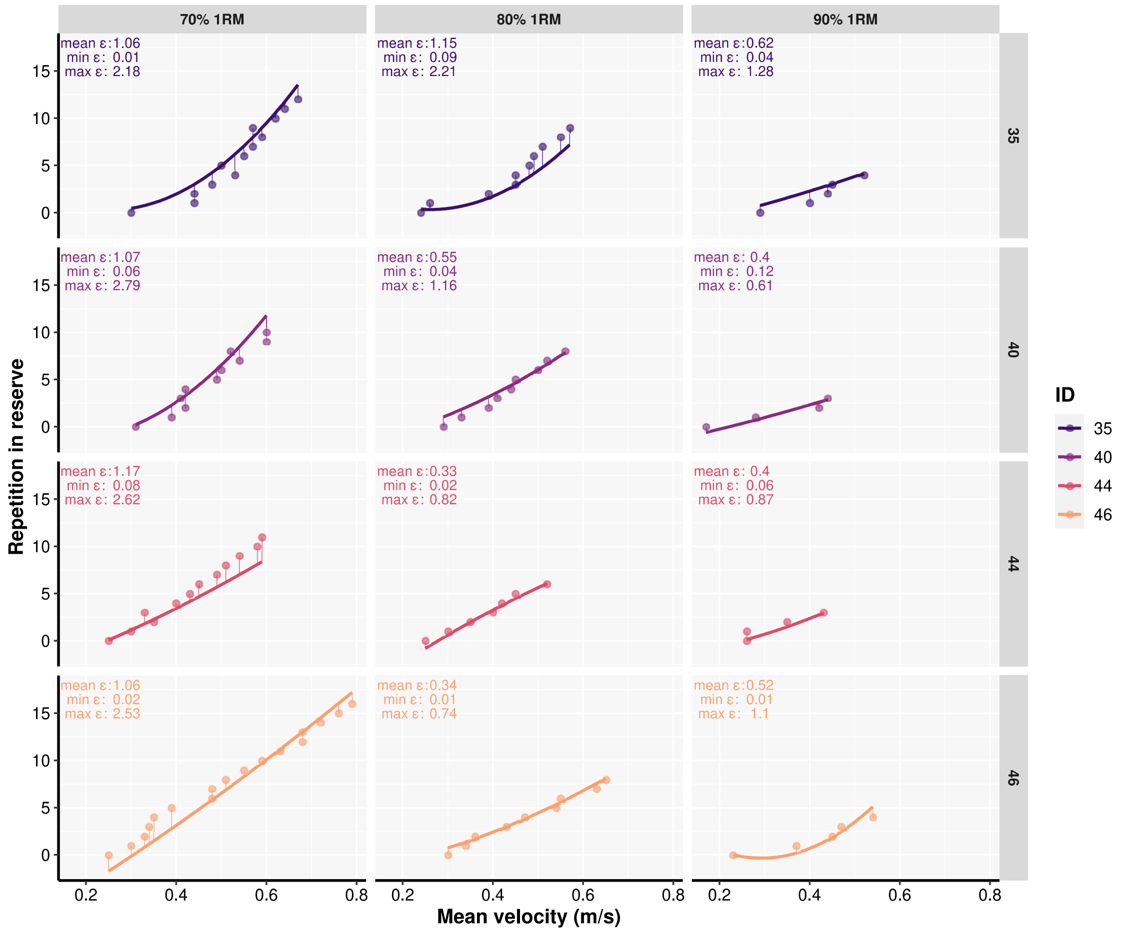
	Absolute differences			Exceeding the error		
Predictors	Estimates	CI	p	OR	CI	p
(Intercept)	1.10	-0.32 – 2.53	0.130	0.02	0.00 – 0.25	0.002
Sex [male]	-0.29	-0.74 – 0.17	0.215	0.30	0.14 – 0.67	0.003
Polynomial model	-0.03	-0.13 – 0.07	0.580	0.97	0.80 – 1.16	0.714
Load [80% 1RM]	-0.41	-0.52 – -0.30	<0.001	0.63	0.51 – 0.77	<0.001

Load [90% 1RM]	-0.81	-0.95 – -0.67	<0.001	0.24	0.17 – 0.33	<0.001
Emotional Stability	0.01	-0.02 – 0.04	0.697	1.03	0.99 – 1.08	0.151
Conscientiousness	0.01	-0.02 – 0.05	0.462	1.04	0.99 – 1.09	0.095
Training experience [> 3 years]	-0.11	-0.55 – 0.34	0.633	0.78	0.42 – 1.43	0.424
Habitual repetitions [8 – 12]	0.00	-0.51 – 0.51	0.992	1.27	0.63 – 2.55	0.508
Habitual repetitions [> 12]	0.56	-0.00 – 1.13	0.051	2.65	1.23 – 5.74	0.013
Habitual loads [70 – 80% 1RM]	0.26	-0.31 – 0.82	0.371	0.90	0.42 – 1.95	0.787
Habitual loads [> 80% 1RM]	0.12	-0.54 – 0.77	0.723	1.16	0.48 – 2.79	0.747
Habitual repetitions in reserve [> 2 RIR]	0.14	-0.32 – 0.59	0.552	1.18	0.64 – 2.18	0.593
Random Effects						
σ^2		1.70			3.29	
$\tau_{00\ ID}$		0.37			0.61	
ICC		0.18			0.16	
N_{ID}		46			46	
Observations		2607			2607	
Marginal R^2 / Conditional R^2		0.099 / 0.261			0.147 / 0.281	

Note. Reference groups were the following: Load [70% 1RM], Sex [female], Training experience [< 3 years], Habitual loads [< 70% 1RM], Habitual repetitions [< 8 repetitions], Habitual repetitions in reserve [< 2 RIR]. 1RM, one repetition maximum; BM, body mass; RIR, repetitions in reserve; OR, odds ratio; R^2, coefficient of determination; RSE, residual standard error; CI, 95% confidence intervals; p, p value; RIR-velocity relationship, relationships between repetitions in reserve and their mean velocity.

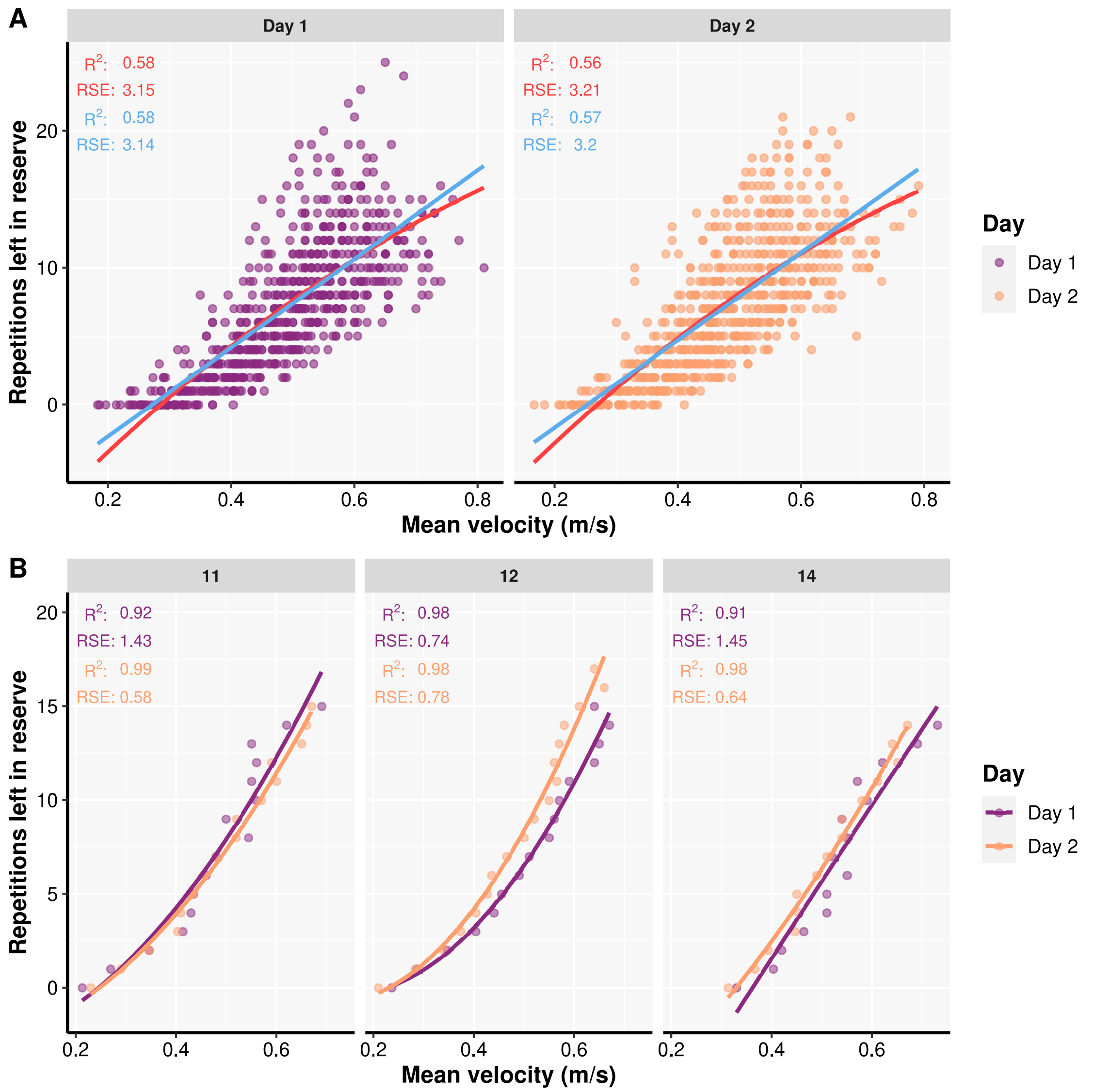
When the overlapping RIRs across sets performed to failure with different loads were averaged, general and individual RIR-velocity relationships' goodness of fit was generally comparable to relationships fitted for each load separately (Appendix F Ch. 7 File V). Similarly, the goodness of fit of individual RIR-velocity relationships was affected by the same factors as previously reported – apart from training experience which was not a significant predictor in these models – for relationships established for each load separately (Appendix F Ch. 7 File V). Predictive validity of individual but not general RIR-velocity relationships averaged across loads was acceptable, with comparable prediction errors for both linear and polynomial models (Appendix F Ch. 7 File V). Finally, models investigating factors affecting predictive validity of individual RIR-velocity relationships averaged across loads revealed only habitual repetitions practices were influential factors, similar to the results reported for RIR-velocity relationships established for each load separately (Appendix F Ch. 7 File V).

Figure 7-3 Individual relationships between repetitions left in reserve and mean absolute velocity established with the second order polynomial regression in the first testing session (line) and fitted to the data of the second testing session (dots).



Note. Thin vertical lines connecting thick lines and dots across participants represent distances (or residual errors) between predicted and observed data. Mean (mean ε), minimal (min ε), and maximal (max ε) errors are also presented for each participant and load. This data is from representative participants where models' prediction errors never exceeded a 2 repetitions error mark.

Figure 7-4 General relationship (A) between repetitions left in reserve and mean absolute velocity fitted with linear (red line) and second order polynomial regression (light blue line) models. Individual relationships (B) between repetitions left in reserve and mean absolute velocity fitted with second order polynomial regression models for representative participants.



Note. Velocities associated with different repetitions left in reserve were averaged across 70, 80 and 90% of 1RM for both general (A) and individual (B) relationships in this figure. Coefficient of determination (R^2) as well as residual standard errors (RSE) are also presented for both testing sessions and relationships.

7.4 Discussion

To our knowledge, this is the first study that examined the goodness of fit and prediction accuracy of general and individual RIR-velocity relationships in a free-weight back squat exercise while also exploring the effects of modelling strategies, sex, training status and history, as well as personality traits on goodness of fit and accuracy of those relationships. The main findings of this study were 1) individual rather than general RIR-velocity relationships yielded a higher goodness of fit for all loads and on both testing sessions; 2) goodness of fit for both individual and general relationships was higher among more experienced compared to less experienced individuals and with higher (i.e., 90 and 80% 1RM) compared to lower loads (i.e., 70% 1RM), but was not affected by sex, training practices nor personality traits; 3) for individual RIR-velocity relationships, second order polynomial regression models yielded a better goodness of fit compared to linear models whereas both regression models fit the data equally well for the general RIR-velocity relationship; 4) individual, but not general, RIR-velocity relationships displayed acceptable *RSE*, regardless of the load or testing session; 5) individual RIR-velocity relationships established in the first testing session always provided acceptable predictions of RIR in the second testing session, regardless of the load, whereas general RIR-velocity relationships yielded acceptable prediction errors only with 80% and 90% 1RM loads; 6) prediction accuracy was only affected by sex and habitual repetition practices in models from males, and those performing less than 12 repetitions during their own training, having a slightly lower prediction accuracy; and 7) goodness of fit and prediction accuracy of individual RIR-velocity relationships averaged across loads were comparable to the ones observed for the relationships established for each load separately. Therefore, these findings support the use of individual RIR-velocity relationships for free-weight RT monitoring and prescription, potentially improving adaptation and fatigue management.

Instead of prescribing a given, fixed number of repetitions per set, some authors recommended that each training set should be terminated when a given VL is reached due to a strong relationship that exists between VL and the percentage of performed repetitions out of the maximum possible for different Smith machine exercises [14]. However, more recently researchers reported methodological issues with this concept with implications for RT volume prescription [45]. For instance, even if a percentage of completed repetitions out of the maximum possible can be determined based on VL experienced in a set, the exact number of RIR remains unknown. This is important since the last repetitions of a set contribute more to the alteration of muscle energy balance and the abrupt increase in metabolites such as ammonia [15, 18, 19] A very practical approach to monitoring RIR is through the use of the RIR-based RPE scale [181] whereby individuals estimate how many additional repetitions they could have performed after finishing a training set. However, this method is subjective, and its accuracy can depend upon prior RT experience and is less accurate when training farther from failure and with moderate- to high-repetition sets [191, 192]. To address this problem, Garcia-Ramos et al. [120] formally established the general RIR-velocity relationship in a Smith machine bench press exercise whereas Moran Navarro et al. [40] examined velocities associated with 2, 4, 6, and 8 RIR in several Smith machine exercises. Both research groups observed some variability – expressed with coefficients of variation – in velocities associated with different RIR which was especially noticeable for upper body exercises [40, 120] and less experienced individuals [40]. In agreement with their observations, the goodness of fit for individual RIR-velocity relationships was considerably greater in the present study, with R^2 values being twice as high for individual compared to general RIR-velocity relationships in the free-weight back squat. The current study also aimed to examined factors affecting the goodness of fit of individual RIR-velocity relationships. Only the load and training experience affected the goodness of fit, with less experienced individuals' RIR-velocity relationships having a lower RSE ($p = 0.035$) compared to more experienced people. In addition, RIR-velocity relationships with greater loads generally displayed lower RSE ($p < 0.001$). However, it should be noted that the median RSE for less experienced individuals (RSE ≤ 1.67) and RIR-velocity relationships with lower loads (RSE ≤ 1.18) was still generally low (even lower when fitted with polynomial regression models) and comparable to more experienced people which was also mirrored by similar R^2 values for the models fit. Considering this, and the lack of significant effects from training status, history, and personality traits on the stability of individual RIR-velocity relationships, these findings could likely be generalised to the resistance-trained population using free-weight exercises.

To gauge the practical usefulness of RIR-velocity relationships, their predictive validity must be evaluated. Thus, the present study investigated the ability of general and individual RIR-velocity relationships established in an initial testing session to predict RIR in a subsequent testing session. Despite a comparatively weak goodness of fit of general RIR-velocity relationships, their predictive validity was unacceptable only for 70% of 1RM (> 2 repetitions). In contrast, regardless of the load and modelling strategy used, individual RIR-velocity relationships displayed lower, acceptable mean prediction errors. These prediction errors of individual RIR-velocity relationships were affected by sex, load, and habitual repetitions practices (Table 7-2). While examination of prediction errors by sex and load in isolation always yielded mean prediction errors lower than 2 repetitions, females tended to have slightly higher prediction errors than the pre-determined criteria (< 2.07 repetitions) with lower loads. Additionally, individuals who typically performed more than 12 repetitions during their own training had higher than 2 repetitions prediction errors with 70% of 1RM. This suggests that the accuracy of individual RIR-velocity relationships might be slightly compromised with lower loads (e.g., 70% 1RM), especially with individuals who usually perform many repetitions during their training sets. It may be that those individuals generally possess a greater variability in performance for reasons unexplored in the present study. Finally, it should be noted that polynomial regression models should be used to maximize prediction accuracy. Nevertheless, individual, but not general RIR-velocity relationships always demonstrated a high goodness of fit and acceptable accuracy, and thus can be used for RT monitoring and prescription.

Despite acceptable mean prediction accuracy being observed for individual RIR-velocity relationships in the present study, it is important to note that models' prediction errors might not be acceptable for all individuals, or RIRs thereof. For instance, Figure 7-3 illustrates 4 individuals whose models' prediction errors were on average almost perfect (~ 1 repetition). However, a maximal prediction error for individual RIR should also be appreciated from the figure. This is important as only focusing on the mean error across different RIRs can hide the inability of the model to accurately predict the entire RIR-velocity spectrum. Furthermore, thorough inspection of the descriptive data of average prediction errors revealed that females, less strong individuals, and those with less than 3 years of RT experience, tended to have slightly higher mean prediction errors compared to their respective counterparts (Appendix F Ch. 7 File IV). Therefore, individual RIR-velocity relationships should be evaluated, and their usefulness determined on a case-by-case basis, with special attention given to less experienced and weaker individuals.

The present study also attempted to evaluate both general and individual RIR-velocity relationships averaged across the loads. For this purpose, velocities of overlapping RIR (i.e., different RIR not unique across the three loads used in this study) were averaged to examine whether such RIR-velocity relationship could yield a high goodness of fit and acceptable prediction accuracy. Indeed, with velocities associated with overlapping RIRs averaged across loads both general and individual RIR-velocity relationships' goodness of fit was generally comparable to relationships fitted for each load separately (Figure 7-4). Similarly, predictive validity of individual but not general RIR-velocity relationships averaged across loads was acceptable, with comparable prediction errors for both linear and polynomial models (Appendix F Ch. 7 File V). Finally, results of the models investigating factors affecting both goodness of fit and predictive validity of individual RIR-velocity relationships averaged across loads were similar to results reported for RIR-velocity relationships established for each load separately (Appendix F Ch. 7 File V). Therefore, the process of establishing and using RIR-velocity relationships in practice could further be simplified by establishing a single relationship which covers a range of loads (i.e., 70 to 90% of 1RM), rather than having a profile for each load separately. This opens another possibility of using individual RIR-velocity relationships which goes beyond set termination and equating for effort across individuals when prescribing RT. For example, a training program could call for 3 sets of 6 repetitions at 2RIR rather than assigning a percentage (e.g., 85% of 1RM) to the prescribed repetitions. Then, the load could be selected based on the "starting velocity" (i.e., the velocity associated with 6RIR) and the set terminated when the velocity associated with 2RIR is reached (i.e., a "stopping velocity"). Furthermore, this approach allows for autoregulation of training loads which can be adjusted for subsequent sets (or workouts) to meet the training goal; this is important when considering possible day-to-day variations in performance. Essentially, the proposed ways in which RIR-based RPE can be used to auto regulate load selection and set termination [181, 191] can also be performed using individual RIR-velocity relationships, but with greater accuracy, especially among individuals who may be worse at subjectively gauging RIR. Therefore, the individual RIR-velocity relationship can be used in lieu of traditional RT methods to monitor, prescribe and adjust both the training load and set-volume more accurately.

The present study comprehensively examined the goodness of fit and predictive validity of RIR-velocity relationships for monitoring and prescribing RT while also exploring the effects of a range of factors on these relationships. However, there are several considerations worth noting when interpreting the results. First, it is unknown whether the findings of the present study extend beyond free weight squats and transfer to other exercises. However, even if other exercises prove less or more reliable, it is likely that the effects of training history and status, sex, and personality are similar across exercises. Second, all participants in the present study had at least 6 months of RT experience, so the extent to which the current findings translate to those without RT experience is unknown. Third, the number of females included in the analysis was considerably lower than males, so the male data may be more generalisable. With that said, the females in the present study had a wide range of strength levels, training experience, and habitual training practices, possibly improving the sample's generalisability. Finally, it is important to highlight that a different choice for the acceptable repetition error threshold for the RIR-velocity relationships could have influenced the findings and subsequent interpretation. However, a RT monitoring and prescription method with higher than a 2 repetitions error, especially one that has a financial cost, may not be justified in practical settings, given this would be higher than the average error of subjectively rated RIR in most cases [193].

7.5 Conclusion

The present study is the first to thoroughly examine the utility of general and individual RIR-velocity relationships with free-weight exercises. Regardless of the load and modelling strategy used, individualised RIR-velocity relationships provided twice as high goodness of fit and were always able to predict RIR in a subsequent testing session with acceptable accuracy compared to general RIR-velocity relationships. Females, less strong individuals, and those with less than 3 years of RT experience tended to have slightly higher mean prediction errors compared to their respective counterparts. However, the prediction error for females was only slightly higher with respect to the pre-determined criteria, and only present with lower loads. Therefore, individual RIR-velocity relationships should be evaluated, and their usefulness determined on a case-by-case basis, with special attention given to less experienced and weaker individuals. Using RIR-velocity relationships in practice could further be simplified by establishing a single relationship which covers a range of loads (i.e., 70 to 90% of 1RM), rather than having a profile for each load separately. This allows selection of the loads based on the "starting velocity" (i.e., the velocity associated with an indented load that can be lifted a given number of times) and termination of the sets when the "stopping velocity" (i.e., velocity associated with an intended RIR) is reached. Therefore, the individual RIR-velocity relationship can be used in lieu of traditional RT methods to monitor, prescribe and adjust both the training load and set-volume more accurately, potentially allowing for more efficient adaptation and better fatigue management.

Chapter 8: Acute effects of cluster and rest redistribution set structures on mechanical, metabolic, and perceptual fatigue during and after resistance training: A systematic review and meta-analysis

Preface

While prior chapters demonstrated how monitoring velocity loss (VL) during resistance training (RT) is not useful for set volume prescription, monitoring VL still allows for valid assessment of neuromuscular fatigue during a set. As discussed, VL thresholds < 20% maximise various training adaptations while preserving expression of IIX muscle fibres. A simple way to manage VL and fatigue during RT, without monitoring velocity with expensive devices, is manipulating set configuration. Cluster sets (CS) improve acute performance compared to traditional sets (TS), but at the cost of added intra-set. Since adding extra rest increases total training time, which is not always practical, redistributing inter-set rest to create shorter, more frequent sets is a viable alternative. This strategy, known as rest redistribution (RR), is also effective for maintaining mechanical performance while reducing perceptual and metabolic fatigue during RT, without increasing training time. Although “cluster” and “rest-redistribution” sets are terms often used interchangeably, CS and RR differ (due to the extra rest in CS). Furthermore, the evidence comparing changes in mechanical performance during RT as well as metabolic and perceptual responses between set structure types has not yet been synthesised. Importantly, CS and RR could be used as a no-cost substitute for VL thresholds. Therefore, this Chapter quantifies the acute effects of CS and RR set structures during RT, and serves as a basis for the later Chapter investigating the use of CS and RR as free, ad-hoc alternatives to RT prescription using VL.

This Chapter is published in *Sports Medicine* journal.

8.1 Introduction

Resistance training (RT) is traditionally utilised by athletes to increase their muscular strength, power, speed, endurance, balance, coordination and lean body mass, which can ultimately lead to improvements in sport performance tasks [2, 1]. In addition, RT has an important role in injury prevention and rehabilitation, as well as general well-being due to numerous beneficial effects on health and quality of life [30-32]. In order to design an efficacious RT program tailored to the individual's training goals, several factors such as the choice and order of the exercises, load, number of repetitions and sets, frequency, and length of designated rest periods are typically considered [30, 195-197]. However, the ability to alter the structure of individual sets during RT has also gained considerable attention from the sport science community, since set structure alteration can be used to manipulate mechanical [198-200, 23, 201, 25], metabolic [202, 198, 203-205] and perceptual [206-210] responses, potentially impacting the resultant training adaptations [211-213].

Traditionally, repetitions within a set are performed consecutively without rest between repetitions, and with a specified inter-set period before commencing subsequent sets. These so called "traditional sets" (TS) are often used in RT programs to target specific portions of the force-velocity spectrum [214-216, 2]. When doing so, athletes are often encouraged to perform concentric muscle actions as explosively as possible since lifting at maximal intended velocity may induce superior adaptations in strength and power compared to voluntarily lifting at a submaximal velocity [217, 37, 218]. However, regardless of the number of repetitions performed and the loads used, performing multiple repetitions in a consecutive fashion inevitably results in fatigue accumulation as evidenced by a decrease in movement velocity, increased perceived exertion, and metabolite accumulation, such as lactate [198, 205, 210, 23]. Since all these events represent adverse mechanical, perceptual, and metabolic responses which could then compromise certain training adaptations, alternative set structures such as cluster and rest redistribution set structures can be used to combat fatigue and performance decrements associated with TS.

The implementation of cluster sets (CS), where intra-set rest periods are added within a training set alongside standard inter-set rest periods, is an effective strategy to off-set mechanical [25, 23, 160], perceptual [207, 205] and metabolic [205, 203, 219, 212] fatigue often seen during TS. While the exact mechanisms through which CS ameliorate fatigue are not clearly established, it can be hypothesised that longer and more frequent rest periods during CS allow for greater maintenance of phosphocreatine stores, adenosine triphosphate resynthesis and increased metabolite clearance within the working muscles, resulting in enhanced recovery and performance maintenance [220-223, 19, 224]. However, extra rest periods during CS might not always be feasible since they extend total training time, which is not always possible to do in real-world settings [23]. In this regard, researchers have investigated other possible alternatives to CS such as redistributing the total rest time of TS structures, abbreviating inter-set rest and shifting it to include shorter but more frequent rest intervals [24]. This strategy, known as a rest redistribution set structure (RR), is more effective than TS for maintaining mechanical performance and mitigating fatigue - similarly to CS - but avoids the increased training time associated with CS [116, 210, 225, 226]. Collectively, although both CS and RR structures appear to be superior to TS in acute performance maintenance, they are divergent concepts. However, although these protocols have been used interchangeably in the literature (for a more detailed discussion of the evolution and terminology of alternative set structures, see review by Tufano, Brown and Haff, 2017 [24, 226]), it is important to make a clear distinction between them as they could provide a different training stimulus.

For instance, Tufano et al. [23], Garcia Ramos et al. [198] and Gonzalez-Hernandez et al. [205] all showed CS to positively affect mechanical, metabolic and perceptual responses during RT. While studies examining the effectiveness of RR often come to similar conclusions, the magnitude of these effects are generally lower than those reported in studies comparing TS and CS. This is not surprising considering CS contain additional rest compared to TS and RR structures. However, inconsistencies in magnitudes of the effect exist even among studies that independently compared either CS or RR to TS. This variability in the results is likely caused by various confounding factors such as training to muscular failure, the number of repetitions performed, or the loads used, all of which could contribute to the different magnitude of effects observed between TS and CS or RR. For example, it is reasonable to assume that the benefits of CS and RR are exaggerated when TS are performed to failure and when the number of repetitions performed, and loads used are increased. Furthermore, although less explored, recent studies suggest that the effects of CS and RR on post-session mechanical, perceptual and metabolic fatigue might differ from the fatigue examined during the session (i.e., after each repetition or set). Considering the above, CS and RR likely impose different training stimuli and have different benefits which vary depending upon several factors which limits the conclusions that can be drawn from the existing literature.

A recent systematic review [227] compared the acute neuromuscular responses of RT sessions using alternative set structures (grouping CS and RR, together) and TS. The authors of the review concluded that alternative set structures allow for higher absolute velocity, power and peak force during RT, but also pointed out that several factors could potentially influence the observed differences (e.g., greater differences when using moderate-heavy loads). Although a valuable insight into the effectiveness of alternative set structures was provided, it is important to note that the specific, selective effects of CS and RR structures were not examined, and potential moderators such as the number of repetitions performed and muscular failure were not considered, limiting the generalisability of the findings. Furthermore, evidence regarding changes in mechanical performance during RT as well as mechanical, metabolic, and perceptual responses after RT differing only in set structure, has not been synthesised to date. If we only observe the results from individual studies comparing either CS or RR to TS, the conclusions regarding the effects of CS and RR on mechanical, perceptual and metabolic responses might be that: (1) CS and RR are equally effective; (2) CS are more effective than RR; or (3) RR is more effective than CS. This clearly demonstrates the inconsistencies in the current body of evidence regarding the effects of CS and RR on the mechanical, perceptual and metabolic markers of fatigue during RT. Therefore, the aim of this systematic review and meta-analysis was to synthesise the available evidence on differences in mechanical, perceptual and metabolic responses between TS and CS or RR structures. This review will also provide an overview of the factors that may influence fatigue responses between the set structures, allowing researchers and practitioners to compare and contrast these set structures with more nuance. Such evidence is important to inform RT prescription strategies, ultimately allowing for better fatigue management.

8.2 Methods

8.2.1 Registration of systematic review protocol

A systematic review of the literature was performed according to the *Cochrane Handbook for Systematic Reviews of Interventions* (version 5.1.0) and following the checklist for the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [228]. The original protocol was prospectively registered with the International Prospective Register of Systematic Reviews (PROSPERO) in June 2019 and involved a larger systematic review project comparing TS, CS, and RR set structures during resistance training across a broader range of outcome measures (Registration number CRD42019138954). The protocol registration occurred before any of the searches were conducted.

8.2.2 Literature search

A PICO strategy was used to build search criteria for electronic databases. It consisted of terms for traditional, cluster, and rest redistribution set structures; resistance training and acute mechanical, perceptual, and metabolic outcomes; and muscular strength, power and hypertrophy adaptations. The following bibliographic databases were searched from inception to June 6th, 2019: PubMed/MEDLINE, SCOPUS, CINAHL (Cumulative Index to Nursing and Allied Health), SPORTDiscus and Web of Science. The following syntax was adapted for each database and applied to the title, abstract, and keyword search fields: ("cluster set*" OR "rest redistribution" OR "set structure*" OR "set configuration*" OR "inter-set rest" OR "inter set rest" OR "intra-set rest" OR "intra set rest" OR "inter-repetition rest") AND ("strength" OR "resistance" OR "exercise" OR "training" OR "jump*" OR "plyo*" OR "weightlifting" OR "velocity" OR "power" OR "output" OR "velocity loss" OR "power loss" OR "velocity-loss" OR "power-loss" OR "force" OR "kinetic" OR "kinematic" OR "rpe" OR "rating of perceived exertion" OR "exertion" OR "effort" OR "perceptual" OR "lactic" OR "lactate" OR "fatigue" OR "metabolic" OR "hypertrophy" OR "muscle size" OR "muscle fiber" OR "growth" OR "cross-sectional area"). In the secondary search, the reference lists of all included publications were screened and the studies that cited the included studies were examined through the Google Scholar database. Although not relevant to this specific paper, muscular strength, power and hypertrophy terms were used since the search was a part of a larger systematic review project comparing traditional, cluster, and rest redistribution set structures. Free-text terms were chosen based on pilot searches that achieved an appropriate balance between search sensitivity and precision without the use of controlled vocabulary (e.g., MeSH [Medical Subject Headings]). The strategy included only terms relating to or describing the intervention. Conference abstracts and proceedings were excluded.

8.2.3 Inclusion criteria

All studies included in the systematic review met the following inclusion criteria: (1) the study was peer-reviewed and published in English; (2) the study compared at least one acute mechanical, metabolic, or perceptual responses between traditional and cluster or traditional and rest redistribution set structures; (3) included a control group (i.e., TS) in which multiple repetitions within a set were performed in a consecutive fashion (i.e. without intra-set rest between repetitions) and from which intervention groups were derived (i.e. CS or RR); (4) the study included an intervention group (CS) which included intra-set rest intervals, resulting in longer total rest periods compared to the control group, and/or included a second intervention group (RR) during which total rest periods were the same compared to control group; (5) the load and volume (set x repetitions) were matched between the conditions; (6) the study included multiple sets of repetitions; (7) both intervention and control groups performed iso-inertial or bodyweight exercises; (8) participants had no known medical conditions or injuries.

8.2.4 Study selection

Study eligibility assessments were completed independently by two reviewers (IJ and AGR). Records were downloaded into Endnote (version X8.2, Clarivate Analytics, Philadelphia, PA, USA) and duplicates were removed before being screened by title and abstract. The full texts of the remaining records were then retrieved and assessed for eligibility. Any discrepancies throughout the study selection process were settled through consultation with a third reviewer (JJT) or until a consensus decision was reached.

8.2.5 Study coding and data extraction

From the studies that met the inclusion criteria, the following data were extracted into an Excel spreadsheet: (1) study identification information; (2) study design; (3) sample size; (4) participants' characteristics, including age, body mass, sex, strength levels, and training experience; (5) resistance training prescription details for TS, CS, and RR set structures; and (6) means and standard deviations for relevant outcome measures. If insufficient data were reported, the authors of those studies were contacted by-email. The Web Plot Digitizer software (Version 4.1; TX, USA) was used for the extraction of data from figures when the authors of the original studies did not report the data. Data extraction was completed independently by two authors (IJ and AGR) using a pilot-tested form on five randomly selected studies which was then modified accordingly. Coding files were cross-checked between the authors, and any observed differences were resolved via discussion and agreement, or with a third reviewer (JJT).

8.2.6 Risk of bias assessment

A risk of bias assessment was performed using a modified Cochrane Collaboration's tool for assessing the risk of bias in randomised trials [54]. Modifications included removing the performance bias criterion and adding equipment bias, effort bias, and familiarisation bias. The performance bias criterion was removed because it was considered impossible to successfully blind participants and personnel in supervised exercise intervention studies [229, 55, 230]. Equipment bias was considered important for this review, and it was related to the reliability and appropriateness of the equipment or instruments that were used to assess outcomes of interest in a given study. For instance, if previous research failed to show the reliability of a given device being used in a study to record kinematic variables, this may have induced bias. Bias may have also arisen if an inappropriate instrument was used to measure the outcome (e.g. using rating of perceived exertion scales not validated for the use in resistance training). Effort bias related to whether the authors explicitly stated that all participants were constantly encouraged to perform the concentric phase of the movement as explosively as possible. Where this was not explicitly stated, there was a chance that the mechanical, metabolic, or perceptual measures of fatigue were affected by different tempo of lifting. Familiarisation bias was related to whether the participants were adequately familiarised with the protocols in a given study. If the authors did not clearly state that familiarisation session took place or that their participants were regularly performing exercises and performance tasks used in a given study, bias may have risen from the participants being unaccustomed to the study protocols. This was deemed important regardless of the participants' training experience in a given study since performing exercises with maximal intent is not considered to be the norm and can highly influence the outcomes investigated in this review.

Risk of bias was assessed based on the information reported in the published papers not on information provided in Table 8-1 of this review. Assessments were completed independently by two reviewers (IJ and AGR) while any observed differences were resolved via discussion and agreement before merging the scores into a single spreadsheet. Risk of bias was considered in the interpretation of the results by applying the Grading of Recommendations Assessment, Development and Evaluation (GRADE) system [231], similarly to previous reviews investigating physiological and biomechanical outcomes between different exercise modalities [229, 55]. Specifically, the overall quality of the evidence synthesis was rated as high and downgraded one level to moderate, low, or very low for each of the following limitations: total sample size < 100 participants (imprecision), high statistical heterogeneity (inconsistency), more than 50% of studies in a given meta-analysis had > 1 risk of bias item assessed to be high-risk (risk of bias).

8.2.7 Statistical analysis

A separate random-effects meta-analysis for each review outcome was performed using the *Meta* and *Metafor* statistical packages [73, 232] in R language and environment for statistical computing (version 3.6.3, The R foundation for Statistical Computing, Vienna, Austria) [233], when two or more studies reported on the same outcome. Model parameters were calculated by the restricted maximum likelihood method, and the observations were weighted by the inverse of the sampling variance [234]. For cross-over studies standardised mean differences with Hedges' g correction (SMD) and 95% CIs were calculated between traditional and alternative set structure trials based on the means and standard deviations of mechanical, perceptual, and metabolic outcomes, the correlation between the trials, and the number of participants. For between-subject studies, SMDs were calculated using the mean and pooled standard deviation data, as described by Borenstein et al. [58]. Since no studies reported any correlations between traditional and alternative set structures measurements, we estimated correlations when exact p values were available. However, it was often unclear whether studies reported post-hoc corrected or uncorrected p values, which resulted in implausible correlations. Therefore, to ensure that a maximal number of studies was included in the meta-analysis, a conservative correlation coefficient of 0.5 was used in all meta-analyses [57]. The SMD magnitude was interpreted as: small (0.20 – 0.49), moderate (0.50 – 0.79) and large (> 0.80) [62]. Sub-group analyses explored the effects of cluster and rest redistribution set structures on every outcome. Meta-regressions were performed when at least six effects were available for a given outcome [235] based on whether traditional sets were performed to muscular failure as a categorical covariate, and using the loads and the number of repetitions being performed in the traditional group as continuous covariates. The heterogeneity of the studies was assessed using the I^2 statistic. The I^2 statistic represents the percentage of total variation in estimated effects across studies due to heterogeneity rather than chance and was interpreted as small ($I^2 < 25\%$), moderate ($I^2 = 25–49\%$) and high ($I^2 > 50\%$) [79]. To explore the extent to which having both a within- and between-subject design in the same study impacted the pooled findings, we conducted a sensitivity analysis by excluding the studies with a between-subject design (k = 4) only for the outcome with the greatest number of studies. This was done since all studies with a between-subject design were included for that outcome (i.e., mean velocity) whereas only one or none of them were included for other outcomes in this review. Publication bias was not assessed because there was only a small number of studies included in most meta-analyses and all studies were of a similar size, as recommended in *Cochrane Handbook for Systematic Reviews of Interventions* [236]. In addition, there was no reason to expect that studies finding no difference between different set structures would be less likely to be published than studies reporting a statistically significant difference.

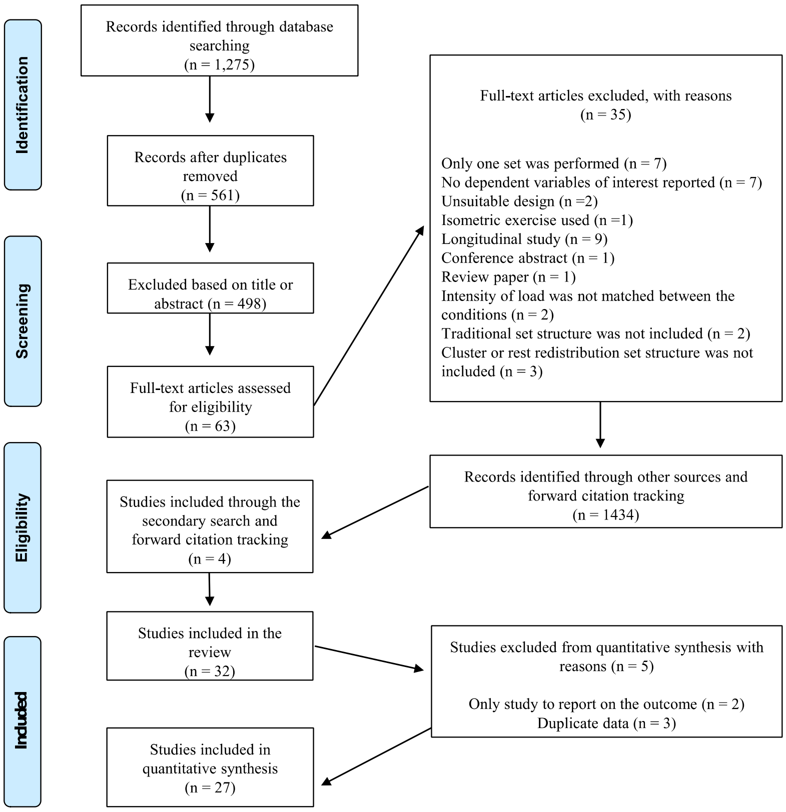
When multiple study effects were reported that were not of a direct interest to this review (e.g., separate effects for two or more TS, CS, or RR set structures) a combined effect was computed across these outcome measures with study-design specific formulas, as outlined by Borenestein et al. [58] for dependent and independent continuous outcomes to avoid double counting individuals from those studies in the meta-analysis. One study [199] reported separate effects for males and females. Since the sample size of each group was similar or higher than in most of the studies in the meta-analysis, the effects were not combined into one, but the groups were treated as two different studies in order to increase the statistical power. Similarly, Mora-Custodio et al. [203] reported separate effects for multiple loads and only the 60% 1RM load was used for the analysis since the other (greater) loads in study by Mora-Custodio et al. [203] were much more prevalent among the studies included in this review. This decision was further justified by the fact that number of repetitions decreased as the load increased in the study by Mora-Custodio et al. [203] which resulted in extremely similar effects between the groups regardless of the load being studied. Four studies [237-240] in which countermovement or squat jumps were performed reported loads in absolute terms or percentages of participants' body mass. In this case, they were converted to percentages of back squat 1RM, based on findings by Cormie et al. [241], in order to simplify the analyses. When studies did not specify whether the repetitions during traditional sets were performed to the muscular failure, the study protocol was classified as "to failure" when some of the participants either failed to complete the protocol or when the combination of the number of repetitions and the load clearly suggested that to be the case. When studies reported mean propulsive velocity instead of mean velocity, both variables were pooled and considered for the analysis. For the meta-analyses on mean velocity decrement, peak velocity decrement, mean power decrement, peak power decrement, velocity loss against a fixed load or jump height loss immediately after the session, lactate accumulation, and perceived exertion, effects were expressed such that positive values represent results in favour of CS or RR set structures over TS (i.e., lower decline in performance, lactate accumulation, and perceived effort).

8.3 Results

8.3.1 3.1 Search results

The flow diagram of the literature search is presented in Figure 8-1. The initial search from the databases resulted in a total of 1275 search results. After the removal of duplicates, the number of search results was reduced to 561. Title and abstract screening resulted in the exclusion of an additional 498 search results. Of those 498, 63 full-text papers were screened based on inclusion/exclusion criteria. Forward citation tracking and reference list screening resulted in another 1434 publications to be screened, of which, four were included. Of those 67 papers, 35 full texts were excluded based on inclusion/exclusion criteria. As a result, the final number of studies included in this review is 32.

Figure 8-1 Literature search flow chart.



Note. n, number of studies.

8.3.2 Study Characteristics

A total of 28 studies compared TS to alternative set structures with a within-subject design, and only 4 studies used a between-subject design. The pooled number of participants across studies was 481 (442 males and 39 females). However, after careful inspection, it was observed that the data from the same participants was used in multiple studies [242-245]. Taking that into account, the total number of participants was reduced to 416 (377 males and 39 females). Of the studies included in this review, one study included females only [225], four studies included both males and females [246, 208, 199, 209], and the rest of the studies included only males. Twenty-three studies recruited participants with at least 1 year of resistance training experience, participants in 4 studies had at least 6 months of resistance training experience, and this information was unclear in 5 studies. Twenty studies compared RR to TS, and 12 studies compared CS to TS. In 11 studies, TS were performed to muscular failure. The median number of repetitions performed during TS in the included studies was 7 (range: 4-12) while the external load ranged from body mass to 90% of 1RM (median = 75% of 1RM). Twenty-three studies investigated free weight exercises, 8 studies used a Smith Machine, and 1 study used a leg press machine. A more detailed description of the included studies can be found in Table 8-1.

Table 8-1 Summary of the studies included in the review.

Study	Participants information		Conditions				Outcomes
	N (male); N (female); age (years);	Training experience; relative strength levels (BM/1RM)	Structure Description Sets x repetitions; inter-set rest; intra-set rest	Load	Exercise	Total rest time	
Davies et al. 2019 [246]	12; 9; 25 ± 7	Less than 1 year on average; 0.83 ± 0.14	TS: 4 x 5; 3 min; none CS: 4 x 5; 3 min; 30sec	85% 1RM	Free-weight bench press	TS: 15 min CS: 17 min	Mean velocity Peak velocity
Denton et al. 2006 [247]	10; 0; 25 ± 4	At least 1 year; unclear	TS: 4 x 6; 302 sec; none RR: 8 x 3; 130 sec; 1 min	85% 1RM	Smith-machine bench press	TS: 15 min and 10 seconds RR: 15 min and 10 seconds	Lactate
Garcia-Ramos et al. 2020 [198]	10; 0; 29 ± 4	3 years; 1.31 ± 0.21	TS: 3 x 10; 5 min; none CS1: 3 x 10; 5 min; 5 sec CS2: 3 x 10; 5 min; 10 sec CS3: 3 x 10; 5 min; 15 sec	75% 1RM	Smith-machine bench press	TS: 10 min CS1: 12 min and 15 sec CS2: 14 min and 30 sec CS3: 16 min and 45 sec	Mean velocity Lactate
Girman et al. 2014 [248]	11; 0; 23 ± 3	6 years; 1.76 ± unclear	TS1: 4 x 6; 2 min; none TS2: 2 x 4 + 2 x 10; 2 min; none RR1: 4 x (3 x 2); 1 min and 30 sec; 15 sec RR2: 2 x (2 x 2) + 2 x (5 x 2); matching the TS and RR; 15 sec	50 – 75% 1RM	Free-weight clean pull and back squat	TS1: 8 min TS2: 10 min RR1: 8 min RR2: 10 min	Countermovement jump Standing long jump Lactate
González-Hernádez et al. 2020 [205]	11; 0; 23 ± 2	Unclear	TS1: 3 x 10; 5 min; none TS2: 6 x 5; 5 min; none	75 % 1RM	Smith-machine back squat	TS1: 10 min TS2: 25 min	Mean velocity Countermovement jump

			CS1: 3 x 10; 5 min; 10 sec CS2: 3 x 10; 5 min; 15 sec CS3: 3 x 10; 5 min; 30 sec CS4: 3 x 10; none; 15 sec			CS1: 14 min and 30 sec CS2: 16 min and 45 sec CS3: 23 min and 30 sec CS4: 7 min and 15 sec	Lactate RPE
Hansen et al. 2011[240]	20; 0; 20 ± 2	Professional/Semi-professional rugby players; -	TS: 4 x 6; 3 min; none RR1: 4 x 6; 2 min; 12 sec RR2: 4 x 6; 2 min; 30 sec RR3: 4 x 6; 2 min; 50 sec	40 kg absolute load	Free-weight jump squat	TS: 9 min RR1: 9 min RR2: 9 min RR3: 9 min	Peak velocity Peak power
Hardee et al. 2012 [200]	10; 0; 24 ± 1	4 years; 1.39 ± 0.03	TS: 3 x 6; 3 min; none CS1: 3 x 6; 3 min; 20 sec CS2: 3 x 6; 3 min; 40 sec	80% 1RM	Power clean	TS: 6 min CS1: 11 min CS2: 16 min	Peak velocity Peak power
Hardee et al. 2012 [207]	10; 0; 24 ± 1	4 years; 1.39 ± 0.03	TS: 3 x 6; 3 min; none CS1: 3 x 6; 3 min; 20 sec CS2: 3 x 6; 3 min; 40 sec	80% 1RM	Power clean	TS: 6 min CS1: 11 min CS2: 16 min	RPE
Hardee et al. 2013 [242]	10; 0; 24 ± 1	4 years; 1.39 ± 0.03	TS: 3 x 6; 3 min; none CS1: 3 x 6; 3 min; 20 sec CS2: 3 x 6; 3 min; 40 sec	80% 1RM	Power clean	TS: 6 min CS1: 11 min CS2: 16 min	Vertical displacement Horizontal displacement
Hoo et al. 2019 [249]	34; 0; 21 ± 2	unclear; ~ 1	TS: 3 x 6; 3 min; none RR1: 3 x 6; 2 min and 40 sec; 20 sec RR2: 3 x 6; 2 min and 20 sec; 40 sec	85% 1RM (6RM)	Free-weight bench press	TS: 6 min RR1: 6 min RR2: 6 min	RPE

Iglesias-Soler et al. 2012 [204]	10; 0; 23 ± 4	At least 18 months; 1.57 ± 0.34	TS: 3 x 4; 3 min; none RR: 1 x (360s / number of repetitions completed in TS - 1); none; depended upon number of repetitions	90% 1RM (4RM)	Smith-machine back squat	TS: 6 min RR: 6 min	Mean propulsive velocity Lactate
Iglesias-Soler et al. 2014 [250]	9; 0; 24 ± 4	3 years; 1.57 ± 0.34	TS: 3 x 4; 3 min; none RR: 1 x (360s / number of repetitions completed in TS - 1); none; depended upon number of repetitions	90% 1RM (4RM)	Smith-machine back squat	TS: 6 min RR: 6 min	Mean propulsive velocity
Joy et al. 2013 [251]	7; 0; 23 ± 2	At least 1 year; 1.77 ± unclear	TS: 4 x 10; 2 min; none RR: 4 x 10; 1 min; 1 min	75% 1RM	Free-weight back squat	TS: 9 min RR: 9 min	Mean power
Jukic et al. 2019 [206]	26; 0; 28 ± 5	At least 1 year; 1.82 ± 0.33	TS: 3 x 10; 4 min; none RR: 5 x 6; 2 min; none	70% 1RM	Free-weight back squat	TS: 8 min RR: 8 min	Mean velocity Mean power
Koefoed et al. 2018 [239]	10; 0; 27 ± 5	At least 1 year; unclear	TS: 4 x 6; 3 min; none RR: 4 x 6; 2 min and 20 sec; 20 sec	40% of Body Mass load	Free-weight jumps squats	TS: 9 min RR: 9 min	Jump height Peak velocity Peak power
Kurt et al. 2018 [238]	13; 0; 21 ± 2	At least 1 year; unclear	TS: 2 x 10; 90 sec; none RR1: 4 x 5; 30 sec; none RR2: 10 x 2; 10 sec; none	Body mass	Drop jumps	TS: 1 min and 30 sec RR1: 1 min and 30 sec RR2: 1 min and 30 sec	Bounce drop jump height Reactive strength index Ground contact time
Mayo et al. 2014 [209]	7; 1; 24 ± 1	At least 6 months, unclear	TS: 5 x failure; 3 min; none RR: 1 x number of repetitions from a failure session	75% 1RM (10RM)	Smith-machine back squat	TS: 12 min RR: 12 min	Mean propulsive velocity

			(individualised); rest = (720 sec/number of repetitions in failure session - 1); depended upon number of repetitions		Smith-machine bench press		RPE
Mayo et al. 2019 [208]	12; 5; 23 ± 2	At least 6 months; unclear	TS: 5 x 8; 3 min; none RR1: 40 x 1 repetition; none; 18.5 sec RR2 = 10 x 4; 1 min and 20 sec; none	75% 1RM (6RM)	Leg press	TS: 12 min RR: 12 min	Mean velocity RPE
Merrigan et al. 2019 [225]	0; 12; 24 ± 4	At least 2 years; 1.6 ± 0.2	TS: 4 x 10; 2 min; none RR: 4 x 10; 1 min and 30 sec; 30 sec	70% 1RM	Free-weight back squat	TS: 9 min RR: 9 min	Mean velocity Mean power Peak velocity Peak power
Mora-Custodio et al. 2018 [203]	30; 0; 23 ± 3	At least 1 year and a half; 1.45 ± 0.24	TS: 3 x 6; 4 min; none CS1: 3 x 6; 4 min; 10 sec CS2: 3 x 6; 4 min; 20 sec	60% 1RM	Smith-machine back squat	TS: 8 min CS1: 10 min and 30 sec CS2: 13 min	Mean propulsive velocity Countermovement jump Lactate
Morales-Artacho et al. 2018 [237]	18; 0; 24 ± 5	Unclear; 2.74 ± 0.41 (half squat)	TS: 6 x 6; 5 min; none RR: 6 x 6; 4 min; 30 sec	20 % Body Mass load	Countermovement jump	TS: 25 min RR: 25 min	Mean velocity Peak velocity
Moreno et al. 2014 [252]	26; 0; 22 ± 2	At least 6 months; unclear	TS: 2 x 10; 90 sec; none RR1: 4 x 5; 30 sec; none RR2: 10 x 2; 10 sec; none	Body mass only	Countermovement jump	TS: 1 min and 30 sec RR1: 1 min and 30 sec RR2: 1 min and 30 sec	Peak power Jump height

Nicholson et al. 2016 [212]	23; 0; 21 ± 2	At least 1 year; 1.6 ± 0.3	TS: 4 x 6; 5 min; none CS: 4 x 6; 5 min; 25 sec	85% 1RM	Free-weight back squat	TS: 15 min CS: 23 min and 20 sec	Mean velocity Mean power Lactate
Oliver et al. 2015 [245]	23; 0; 25 ± 5	Trained: at least 3 years; 1.75 ± 0.34 Untrained: unclear; 1.07 ± 0.38	TS: 4 x 10; 2 min; none RR: 4 x 10; 1 min and 30 sec; 30 sec	70% 1RM	Free-weight back squat	TS: 9 min RR: 9 min	Mean power Lactate
Oliver et al. 2016 [26]	24; 0; 25 ± 5	Trained: at least 3 years; 1.75 ± 0.34 Untrained: unclear; 1.07 ± 0.38	TS: 4 x 10; 2 min; none RR: 4 x 10; 1 min and 30 sec; 30 sec	70% 1RM	Free-weight back squat	TS: 9 min RR: 9 min	Mean velocity Mean power
Oliver et al. 2016 [219]	10; 0; 27 ± 4	At least 3 years; 1.96 ± 0.35	TS: 4 x 10; 2 min; none RR: 4 x 10; 1 min and 30 sec; 30 sec	70% 1RM	Free-weight back squat	TS: 9 min RR: 9 min	Mean velocity Mean power
Stone et al. 2019 [253]	8; 0; 24 ± 3	6 ± 3 years; 1.8 ± 0.3	TS: 4 x 6; 2 min; none RR: 4 x 6; 1 min and 30 sec; 30 sec	80% 1RM	Free-weight back squat	TS: 6 min RR: 6 min	Mean velocity Mean power
Torrejon et al. 2019 [199]	13; 13; Male: 29 ± 2 years Female: 22 ± 1	Male: 6 ± 2 years; unclear Female: 1.2 ± 1 years; unclear	TS: 6 x 4; 3 min; none RR1: 6 x 4; 2 min and 45 sec; 15 sec RR2: 24 x 1; none; 39 sec	85% 1RM (6RM)	Smith-machine back squat	TS: 15 min RR1: 15 min RR2: 15 min	Mean velocity

Tufano et al. 2016 [23]	12; 0; 26 ± 5	At least 6 months; 1.9 ± 0.23	TS: 3 x 12; 2 min; none CS1: 3 x 12; 2 min; 30 sec CS2: 3 x 12; 2 min; 30 sec	60% 1RM	Free-weight back squat	TS: 4 min CS1: 7 min CS2: 11 min and 30 sec	Mean velocity Mean power
Wagle et al. 2018 [243]	11; 0; 26 ± 4	At least 1 year; 1.8 ± 0.3	TS: 3 x 5; 3 min; none CS: 3 x 5; 3 min; 30 sec	80% 1RM	Free-weight back squat	TS: 6 min CS: 12 min	Mean velocity Peak velocity Peak power
Wagle et al. 2018 [254]	11; 0; 26 ± 4	At least 1 year; 1.8 ± 0.3	TS: 3 x 5; 3 min; none CS: 3 x 5; 3 min; 30 sec	80% 1RM	Free-weight back squat	TS: 6 min CS: 12 min	Mean velocity Peak velocity Peak power
Wetmore et al. 2019 [244]	11; 0; 26 ± 4	At least 1 year; 1.8 ± 0.3	TS: 3 x 5; 3 min; none CS: 3 x 5; 3 min; 30 sec	80% 1RM	Free-weight back squat	TS: 6 min CS: 12 min	Mean velocity Peak velocity Peak power

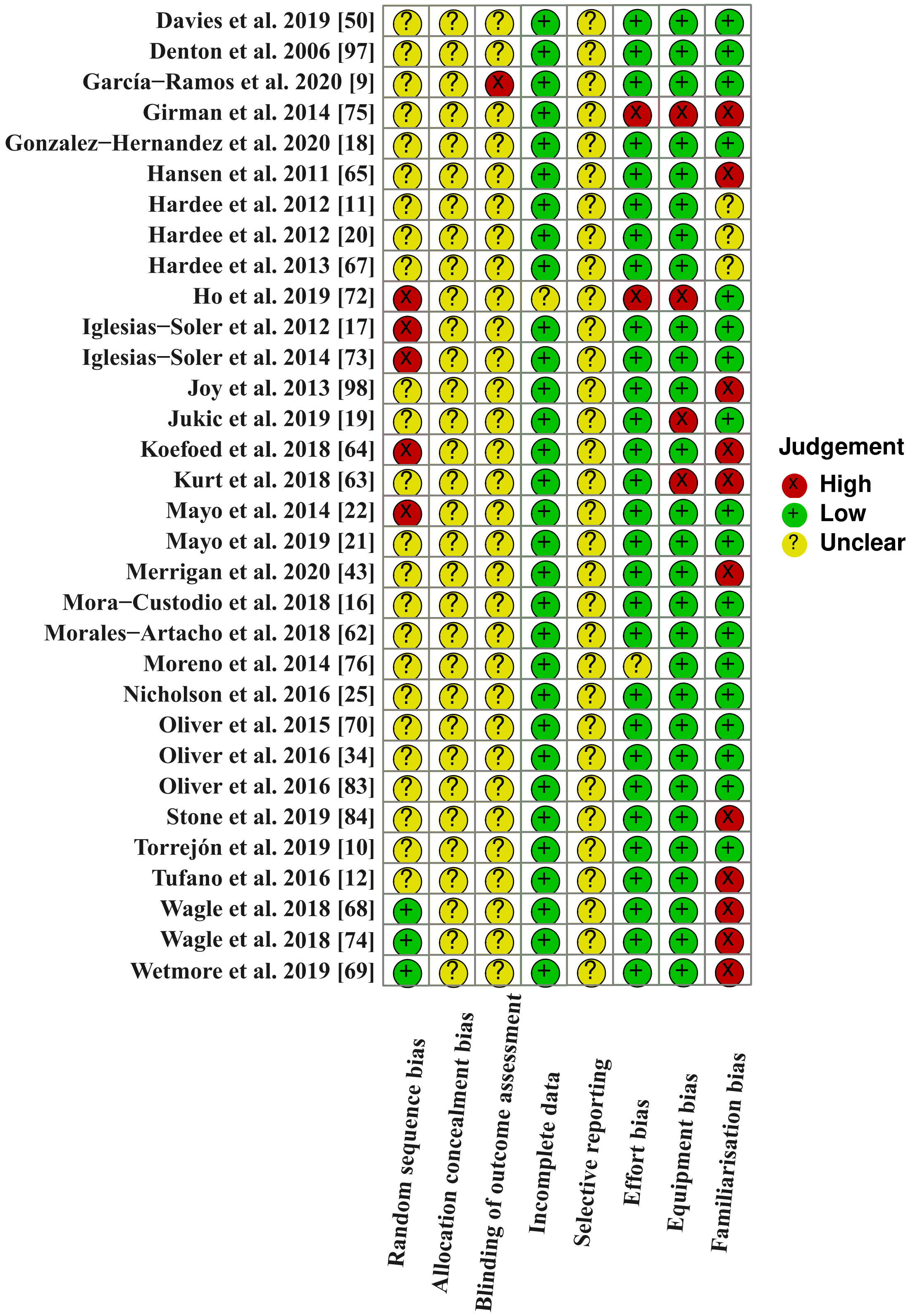
Note. BM body mass*, CS* cluster set structure*, F* female, *M* male, *N*, number of participants, *RM* repetition maximum, *RPE* rating of perceived exertion, *RR* rest redistribution set structure*, TS* traditional sets.

Values are expressed as means ± standard deviations.

8.3.3 Risk of Bias Assessment

Based on the risk of bias assessment, 5 studies [249, 250, 204, 239, 209] were at high risk of an order effect, not reporting any information about randomisation or having a fixed starting condition. Three studies [243, 254, 244] were classified to be of a low risk, while the rest of them were classified to be of an unclear risk since they did not provide sufficient information regarding the method of randomisation. No studies provided information regarding allocation concealment. One study [198] was constantly providing outcome feedback throughout experimental trials and therefore was considered to be of a high risk of outcome blinding bias. The remaining studies were rated to be at unclear risk of bias due to lack of information regarding the outcome blinding procedures. In addition, no studies pre-registered their protocols, so it was unclear whether the risks of selective reporting were present. One study [249] was at unclear risk of attrition bias, not reporting how the outcome of interest was collected when participants couldn't complete the protocols. Two studies were at a high risk of effort bias since the participants were not encouraged to perform the concentric phase of the lift with the maximal intent or they used metronome instead [249, 248], whereas this information was unclear in one study [252]. Three studies were of a high risk of equipment bias since they used non-officially validated equipment to measure jump height or movement velocity [248, 238, 206]. In addition, one study [249] used a rating of perceived exertion scale not validated for resistance training purposes and therefore, was also classified to be at a high risk of equipment bias. In total, eleven studies did not include a familiarisation session because of which high risk of bias may have risen due to the participants not being unaccustomed to the study protocols (Figure 8-2). Three studies [207, 242, 200] were classified as of an unclear risk of familiarisation bias since it was not possible to judge whether the participants performed a familiarisation session or not. A more comprehensive risk of bias assessment is illustrated in Figure 8-2.

Figure 8-2 Risk of bias assessment for all included studies



8.3.4 Mechanical outcomes

Mean velocity

Sub-group analysis indicated that both CS (SMD = 1.00 [0.72, 1.30]; $p < 0.001$; $I^2 = 0\%$; k = 7) and RR (SMD = 0.39 [0.20, 0.58]; $p < 0.001$; $I^2 = 33\%$; k = 12) set structures allowed for significantly greater mean velocity when compared to traditional set structures. When the effects from alternative set structures were pooled, mean velocity was significantly greater than during TS (SMD = 0.60 [0.40, 0.80]; $p < 0.001$; $I^2 = 49.6\%$; k = 19) (Figure 8-3). The sensitivity analysis, in which the four studies [246, 212, 203, 237] with a between-subject design were excluded, resulted in a pooled effect favouring alternative over TS (SMD = 0.55 [0.32, 0.78]; $p < 0.001$; $I^2 = 55\%$; k = 15). Pooled results and sub-group results for CS and RR all provided high GRADE quality of evidence (Table 8-2). Performing repetitions to muscular failure (b = 0.15 [-0.27, 0.56]; p = 0.492), the number of repetitions being performed during TS (b = 0.01 [-0.07, 0.09]; p = 0.810), and the load used (b = -0.01 [-0.02, 0.01]; p = 0.456) were not significant moderators of the SMD in mean velocity (Figure 8-4). Likewise, when analysing CS and RR set structures separately, performing repetitions to muscular failure (CS: b = 0.31 [-0.29, 0.92]; p = 0.307; RR: b = 0.22 [-0.15, 0.59]; p = 0.247), the number of repetitions being performed during TS (CS: b = 0.05 [-0.05, 0.15]; p = 0.322; RR: b = -0.03 [-0.10, 0.05]; p = 0.480), and the load used (CS: b = -0.01 [-0.03, 0.03]; p = 0.991; RR: b = -0.01 [-0.02, 0.01]; p = 0.468) were not significant moderators of the SMD in mean velocity (Figure 8-5).

Table 8-2 Summary of meta-analysis findings and quality of evidence synthesis.

Outcome	Summary of findings				Quality of evidence synthesis (GRADE)			
	k	n	Effect (95% CI)	Direction of the effect compared to traditional sets	Imprecision	Inconsistency	Risk of bias	Overall quality
Mechanical outcomes								
Mean velocity (m/s)								
Cluster set	7	118	1.01 (0.72, 1.30)	↑	None	None	None	High
Rest redistribution	12	151	0.39 (0.20, 0.58)	↑	None	None	None	High
All	19	269	0.60 (0.40, 0.81)	↑	None	None	None	High
Mean Power (W)								
Cluster set	2	35	0.83 (0.33, 1.34)	↑	-1	None	None	Moderate
Rest redistribution	6	80	0.24 (0.04, 0.45)	↑	-1	None	None	Moderate
All	8	115	0.33 (0.14, 0.51)	↑	None	None	None	High
Peak Velocity (m/s)								
Cluster set	3	44	0.67 (0.29, 1.05)	↑	-1	None	None	Moderate
Rest redistribution	4	51	0.28 (0.00, 0.55)	↔	-1	None	None	Moderate
All	7	95	0.41 (0.19, 0.64)	↑	-1	None	None	Moderate
Peak Power (W)								
Cluster set	2	23	0.54 (0.06, 1.03)	↑	-1	None	None	Moderate
Rest redistribution	3	42	0.30 (-0.01, 0.62)	↔	-1	None	None	Moderate

All	5	65	0.38 (0.14, 0.63)	↑	-1	None	None	Moderate
Mean velocity decrement (%)								
Cluster set	6	97	2.32 (1.34, 3.30)	↑	-1	-1	None	Low
Rest redistribution	4	64	0.29 (0.04, 0.53)	↑	-1	None	None	Moderate
All	10	161	1.47 (0.63, 2.30)	↑	None	-1	None	Moderate
Mean velocity maintenance (%)								
Cluster set	2	33	1.30 (0.70, 1.90)	↑	-1	None	None	Moderate
Rest redistribution	2	38	0.62 (- 0.51, 1.75)	↔	-1	-1	None	Low
All	4	71	0.95 (0.24, 1.66)	↑	-1	-1	None	Low
Mean power decrement (%)								
Rest redistribution	3	46	0.70 (0.07, 1.33)	↑	-1	-1	None	Low
All	4	58	0.83 (0.28, 1.38)	↑	-1	-1	None	Low
Mean power maintenance (%)								
Rest redistribution	2	38	0.67 (- 0.56, 1.89)	↔	-1	-1	None	Low
All	3	50	0.78 (- 0.01, 1.57)	↔	-1	-1	None	Low
Peak velocity decrement (%)								
Cluster set	2	22	1.93 (0.14, 3.71)	↑	-1	-1	None	Low
Rest redistribution	2	32	2.08 (0.45, 3.70)	↑	-1	-1	None	Low
All	4	54	1.97 (0.98, 2.95)	↑	-1	-1	None	Low
Peak velocity maintenance (%)								
Cluster set	2	23	0.91 (0.39, 1.44)	↑	-1	None	None	Moderate

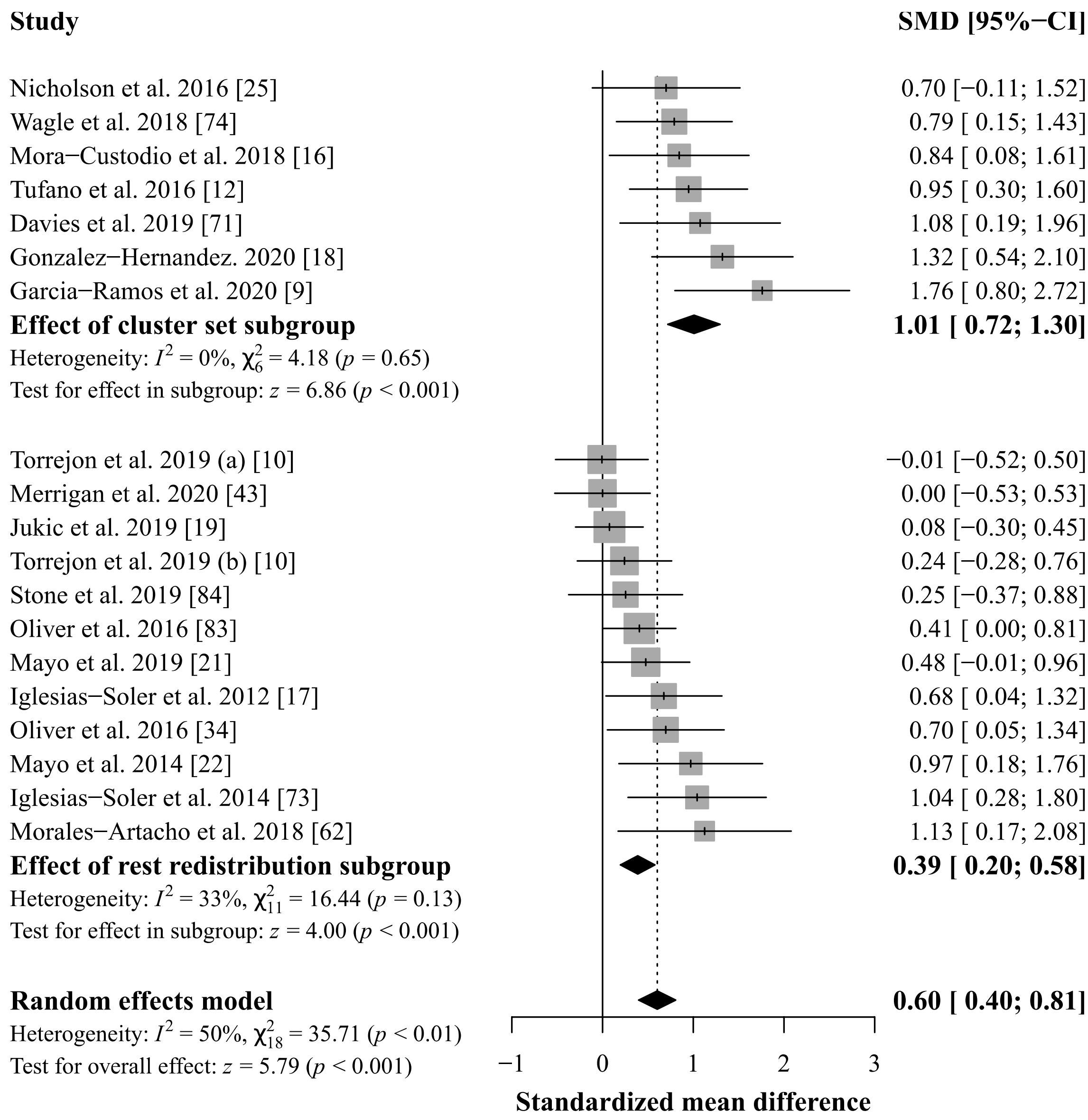
All	3	35	1.36 (0.33, 2.40)	↑	-1	-1	None	Low
Peak power decrement (%)								
Cluster set	3	33	1.48 (0.82, 2.13)	↑	-1	None	None	Moderate
Rest redistribution	3	58	1.95 (0.28, 3.62)	↑	-1	-1	None	Low
All	6	91	1.71 (0.92, 2.49)	↑	-1	-1	None	Low
Peak power maintenance (%)								
All	2	24	1.47 (0.40, 2.55)	↑	-1	-1	None	Low
Post session jump height loss or velocity against fixed load loss (%)								
Cluster set	3	52	0.65 (0.29, 1.01)	↑	-1	None	None	Moderate
All	4	62	0.58 (0.27, 0.89)	↑	-1	None	None	Moderate
Metabolic outcome								
Lactate (mmol·L^{-1})								
Cluster set	5	83	2.17 (1.18, 3.17)	↑	-1	-1	None	Low
Rest redistribution	3	43	1.27 (0.87, 1.66)	↑	-1	None	None	Moderate
All	8	126	1.61 (1.18, 2.04)	↑	None	-1	None	Moderate
Perceptual outcome								
Rating of perceived exertion (a.u.)								
Cluster set	2	21	1.14 (0.61, 1.67)	↑	-1	None	None	Moderate
Rest redistribution	4	75	0.69 (0.28, 1.11)	↑	-1	-1	None	Low

All	6	96	0.81 (0.45, 1.17)	↑	-1	-1	None	Low

Note. CI confidence intervals, *GRADE* Grading of Recommendations Assessment, Development and Evaluation, *k* number of studies, *n* number of participants.

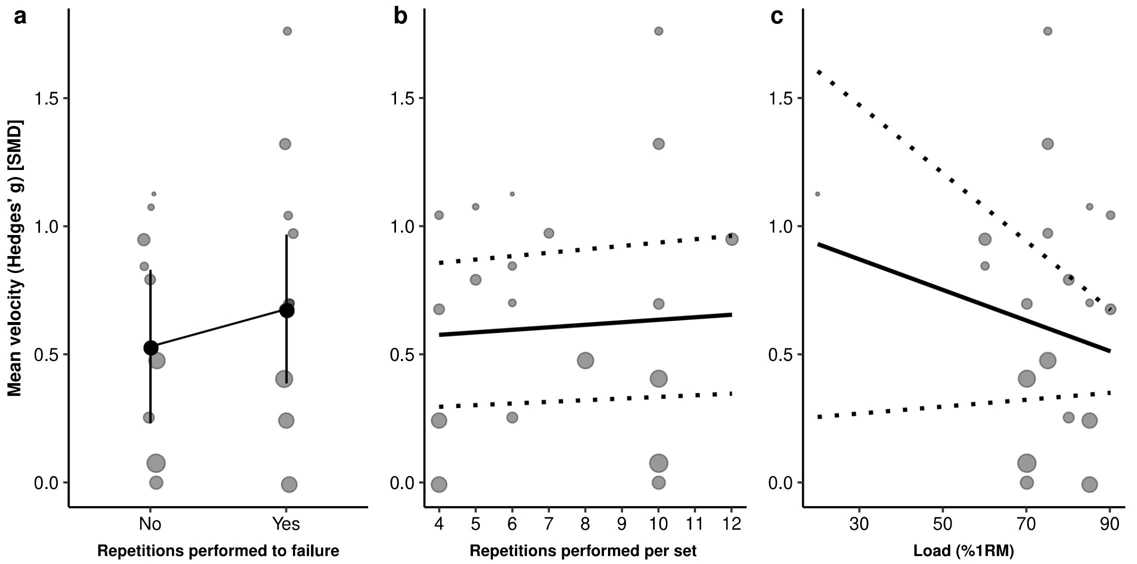
Only outcomes with k > 1 are included in this table.

Figure 8-3 Random-effects meta-analysis of absolute mean velocity during alternative set structures (i.e., CS and RR) compared to TS. Subgroup analysis based on the effects of CS and RR separately.



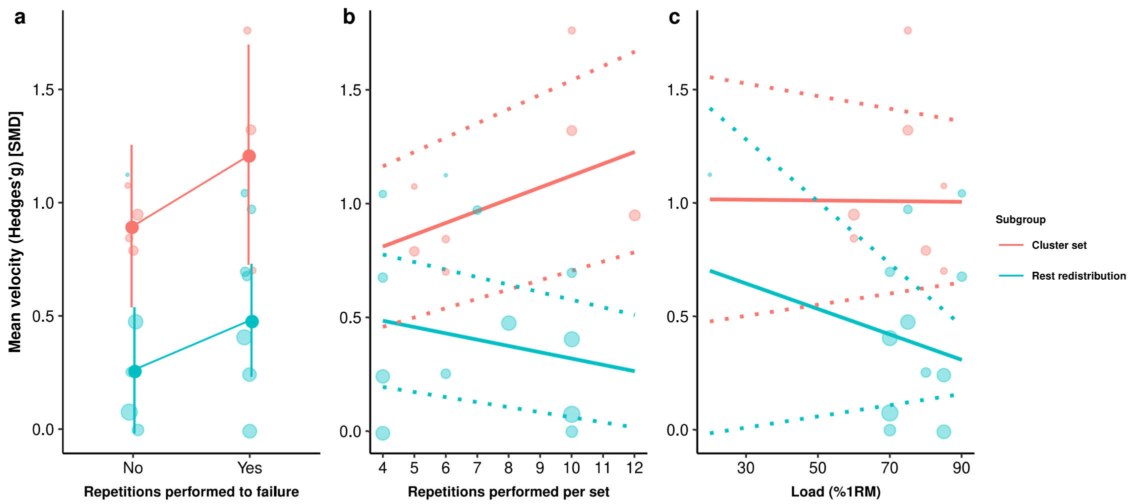
Note. For the study that analysed males and females separately, the effects are presented independently and are marked as (a) and (b), respectively. CI, confidence interval; CS, cluster set structure; RR, rest redistribution set structure; SMD, standardised mean difference; TS, traditional set structure.

Figure 8-4 Random-effects meta-regression of absolute mean velocity during alternative set structures (i.e, CS and RR combined) compared to TS while controlling for the effects of muscular failure during TS (a), number of repetitions performed during TS (b) and the load used (c).



Note. Larger data points received greater weighting than smaller data points. Solid (non-vertical) lines represent the estimated relationship, solid vertical lines and dotted lines represent the upper and lower 95% confidence intervals. CS, cluster set structure; RM, repetition maximum; RR, rest redistribution set structure; TS, traditional set structure.

Figure 8-5 Random-effects meta-regression of absolute mean velocity during alternative set structures (i.e, CS and RR separately) compared to TS while controlling for the effects of muscular failure during TS (a), number of repetitions performed during TS (b) and the load used (c).

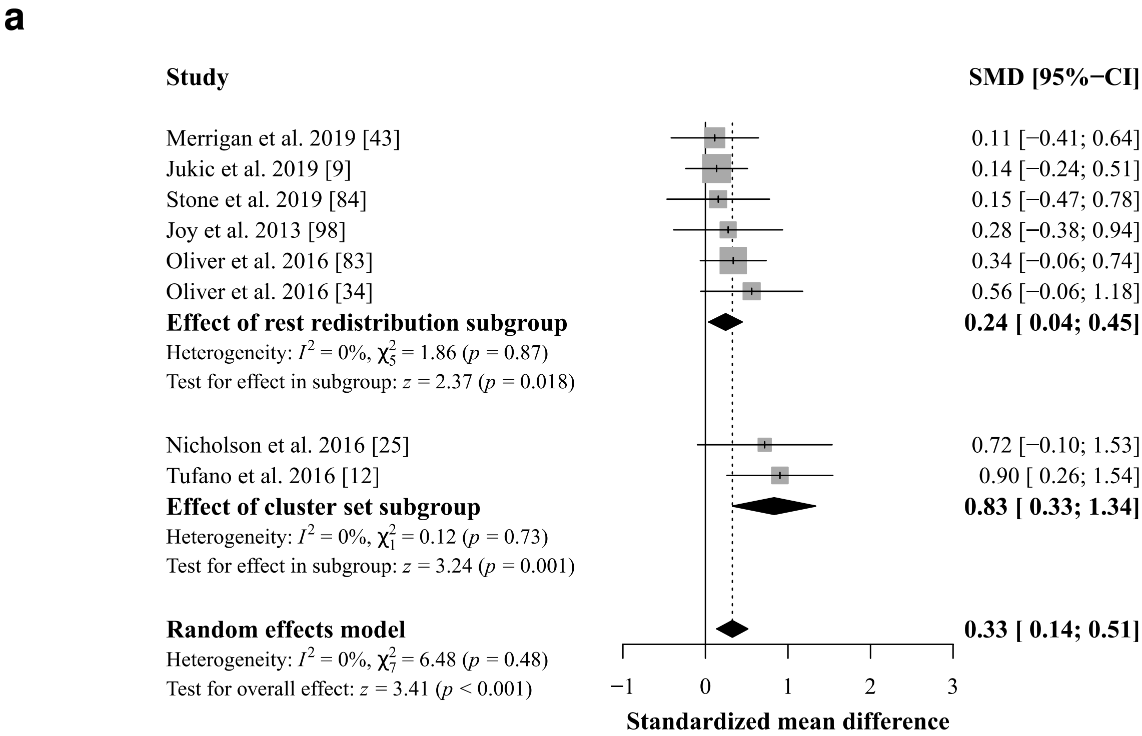


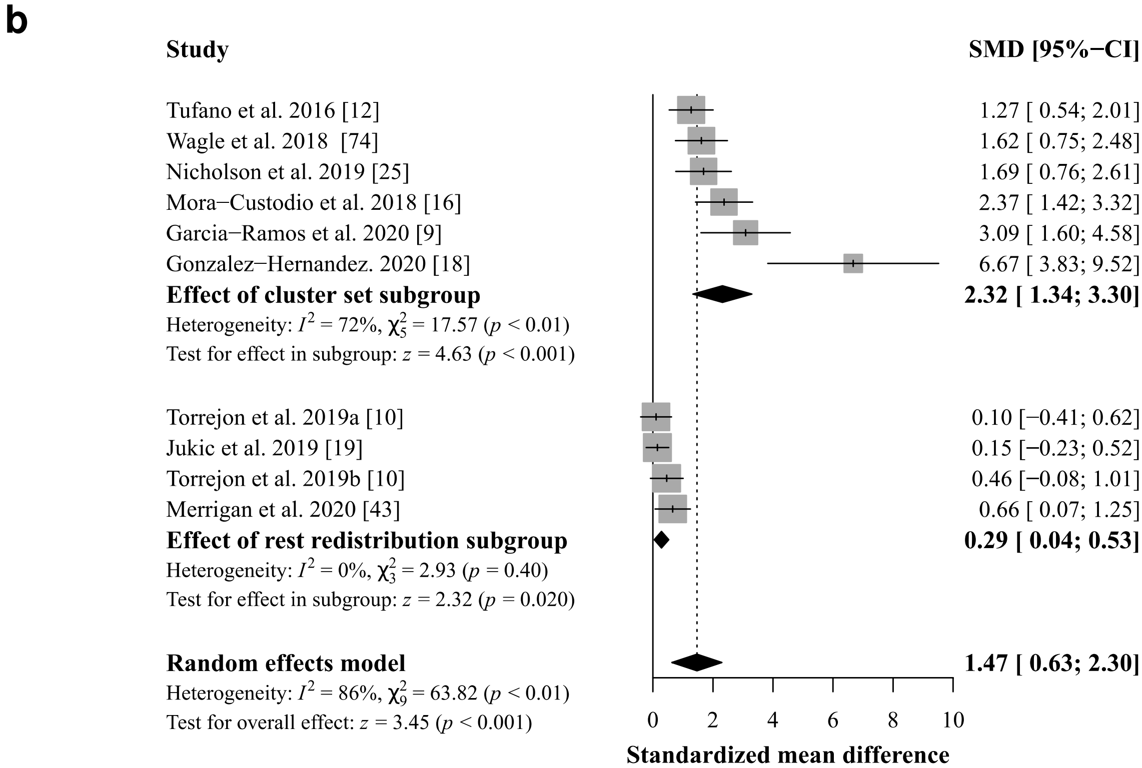
Note. Solid red lines and circles indicates data for CS, while green lines and circles indicated data for RR. Larger data points received greater weighting than smaller data points. Solid (non-vertical) lines represent the estimated relationship, solid vertical lines and dotted lines represent the upper and lower 95% confidence intervals. CS cluster set structure, RM repetition maximum, RR rest redistribution set structure, TS traditional set structure.

Mean power

Subgroup analysis indicated that both CS (SMD = 0.83 [0.33, 1.34]; p = 0.001; I^2 = 0%; k = 2) and RR (SMD = 0.24 [0.04, 0.45]; p = 0.018; I^2 = 0%; k = 6) set structures allowed for significantly greater mean power when compared to TS (Figure 8-6). When the effects from alternative set structures were pooled, mean power was significantly greater than during TS (SMD = 0.33 [0.14, 0.51]; p < 0.001; I^2 = 0%; k = 8). Sub-group results for CS and RR provided moderate while pooled results for provided high GRADE quality of evidence (Table 8-2). Performing repetitions to failure (b = 0.19 [-0.20, 0.58] p = 0.331), the number of repetitions being performed during TS (b = 0.03 [-0.09, 0.15]; p = 0.603), and the load used (b = -0.01 [-0.05, 0.02]; p = 0.509) were not significant moderators of the SMD in mean power (Figure 8-7). Likewise, when analysing RR set structures separately, performing repetitions to muscular failure (b = 0.25 [-0.17, 0.67]; p = 0.246), the number of repetitions being performed during TS (b = -0.01 [-0.08, 0.06]; p = 0.764), and the load used (b = -0.01 [-0.14, 0.19]; p = 0.300) were not significant moderators of the SMD in mean velocity.

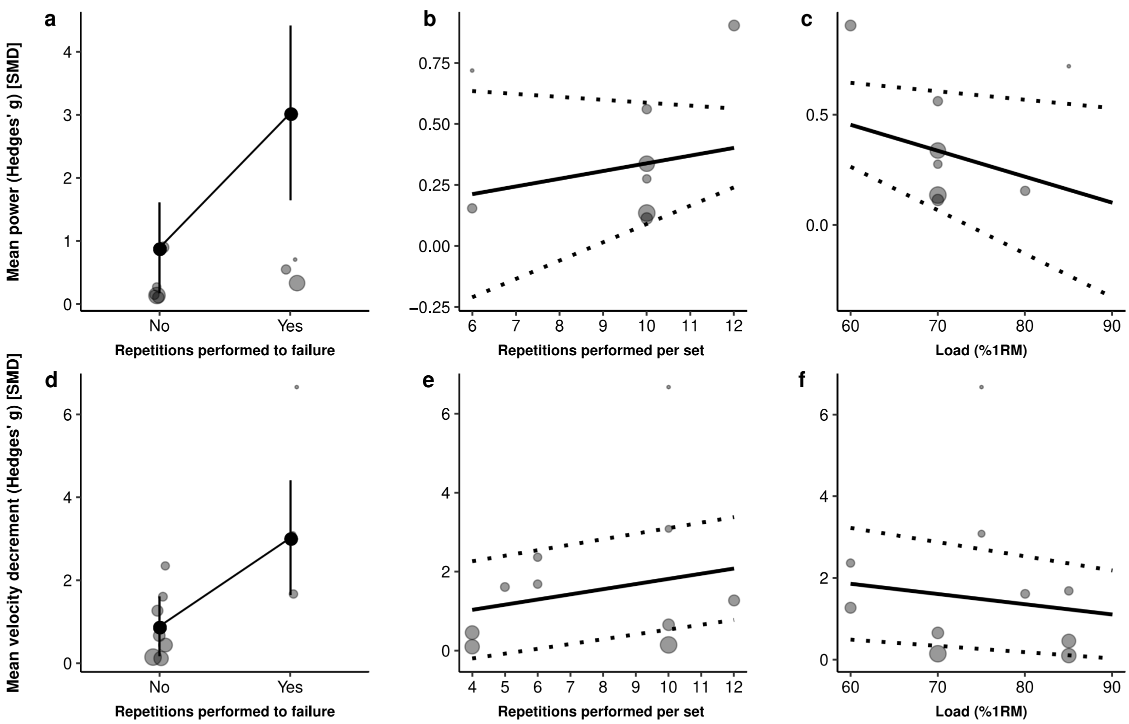
Figure 8-6 Random-effects meta-analysis of absolute mean power (a) and mean velocity decrement (b) during alternative set structures (i.e., CS and RR) compared to TS. Subgroup analysis based on the effects of CS and RR separately.





Note. CI confidence interval, CS cluster set structure, RM repetition maximum, RR rest redistribution set structure, SMD standardised mean difference, TS traditional set structure.

Figure 8-7 Random-effects meta-regression of absolute mean power (top row) and mean velocity decrement (bottom row) during alternative set structures (i.e, CS and RR combined) compared to TS while controlling for the effects of muscular failure during TS (a, d), number of repetitions performed during TS (b, e) and the load used (c, f).



Note. Larger data points received greater weighting than smaller data points. Solid (non-vertical) lines represent the estimated relationship, solid vertical lines and dotted lines represent the upper and lower 95% confidence intervals. *CS* cluster set structure, *RM* repetition maximum, *RR* rest redistribution set structure, *TS* traditional set structure.

Peak velocity

Subgroup analysis indicated that both CS (SMD = 0.67 [0.29, 1.05]; $p = 0.001$; $I^2 = 0\%$; k = 3) and RR (SMD = 0.28 [0.00, 0.55]; $p = 0.050$; $I^2 = 0\%$; k = 4) set structures allowed for significantly greater peak velocity when compared to TS. When the effects from alternative set structures were pooled, peak velocity was significantly greater than during TS (SMD = 0.41 [0.19, 0.64]; $p < 0.001$; $I^2 = 18\%$; k = 7). Pooled results and sub-group results for CS and RR all provided moderate GRADE quality of evidence (Table 8-2). Neither the number of repetitions being performed during TS (b = 0.01 [-0.09, 0.11]; p = 0.847) nor load used (b = 0.003 [-0.005, 0.01]; p = 0.404) were significant moderators of the SMD in peak velocity.

Peak power

Subgroup analysis indicated that CS (SMD = 0.54 [0.06, 1.03]; $p = 0.027$; $I^2 = 26\%$; $k = 2$) but not RR (SMD = 0.30 [0.00, 0.55]; $p = 0.050$; $I^2 = 0\%$; $k = 3$) set structures allowed for significantly greater peak velocity when compared to TS. When the effects from alternative set structures were pooled, peak power was significantly greater than during TS (SMD = 0.38 [0.14, 0.63]; $p = 0.002$; $I^2 = 4\%$; $k = 5$). Pooled results and sub-group results for CS and RR all provided moderate GRADE quality of evidence (Table 8-2).

Mean velocity decrement

Subgroup analysis indicated that both CS (SMD = 2.32 [1.34, 3.30]; $p < 0.001$; $I^2 = 71.5\%$; $k = 6$) and RR (SMD = 0.29 [0.04, 0.53]; $p = 0.020$; $I^2 = 0\%$; $k = 4$) set structures resulted in significantly lower mean velocity decrement when compared to TS (Figure 8-6). When the effects from alternative set structures were pooled, mean velocity decrement was significantly lower than during TS (SMD = 1.47 [0.63, 2.30]; $p < 0.001$; $I^2 = 86\%$; $k = 10$). Sub-group results for CS provided low while pooled results and sub-groups results for RR provided moderate GRADE quality of evidence (Table 8-2). The loads used (b = -0.03 [-0.12, 0.07]; $p = 0.611$) or the number of repetitions performed during TS (b = 0.13 [-0.19, 0.45]; $p = 0.418$) were not significant moderators of the SMD for mean velocity decrement. However, performing repetitions to failure during traditional sets was a significant moderator of the SMD in mean velocity decrement with failure resulting in a greater difference in favour of alternative set structures (b = 2.14 [0.58, 3.70]; $p = 0.007$) (Figure 8-7). When analysing CS set structures separately, however, performing repetitions to muscular failure (b = 1.44 [-0.69, 3.56]; $p = 0.184$), the number of repetitions being performed during TS (b = 0.01 [-0.12, 0.15]; $p = 0.832$), and the load used (b = 0.13 [-0.36, 0.62]; $p = 0.594$) were not significant moderators of the SMD in mean velocity.

Mean velocity maintenance

Subgroup analysis indicated that CS (SMD = 1.30 [0.70, 1.90]; $p < 0.001$; $I^2 = 11\%$; $k = 2$), but not RR (SMD = 0.62 [-0.51, 1.75]; $p = 0.283$; $I^2 = 87\%$; $k = 2$) set structures resulted in significantly greater mean velocity maintenance when compared to TS. When the effects from alternative set structures were pooled, mean velocity maintenance was significantly greater than during TS (SMD = 0.95 [0.24, 1.75]; $p = 0.009$; $I^2 = 83\%$; k = 4). Sub-group results for CS provided moderate whereas pooled results and sub-group results for RR provided low GRADE quality of evidence (Table 8-2).

Mean power decrement

Subgroup analysis indicated that both CS (SMD = 1.26 [0.53, 1.99]; $p < 0.001$; $I^2 = 0\%$; k = 1) and RR (SMD = 0.70 [0.07, 1.33]; $p = 0.029$; $I^2 = 70\%$; k = 3) set structures resulted in significantly lower mean power decrement when compared to TS. When the effects from alternative set structures were pooled, mean power decrement was significantly lower than during TS (SMD = 0.83 [0.28, 1.37]; $p = 0.003$; $I^2 = 71\%$; k = 4). GRADE quality of evidence for pooled results and sub-group results for RR was low (Table 8-2).

Mean power maintenance

Subgroup analysis indicated that CS (SMD = 1.09 [0.40, 1.77]; $p = 0.002$; $I^2 = 0\%$; k = 1), but not RR (SMD = 0.67 [-0.56, 1.89]; $p = 0.286$; $I^2 = 88\%$; k = 2) set structures resulted in significantly greater mean power maintenance when compared to TS. When the effects from alternative set structures were pooled, mean power maintenance was not significantly greater than during TS (SMD = 0.78 [-0.01, 1.57]; $p = 0.053$; $I^2 = 84\%$; k = 3). GRADE quality of evidence for pooled results and sub-group results for RR was low (Table 8-2).

Peak velocity decrement

Subgroup analysis indicated that both CS (SMD = 1.97 [0.14, 3.71]; $p = 0.02$; $I^2 = 81\%$; k = 2), and RR (SMD = 2.08 [0.45, 3.70]; $p = 0.012$; $I^2 = 85\%$; k = 2) set structures resulted in significantly lower peak velocity decrement when compared to TS. When the effects from alternative set structures were pooled, peak velocity decrement was significantly lower than during TS (SMD = 1.97 [0.98, 2.95]; $p < 0.001$; $I^2 = 77\%$; k = 4). Pooled results and sub-group results for CS and RR all provided low GRADE quality of evidence (Table 8-2).

Peak velocity maintenance

Subgroup analysis indicated that both CS (SMD = 0.91 [0.39, 1.44]; $p < 0.001$; $I^2 = 0\%$; k = 2) and RR (SMD = 2.57 [1.42, 3.73]; $p < 0.001$; $I^2 = 0\%$; k = 2) set structures resulted in significantly greater peak velocity maintenance when compared to TS. When the effects from alternative set structures were pooled, peak velocity maintenance was significantly greater than during TS (SMD = 1.36 [0.33, 2.39]; $p = 0.009$; $I^2 = 71\%$; k = 4). Sub-group results for CS provided moderate whereas pooled results provided low GRADE quality of evidence (Table 8-2).

Peak power decrement

Subgroup analysis indicated that both CS (SMD = 1.48 [0.82, 2.13]; $p < 0.001$; $I^2 = 47\%$; k = 3), and RR (SMD = 1.95 [0.28, 3.62]; $p = 0.022$; $I^2 = 88\%$; k = 3) set structures resulted in significantly lower peak power decrement when compared to TS. When the effects from alternative set structures were pooled, peak power decrement was significantly lower than during TS (SMD = 1.71 [0.92, 2.49]; $p < 0.001$; $I^2 = 76\%$; k = 6). Sub-group results for CS provided moderate whereas pooled results and sub-group results for RR provided low GRADE quality of evidence (Table 8-2). The load used (b = -0.01 [-0.03, 0.02]; $p = 0.773$) or the number of repetitions performed during TS (b = -0.22 [-0.48, 0.04]; $p = 0.105$) were not significant moderators of the SMD for peak power decrement.

Peak power maintenance

Subgroup analysis indicated that both CS (SMD = 0.99 [0.33, 1.64]; $p = 0.003$; $I^2 = 0\%$; k = 1), and RR (SMD = 2.09 [1.10, 3.08]; $p < 0.001$; $I^2 = 0\%$; k = 1) set structures resulted in significantly greater peak power maintenance when compared to TS. When the effects from alternative set structures were pooled, peak power maintenance was significantly greater than during TS (SMD = 1.47 [0.40, 2.55]; $p = 0.007$; $I^2 = 70\%$; k = 2). GRADE quality of evidence for pooled results was low (Table 8-2).

Post-session jump height loss or velocity against fixed load loss

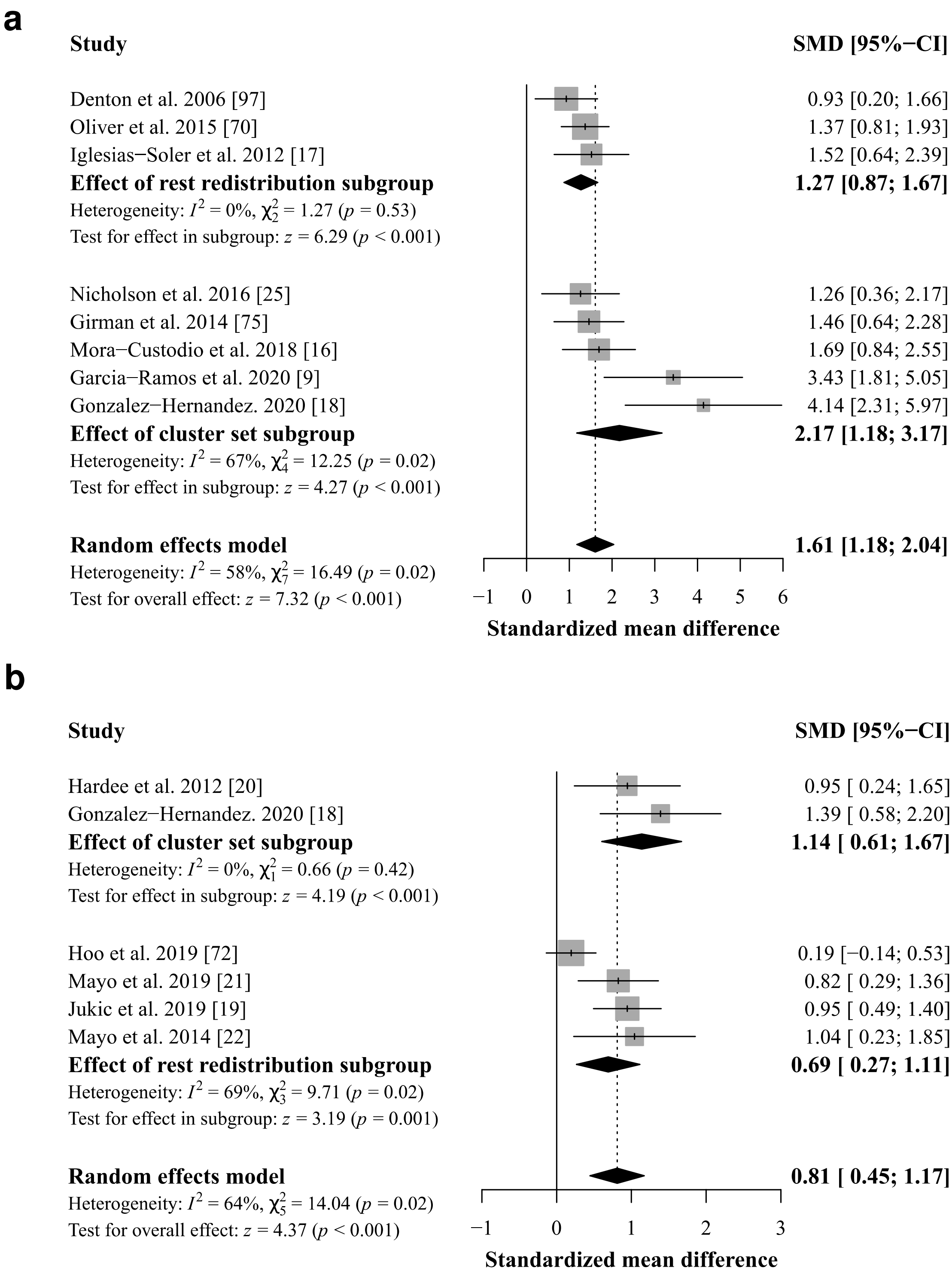
Subgroup analysis indicated that CS (SMD = 0.65 [0.29, 1.01]; $p < 0.001$; $I^2 = 0\%$; k = 3), but not RR (SMD = 0.39 [-0.20, 0.98]; $p = 0.195$; $I^2 = 0\%$; k = 1) set structures resulted in significantly lower post-session jump height or velocity against fixed load loss when compared to TS. When the effects from alternative set structures were pooled, post-session jump height or velocity against fixed load loss were significantly lower than during TS (SMD = 0.58 [0.27, 0.89]; $p < 0.001$; $I^2 = 0\%$; k = 4). GRADE quality of evidence for pooled results and sub-group results for CS was moderate (Table 8-2).

3.5 Metabolic outcomes

Lactate

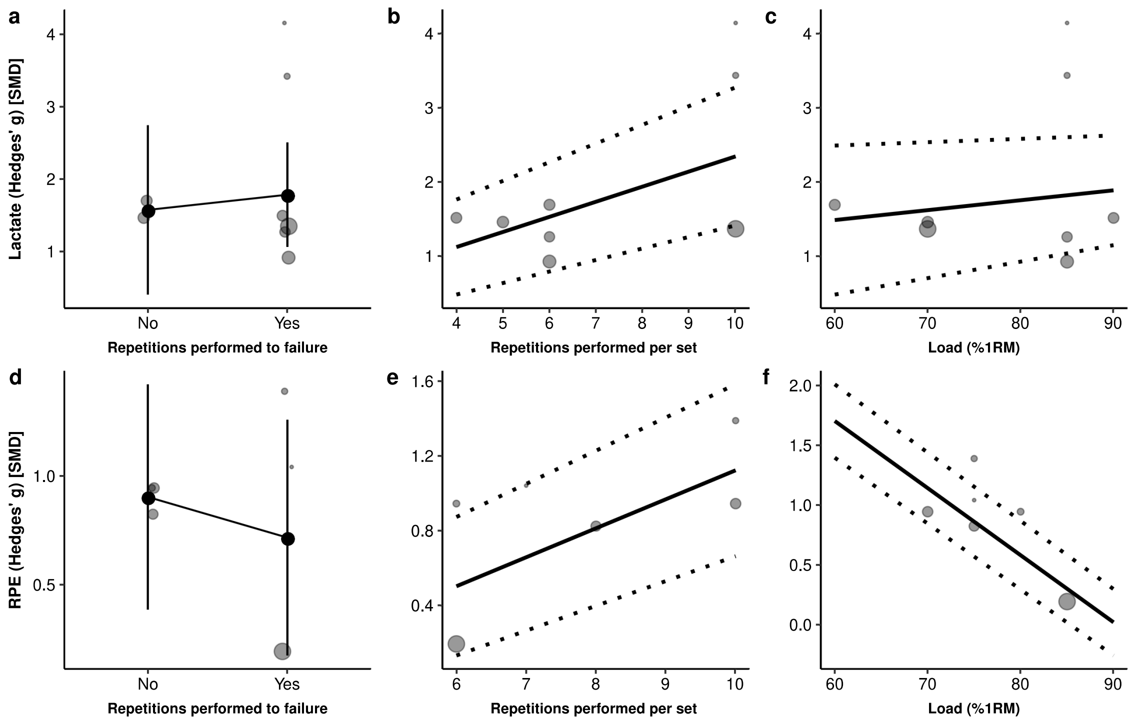
Subgroup analysis indicated that both CS (SMD = 2.17 [1.18, 3.17]; $p < 0.001$; $I^2 = 67\%$; k = 5) and RR (SMD = 1.27 [0.87, 1.67]; $p < 0.001$; $I^2 = 0\%$; k = 3) set structures resulted in significantly lower post-session lactate values when compared to TS (Figure 8-8). When the effects from alternative set structures were pooled, lactate values were significantly lower than during TS (SMD = 1.61 [1.18, 2.04]; $p < 0.001$; $I^2 = 58\%$; k = 8). Sub-group results for CS provided low whereas pooled results and sub-group results for RR provided moderate GRADE quality of evidence (Table 8-2). Performing repetitions to failure (b = 0.21 [-1.16, 1.58]; p = 0.764) or the number of repetitions being performed during TS (b = 0.20 [-0.05, 0.45]; p = 0.112) and the load used (b = 0.01 [-0.05, 0.07]; p = 0.662) were not significant moderators of the SMD in lactate values (Figure 8-9).

Figure 8-8 Random-effects meta-analysis of blood lactate (a) and rating of perceived exertion (b) during alternative set structures (i.e., CS and RR) compared to TS. Subgroup analysis based on the effects of CS and RR separately.



Note. CI, confidence interval; SMD, standardised mean difference; CS, cluster set structure; RR, rest redistribution set structure; TS, traditional set structure.

Figure 8-9 Random-effects meta-regression of blood lactate (top row) and rating of perceived exertion (bottom row) during alternative set structures (i.e, CS and RR combined) compared to TS while controlling for the effects of muscular failure during TS (a, d), number of repetitions performed during TS (b, e) and the load used (c, f).



Note. Larger data points received greater weighting than smaller data points. Solid (non-vertical) lines represent the estimated relationship, solid vertical lines and dotted lines represent the upper and lower 95% confidence intervals. CS, cluster set structure; RM, repetition maximum; RR, rest redistribution set structure; TS, traditional set structure.

8.3.5 Perceptual outcomes

Rating of perceived exertion

Subgroup analysis indicated that both CS (SMD = 1.14 [0.61, 1.67]; $p < 0.001$; $I^2 = 0\%$; $k = 2$) and RR (SMD = 0.69 [0.27, 1.11]; $p = 0.001$; $I^2 = 69\%$; k = 4) set structures resulted in significantly lower ratings of perceived exertion when compared to TS (Figure 8-8). When the effects from alternative set structures were pooled, ratings of perceived exertion were significantly lower than during TS (SMD = 0.81 [0.45, 1.17]; $p < 0.001$; $I^2 = 64\%$; $k = 6$). Sub-group results for CS provided moderate whereas pooled results and sub-group results for RR provided low GRADE quality of evidence (Table 8-2). Performing repetitions to failure ($b = -0.19$ [-0.94, 0.56]; $p = 0.625$) or the number of repetitions being performed during TS ($b = 0.16$ [-0.02, 0.33]; $p = 0.08$) were not significant moderators of the SMD in rating of perceived exertion. However, the load used was a significant moderator of the SMD in rating of perceived exertion with lower loads leading to greater effects of alternative set structures on perceptual exertion (b = -0.06 [-0.09, 0.02]; p = 0.004) (Figure 8-9).

8.4 Discussion

The present systematic review and meta-analysis is the first to synthesise the evidence regarding the efficacy of alternative set structures to alleviate mechanical, metabolic, and perceptual markers of fatigue during and after RT while also accounting for the fundamental differences between CS and RR. Based on the current evidence, the main findings of this review suggest that although both CS and RR set structures positively affect mechanical, metabolic, and perceptual responses during RT compared to TS, the magnitude of these positive effects are generally much greater for CS than for RR. Therefore, the alteration of TS to different alternative set structure (CS or RR) is expected to provide different acute training stimuli which further highlights the need for a clearer distinction between the structures.

8.4.1 Mechanical outcomes

Mean and peak velocity and power (overall for entire protocol)

Moderate to high GRADE quality evidence indicated significant differences between alternative set structures and TS in absolute mean and peak velocity and power. When comparing TS against CS and RR separately, similar moderate to high GRADE quality of evidence was provided. However, the positive effects of CS over TS were much larger (SMD: 0.54 – 1.01) than those observed for RR (SMD: -0.01 – 0.39). Therefore, the extra intra-set rest periods during CS likely allow for immediate energy stores and subsequent performance to be better maintained compared to RR. Furthermore, although RR positively affected both peak power (SMD: 0.30) and peak velocity (SMD: 0.28), this effect was not significant ($p < 0.05$), indicating that CS should be preferred when the aim is to have a greater overall peak velocity and peak power during RT (Figure 8-3). While it may be tempting to conclude that RR is not effective in enhancing peak velocity and power, it must be noted that considerably fewer studies report peak variables as opposed to mean variables, which may have affected the results (i.e., lower statistical power and hence stability of the results). This is further supported by the fact that beneficial effects of CS and RR were greater for the mean variables, again, likely due to the higher number of studies reporting mean velocity and power. Furthermore, neither the presence of muscular failure during TS, the number of total repetitions being performed, nor the load used were significant moderators of the differences between TS and alternative set structures (both combined and separately) (Figure 8-4 and Figure 8-5). However, there was still a tendency to show greater effects of RR and CS for studies in which muscular failure was reached during TS. This probably explains the findings from more recent studies suggesting that when TS are not performed to, or near to, muscular failure, the effects of alternative set structures on absolute measures of mechanical performance are not as profound [206, 160, 255, 256].

Mean and peak velocity and power decrement (loss throughout the protocol)

Although analysing mean and peak velocity and power provides an overview of what happens during TS, CS, and RR, such an overarching approach does not explain what actually happens during exercise, as one continues to perform more repetitions. Therefore, many studies also calculate the decrement of the mechanical variables from the beginning to the end of a set or protocol, which could arguably be seen as a true indicator of fatigue since it represents a change in velocity or power as fatigue manifests. Our meta-analyses provided low to moderate GRADE evidence, indicating positive effects of alternative set structures on mean and peak velocity and power decrement (i.e. the decrease in performance throughout the protocol was not as much as in TS). Specifically, the effects of CS on mean velocity decrement were much greater (SMD: 2.32) compared to RR (SMD: 0.29). However, for mean power and peak velocity decrement, the positive effects of CS and RR over TS were comparable, with RR allowing for even less peak power decrement when compared to TS and CS. The discrepancy between the findings could likely be explained by the varying number of studies reporting decrement variables and the high heterogeneity that affected the results of the subgroup analyses.

Regardless of the decrement variable being calculated, the beneficial effects of alternative set structures (both combined and separately) were always greater than, or varied less than, absolute mean and peak velocity and power variables (i.e., overall values for entire the protocol). Thus, the greater and more consistent effect of RR and CS on velocity and power loss suggests that “absolute” and “decrement” variables should be classified independently. This is further supported by numerous studies, which found how the effects of CS and RR were much smaller on absolute rather than decrement mechanical outcomes [225, 25, 23, 226]. Furthermore, performing repetitions to failure during TS was a significant moderator of the differences between alternative set structures and TS (i.e. less mean velocity loss in CS and RR compared to TS to failure). Although interesting, this finding likely represents a type I error for the following reasons: TS were performed to failure in only 3 out of 10 studies in the meta-analysis, all of which compared TS to CS, and we found no significant association between the effects of alternative set structures and whether repetitions were performed to muscular failure when analysing CS separately. Therefore, we suspect this analysis to be more prone to inferential errors and thus, to represent a false positive finding given the non-significant effects of muscular failure with a more equal distribution (3 vs 3) of "failure" and "non-failure" studies that compared TS and CS only.

Mean and peak velocity and power maintenance (overall for entire protocol)

Meta-analyses in the present review provided low to moderate GRADE evidence that alternative set structures allow for greater maintenance (SMD: 0.95 – 1.47) of mean velocity, peak velocity, and peak power, but not mean power during RT. Although few studies reported these mechanical outcomes in the present review, mean power maintenance was also affected by conflicting findings of the only two studies that reported on this outcome. More specifically, while Merrigan et al. [225] found RR to be effective at maintaining mean power during RT, Jukic et al. [206] reported no significant differences between TS and RR. The discrepancy between findings of these two studies could likely be explained by the differences in the inter-set rest time allowed for the TS group (2 vs 4 minutes). Similar to other mechanical outcomes, CS were more effective than RR at maintaining mechanical performance during RT.

While it may not seem obvious how calculating the decline and the maintenance of mechanical variables could provide a different insight into a training stimulus imposed by altering the set structure during RT, several studies clearly indicated this to be the case [206, 225, 23]. For instance, Tufano et al. [23] showed that TS resulted in a 23% decline in velocity and power from the first repetition to the last, but when the maintenance variable was calculated, which takes into account all repetitions not just the first and the last, TS resulted in a "decrease" of only 8%. Therefore, it is important to note that absolute, decline and maintenance variables of mechanical outcomes may each tell a different story and should, therefore, be classified independently. The emphasis on each of them (combined or in isolation) should probably depend upon the objective of RT. For instance, if power adaptations are desired, decrement variables could be used to quantify a decline in performance from the first repetition to the last, and to detect when the decline started to affect performance (i.e., when caculated for each repetition). On the other hand, maintenance variables could provide a greater inshight into the overall degree of fatigue induced by RT when considering all the repetitions in a given set. Evidently, both decline and manitenance variables provide distinct information which can then better inform future training decisions.

Performance before and after the entire protocol

While results of the present review suggest that alternative set structures are effective at maintaining acute RT performance, it is also important to consider the residual mechanical fatigue induced by RT sessions. For instance, there are many sports (e.g., team-sports) in which RT precedes sport-specific training. In that regard, alternative set structures might also enable less interference with subsequent sport training. Moderate GRADE evidence showed lower mechanical fatigue levels after RT in which alternative set structures were used, as indicated by less jump height loss or less velocity loss against a fixed load (SMD: 0.58). It is important to note that the magnitude of these effects was much lower when compared to the effects on mechanical fatigue assessed during the actual training (i.e., decline and maintenance variables) suggesting that the rate of the post-session recovery might not be as affected by alteration of the set structure. This finding is in agreement with a recent study published after the present review was conducted [226], which showed that RR was more effective in maintaining force production during an isokinetic unilateral knee extension at different velocities than inducing faster peripheral recovery after training. However, since there were a limited number of studies in the present review, which varied in exercise selection, load, and number of sets and repetitions, future research is needed to determine if alternative set structures impact mechanical markers of fatigue differentially during and after RT.

8.4.2 Metabolic and perceptual outcomes

Moderate GRADE evidence indicated significantly lower blood lactate concentrations during alternative set structures when compared to TS (SMD: 1.61). Similar to all mechanical outcomes, when the effects of CS and RR were analysed separately; CSs were more effective than RR in reducing the metabolic stress imposed by RT since much lower blood lactate concentrations were generally observed after CS (SMD: 2.12) than RR (SMD: 1.12) when compared to TS (Figure 8-8). This contention is supported by the literature since various mechanical markers of fatigue have been associated with lactate accumulation during RT [15, 257, 258, 202]. Based on earlier research by Gorostiaga et al. [223, 19, 224] and Bogdanis et al. [221, 220, 222], it is logical that CS inclusive of extra rest periods were effective at reducing metabolic stress during RT. However, it is interesting that RR was also highly effective for managing metabolic fatigue during RT, despite the total rest time not increasing compared to TS. Furthermore, meta-regressions suggest that alternative set structures are effective in reducing metabolic stress compared to TS, irrespective of the load used, the number of repetitions performed, or whether repetitions were performed to failure during TS (Figure 8-9). Collectively, this suggests that higher metabolic stress induced by TS might negatively affect performance of subsequent exercises in a session, which could be alleviated by using alternative set structures.

Low to moderate GRADE evidence indicates that both CS and RR were effective at reducing perceived exertion after RT compared to TS (Figure 8-8). As with every other outcome in this review, CS were more effective than RR, which is not surprising considering the strong relationship between the mechanical, metabolic, and perceptual markers of fatigue reviewed and meta-analysed in this paper [210, 202, 207, 203, 198, 259]. Meta-regressions showed that performing repetitions to muscular failure during TS and the number of repetitions performed were not significant moderators of the magnitude of the effect on RPE (Figure 8-9). Interestingly, however, meta-regression also showed that lower loads were associated with stronger effects of alternative set structures on RPE. Although this might sound counterintuitive on the surface, the range of loads included in the analysis was narrow (i.e., 70 to 85%), and studies using the highest loads showed the smallest effect. In addition, due to its sample size, one study [249] in which repetitions were performed to failure regardless of the set structure, carried greater weight in this analysis. Additionally, only 6 repetitions were performed during TS in this study whereas more than 8 repetitions were performed during TS in other studies included in the analysis. Consequently, this study [249] also affected the relationship between the number of repetitions performed and the effect of alternative set structures on RPE, which was nonsignificant. Since this single study [249] was at a high risk of bias, the number of repetitions performed during TS likely was a significant moderator of the effects of alternative set structures on RPE, with more repetitions per set leading to greater differences between the set structures, whereas the load was not.

8.4.3 Implications for training and research

Overall, the findings of this review suggest that alternative set structures are effective at ameliorating acute mechanical fatigue during and after RT as well as metabolic, and perceptual fatigue after RT. However, greater differences were observed between CS and TS than RR and TS for most outcomes, confirming that CS and RR likely provide different training stimuli and subsequently, may affect recovery in different ways. This is not surprising, considering that when compared to TS, CS structures contain extra rest while RR structures do not, further highlighting that CS and RR should be classified independently. Although on the surface, it may seem obvious to classify CS and RR as two different types of alternative set structures (due to the extra total rest in CS), the term "cluster set" has been used loosely in the literature, resulting in an umbrella term that encompasses different types of set structures [24, 226, 227]. As such, the results of investigations are not always in agreement, which might leave sport professionals unsure of how they should construct set structures in practice. Therefore, we urge future investigators to consider the fundamental differences between alternative set structures. Doing so will allow researchers and sport professionals to compare and contrast different set structure designs with more accuracy and less confusion.

Conclusions regarding the effects of alternative set structures are often based on absolute mechanical performance (e.g., mean and peak velocity and power averaged across the whole session) [227] or the decline and maintenance of these mechanical outcomes during RT [23, 160, 226, 225]. While studies often reach similar conclusions to varying degrees of magnitude, it must be noted that analysing the absolute mean and peak values of a given mechanical variable is not the same as assessing the change in performance throughout the RT session. The findings of this review support this contention, showing greater effects of alternative set structures on decline and maintenance, than on absolute mechanical values during RT. While this might partially be explained by the design of a given set structure, the velocity or power of the initial repetitions of any set structure will most likely be similar, attenuating differences between TS and alternative set structures in the overall response [245, 26, 253, 202]. However, although the differences between TS and CS or RR become more evident when looking at decline or maintenance calculations, the differences become even more apparent as the number of repetitions performed during a set increase. For instance, CS can result in greater absolute velocity and power compared to TS [23], but much larger differences can be observed if the velocity and power maintenance (i.e., considering all the repetitions within sets) are calculated. In addition, a decline in velocity and power (i.e., considering only the last repetition relative to the first) is even more sensitive in detecting fatigue-induced changes in mechanical performance with the greatest differences typically being observed between TS and CS in decline variables. This suggests, as individual studies have hypothesised, that alternative set structures might not be as effective for producing higher absolute velocity or power outputs, but rather, better serve to reduce fatigue [225]. Therefore, it is evident that the absolute, maintenance, and decline of mechanical outcomes may each tell a different story and hence, should be classified independently. By utilising all three during RT, sport professionals will gain a greater insight into: 1) overall mechanical performance; 2) degree of neuromuscular fatigue induced by a given set; 3) when the fatigue-induced changes become apparent, and at what rate they develop.

Similar to mechanical fatigue during RT, alternative set structures were also effective at alleviating post-RT mechanical fatigue. While these effects were generally smaller and suggest that alternative set structures might not be as effective in combating acute residual fatigue induced by RT, the research on this topic is lacking. Therefore, future research is needed to explore the effectiveness of alternative set structures in mitigating residual fatigue after RT. On the other hand, results from this meta-analysis suggest that alternative set structures are highly effective at reducing metabolic stress and perceptual exertion induced by RT when compared to TS. Since low RPE and blood lactate values have been associated with higher velocity and power outputs [198, 205, 260, 207], alternative set structures might be effective not only in stimulating strength-speed and speed-strength adaptations, but also in reducing recovery time following RT [261, 141, 262, 43]. This would be valuable for sport professionals, especially those working in team-sport settings where competitions are held every weekend or even every 3-4 days who need to manage RT fatigue for both game performance and sport specific training sessions [263, 97, 17]. In addition, since sport professionals working in those settings are often time-constrained, RR might be preferable to CS since they do not extend total training time while still aiding fatigue management during and after RT. Furthermore, the metabolic and perceptual outcomes, coupled with mechanical performance findings, could also imply that alternative set structures may enable greater volumes of work to be completed by allowing more sets and repetitions to be performed [160, 250, 26] or greater loads [201, 212] to be lifted which can ultimately result in greater strength adaptations as well as increase in lean body mass [196, 33, 121, 264, 213]. For these reasons, CS or RR set structures provide sport professionals with a multitude of options to design their training to better manage fatigue while inducing the desired adaptations.

8.4.4 Limitations and Considerations

Several aspects of this review should be considered when interpreting the findings. First, the small number of studies including female participants limits the generalisability to female participants, and more research should include females when possible. Second, most meta-analyses on decline and maintenance of mechanical outcomes in the present review were affected by the high levels of heterogeneity. While we attempted to explore the cause of the heterogeneity by performing sub-group analyses and meta-regressions when sufficient studies were available, it is likely the small number of studies was the primary contributor to the observed heterogeneity. In addition, general disagreement between the magnitudes of the effect of CS and RR on some of the outcomes consequently affected the heterogeneity of the pooled results, which can rather be seen as a strength than limitation since the sub-group analysis was effective at identifying the source of heterogeneity. Third, while we performed meta-regression to examine how muscular failure, number of repetitions, and load used during TS impacted the effectiveness of alternative set structures, compared to TS, the number of included studies only allowed this to be performed on several pooled results and only a few sub-group results. In addition, for some of the outcomes, the range of loads was narrow, and studies in which TS were performed to failure were not equally distributed among the subgroups, limiting the generalisability of the meta-regression's findings. Therefore, future studies should compare TS and alternative set structures across a wide range of loads. This is important since one might argue that more frequent racking and un-racking the barbell with very heavy loads (e.g., > 85 % 1RM) might negatively affect RT performance. It is also important to note that other studies contain valuable data that did not fit within the scope of the present review, which should still be considered when designing RT programs. Finally, due to insufficient information from individual studies in this review, a default correlation coefficient of 0.50 was used for all studies, which could have caused an underestimation of the actual differences between TS and alternative set structures.

8.5 Conclusion

The results of the present systematic review and meta-analysis suggest that alternative set structures are very effective at reducing mechanical fatigue, perceptual exertion, and metabolic stress during and after RT. However, fundamental differences in total rest time results in CS being generally more effective than RR for alleviating fatigue during RT. These fundamental differences highlight the importance of classifying alternative set structures independently. In addition, absolute, decline, and maintenance of mechanical variables during RT, as well as residual mechanical fatigue after RT, are all affected differently by alternative set structures, suggesting that each variable may have different implications. Therefore, these variables should be assessed independently and not be used interchangeably when evaluating the effectiveness of alternative set structures. With all of this in mind, researchers, sport professionals, and athletes should take these factors into consideration when choosing to implement CS, RR, or any form of alternative set structure in research and practice.

Chapter 9: The effects of set structure manipulation on chronic adaptations to resistance training: A systematic review and meta-analysis

Preface

In Chapter 8, the superiority of cluster sets and rest redistribution over traditional sets was confirmed with a systematic review and meta-analysis of their effects on mechanical, metabolic, and perceptual responses to resistance training. However, these conclusions were limited to acute effects; the generalisability of the findings to chronic adaptations such as muscle strength, power, endurance and hypertrophy remained uncertain. Understanding the chronic impact of set structure manipulation is particularly important if cluster sets and rest redistribution are to be used as alternatives to resistance training prescription using velocity loss since different amounts of velocity loss modulates the magnitude of resistance training-induced training adaptations. Therefore, this Chapter expands on the previous Chapter and synthesises the available evidence on the effectiveness of traditional, cluster, and rest redistribution structures in promoting chronic resistance training adaptations, while controlling for confounding factors with meta-regression.

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9.1 Introduction

Resistance training (RT) is considered to be the principal mode of exercise for improving muscular strength, power and hypertrophy. While these adaptations often coincide with improvements in jumping, sprinting, agility, and sport-specific performance [1, 2], improvements in muscular strength, power, and muscle mass may also decrease the risk of falling in the elderly and might positively affect cognitive function, psychosocial status, and the quality of life [30-32, 265, 266]. However, the magnitude of their improvements is influenced by the structure of the training program [123]. For instance, training volume, intensity, frequency, rest intervals, exercise selection, exercise order, proximity to muscular failure, repetition velocity, and set structure can all affect the resultant training adaptations. As such, there has been a great deal of research into the programming and manipulation of RT variables. While the influence of most of these variables has been extensively reported in the literature and summarised through recent systematic reviews and meta-analyses [195-197, 33, 230, 121], the effect of set structure manipulation on muscular strength, power and hypertrophy is comparably neglected [24].

Traditionally, the completion of a training set occurs without any rest being taken between repetitions. Subsequently, this basic set configuration, often referred to as a traditional set structure (TS), is continued for a predetermined number of sets prescribed in a training session. In addition, sport professionals often instruct athletes to perform concentric muscle actions as quickly as possible since explosive concentric muscle actions often result in greater training effects compared with intentionally slower concentric actions [218, 217, 37]. However, when using TS, concentric velocity decreases due to fatigue as the number of repetitions increases [13, 14, 97, 15] – this velocity loss is observed across a variety of simple and complex RT exercises and is aggravated by multi-set training with a high number of repetitions. Fatigue-induced velocity loss and concomitant decreases in power outputs result in an increased overall time under tension [267, 268] and increased myoelectrical activity toward the end of a set [251, 269, 270], both of which might be beneficial for inducing strength and hypertrophy adaptations [271-274]. This has led some practitioners and researchers to believe that TS structures seem ideal for promoting both muscular strength and hypertrophy [273, 275-277]. While fatigue is often thought to be of paramount importance for the development of muscle mass and strength, more recent literature [121, 196, 33, 278, 279, 3] repeatedly demonstrates that training volume likely plays a key role in both strength and hypertrophic adaptations as well. In addition, a substantial body of research now indicates that performing repetitions at maximal intended velocity [218, 217, 37] and terminating training sets once a moderate velocity loss is achieved during a training set [97, 17, 46], may be more important for inducing maximal strength gains than increasing time under tension. This, coupled with the widely acknowledged deleterious effects of fatiguing exercise on muscular power development and performance of athletic tasks [97, 17, 280, 281], highlights a need for strategies that limit the typical fatigue-induced reductions in movement velocity often seen during TS. Therefore, alternative set structures, which consist of shorter but more frequent rest periods, have gained considerable attention from the sport science community for the purpose of mitigating acute fatigue during RT.

The simplest and most effective way to off-set acute fatigue and maintain high movement velocities is to add pre-planned rest intervals within a set alongside normal interset rest periods; thus, breaking sets into small clusters of repetitions [282, 24]. Although these so-called “cluster sets” (CS) are frequently used to describe any set structure in which rest periods are more frequent than TS (see Tufano et al. [24] for more detailed discussion), CS simply represent a strategy of adding short rest periods within a set while maintaining normal rest periods between sets to maximise performance of each individual repetition within sets [24]. Thus, an indispensable feature of CS is that they extend total training time relative to TS [25, 23, 202]. From a practical standpoint, this might not always be feasible for sport professionals, especially for those working with athletes who train multiple times a day and who need to manage RT fatigue for both game performance and sport specific training sessions. To overcome these constraints, researchers have investigated other possible alternatives to CS, such as simply redistributing the total rest time of TS structures to include shorter and more frequent rest intervals. While this set structure, known as rest redistribution (RR), can effectively alleviate acute mechanical [225, 26, 237], metabolic [247, 204] and perceptual [209, 208] markers of fatigue during RT, it does so without increasing total training time associated with CS. Indeed, Jukic et al. [128] recently reported alternative set structures were generally superior to TS in a systematic review and meta-analysis on their effects on mechanical, metabolic and perceptual responses to RT. However, conclusions from this review were limited to the acute effects of alternative set structures on RT performance and fatigue management; the generalisability of the findings to chronic adaptations such as muscular strength, power and hypertrophy is uncertain.

Considerable evidence is accumulating from longitudinal studies (> 4 weeks in duration) comparing the effectiveness of TS and alternative set structures on various training adaptations. However, the findings appear equivocal. For instance, Goto et al. [277], Drinkwater et al. [275] and Lawton et al. [276] all emphasised the importance of fatigue during RT in inducing strength gains, as they observed greater increases in strength in groups using TS rather than alternative set structures. In contrast, Oliver et al. [213] suggested that shorter, but more frequent rest periods allow for greater improvements in both strength and power, while Hansen et al. [281] concluded that CS present a viable option for the development of lower-body power, but not strength, when compared to TS. To further complicate matters, other studies reported no significant differences in muscular strength and power-related outcomes when comparing TS to CS or RR [212, 256, 283, 284, 246, 285].

Therefore, these inconsistencies in the literature regarding the long-term effects of alternative set structures on training adaptations justify the need for a comprehensive review and synthesis of the available evidence. Thus, the aim of this systematic review and meta-analysis was to synthesise the available evidence on the effectiveness of TS, CS and RR structures in promoting chronic RT adaptations. To achieve further clarity on the topic, this review also aimed to provide an overview of the factors which might differentially influence the magnitude of specific muscular adaptations between the set structure types, allowing sport professionals to compare and contrast them with more nuance. Such evidence is important to guide RT prescription and ultimately determine the most effective set structure to promote an intended training adaptation.

9.2 Methods

9.2.1 Registration of systematic review protocol

A systematic review of the literature was performed according to the guidelines in the *Cochrane Handbook for Systematic Reviews of Interventions* (version 5.1.0) and following the checklist for the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [228]. The original protocol was prospectively registered with the International Prospective Register of Systematic Reviews (PROSPERO) in June 2019 and was part of a larger systematic review project comparing the acute and chronic effects of alternative set structures across a range of outcomes (Registration number: CRD42019138954). The protocol registration occurred before any of the searches were conducted.

9.2.2 Literature search

A PICO strategy which consisted of terms for traditional, cluster and rest redistribution set structures; resistance training and mechanical, perceptual, and metabolic outcomes as well as muscular strength, power and hypertrophy adaptations was used to build search criteria for electronic databases. The following bibliographic databases were searched from inception to June 6th, 2019: PubMed/MEDLINE, SCOPUS, CINAHL (Cumulative Index to Nursing and Allied Health), SPORTDiscus and Web of Science. The search syntax adapted for each database and applied to the title, abstract, and keyword search fields is reported in the Appendix F Ch. 9 File I. Secondary searches included: (a) screening the reference lists of all included studies and relevant review papers; (b) examining the studies that cited the included studies (i.e., forward citation tracking) through Google Scholar; (c) search alerts to monitor any new search results after the date of the last search up to June 3, 2020. Free-text terms were chosen based on pilot searches that achieved an appropriate balance between search sensitivity and precision without the use of controlled vocabulary (e.g. MeSH [Medical Subject Headings]). No year restrictions were applied in the search. The strategy included only terms relating to or describing the intervention. All trials had to be peer-reviewed and published in an English-language journal while conference abstracts and proceedings were not considered. Three authors (IJ, AGR, and BVH) independently performed the searches. Records were downloaded into Endnote (version X8.2, Clarivate Analytics, Philadelphia, PA, USA) and duplicates were removed with automated and manual methods before being screened by title and abstract. The full texts of the remaining records were then retrieved and assessed for eligibility. Any discrepancies between the authors in the study selection were resolved in consultation with a fourth reviewer (JJT).

9.2.3 Eligibility criteria

All studies included in this systematic review met the following inclusion criteria: (1) the study was published in English; (2) the study compared muscular strength, power-related, endurance, and/or hypertrophy adaptations between TS and CS or RR set structures; (3) the study included an intervention group (CS) during which additional intra-set rest intervals were included and total rest periods extended compared to the control group, and/or a second intervention group (RR) during which total rest periods were the same compared to control group; (4) the study included a control group (TS) in which multiple repetitions within a set were performed in a consecutive fashion while including only rest periods between the sets (i.e., inter-set rest); (5) training volume (set x repetitions) and training frequency were matched between the conditions: (6) in studies that looked at muscular strength and hypertrophy adaptations, both lean body mass changes and changes at the muscle level (whole muscle or muscle fibre) were considered regardless of assessment method (e.g. ultrasound, DEXA or tape with skinfolds), while for muscle strength, tests with a repetition maximum (RM) component (e.g. 1RM, 5RM), or maximum voluntary contraction (MVC) tests were considered; (7) in studies that investigated expressions of muscular power such as changes in jump height, sprint and change of direction times as well as velocity and power outputs at submaximal loads were considered; (8) the interventions lasted a minimum of 4 weeks; (9) participants had no known medical conditions or injuries.

9.2.4 Study coding and data extraction

From the studies that met the inclusion criteria, the following data was extracted into an Excel spreadsheet: (1) study identification information; (2) adherence and study duration; (3) sample size; (4) participants' characteristics, including age, body mass, body height, sex, strength levels, and training experience; (5) resistance training prescription details for TS, CS, and RR set structures; and (6) means and standard deviations as well as raw mean changes and standard deviations of changes for pre- and post-intervention assessments of the relevant outcome measures. If insufficient data were reported, the authors of those studies were contacted by-email. Web Plot Digitizer software (Version 4.1; TX, USA) was used to extract data from figures when the authors did not report or provide the data. Data extraction was completed independently by two authors (IJ and BVH) using a pilot-tested form on five randomly selected studies which was then modified accordingly. Coding files were cross-checked between the authors, and any observed differences were resolved via discussion and agreement, or with a third reviewer (JJT).

9.2.5 Risk of bias assessment

Risk of bias assessment was performed using a modified Cochrane Collaboration's tool for assessing risk of bias in randomised trials [54]. Modifications included removal of the performance bias criterion and adding set structure bias, outcome assessment bias, and familiarisation bias. In addition, while the blinding of outcome assessment bias was not excluded, it was considered of trivial importance in the present review since the training volume and intensity of load were matched between the interventions. Therefore, we did not expect that awareness of intervention allocation would introduce bias. Similar to previous systematic reviews and meta-analyses on exercise intervention studies [230, 229], the performance bias criterion was removed because it was considered impossible to successfully blind participants and personnel in supervised exercise intervention studies. Set structure bias was considered to be important for this review and was related to whether all exercises during the intervention were performed using a single set structure. For instance, if the experimental group performed only one or two exercises using CS, but performed the remaining exercises using TS, this may have introduced bias. Outcome assessment bias was also considered important and was related to the reliability and appropriateness of the equipment or assessor that were used to assess the outcomes of interest. For instance, if previous research showed the reliability of a given device used to record kinetic or kinematic variables to be poor, this may have induced bias (e.g., using a linear position transducer whose reliability was not previously established to assess changes in movement velocity at submaximal loads). Familiarisation bias was related to whether the participants were adequately familiarised with the protocols in a given study. If the authors did not clearly state that a familiarisation session took place or that their participants were regularly performing exercises and performance tasks used in a given study, bias may have risen from the participants being unaccustomed to the study protocols.

Risk of bias was assessed based on the information reported in the published paper and not on information provided by authors (i.e., Table 9-1 and Table 9-2 of this review). Assessments were completed independently by two reviewers (IJ and AGR) while any observed differences were resolved via discussion and agreement before merging the scores into a single spreadsheet. Risk of bias was considered in the interpretation of the results by applying the Grading of Recommendations Assessment, Development and Evaluation (GRADE) system, similarly to previous reviews investigating physiological and biomechanical outcomes between different exercise modalities [231]. Specifically, the overall quality of the evidence synthesis was rated as high and downgraded one level to moderate, low, or very low for each of the following limitations: imprecision, inconsistency, and risk of bias. For imprecision, the level of evidence was downgraded one level if the conclusion about the effect magnitude would be altered based on the lower or upper boundary of the confidence interval. For example, if the mean effect was small, but the 95% confidence interval crossed the threshold for a trivial effect (i.e., $g < 0.2$), the precision was insufficient to support a strong recommendation as the confidence interval does not exclude the possibility for the effect to be trivial. Similarly, if the confidence interval crossed the threshold for a large effect, while the mean effect was moderate, the conclusion was considered imprecise and as such, the level of evidence was also downgraded one level. Finally, if high statistical heterogeneity was observed, and if more than 50% of studies had > 1 risk of bias item assessed to be high risk, the level of evidence was also downgraded one level for inconsistency and risk of bias, respectively.

9.2.6 Statistical analysis

When two or more studies reported on the same outcome, a separate random-effects meta-analysis for each outcome was performed using the Meta and Metafor statistical packages [232, 73] in R language and environment for statistical computing (version 3.6.3, The R foundation for Statistical Computing, Vienna, Austria) [233]. Model parameters were calculated by the restricted maximum likelihood method, and the observations were weighted by the inverse of the sampling variance [234]. Sub-group analyses were used to explore the effects of CS and RR set structures on every outcome.

Meta-regressions were performed when at least six effects were available for a given outcome [235]. These included the effects of TS performed to muscular failure as a categorical covariate, and study duration, loads, and the number of repetitions performed in the TS group as continuous covariates.

The heterogeneity of the studies was assessed using the I^2 statistic. The I^2 statistic represents the percentage of total variation in estimated effects across studies due to heterogeneity rather than chance and was interpreted as small ($I^2 < 25\%$), moderate ($I^2 = 25–49\%$) and high ($I^2 > 50\%$) [79]. Publication bias was not assessed because there was only a small number of studies included in most analyses and all studies were of a similar sample size, as recommended in *Cochrane Handbook for Systematic Reviews of Interventions* [236]. In addition, there was no reason to expect that studies finding no significant difference between different set structures would be less likely to be published than studies reporting a statistically significant difference.

Determination of the effect size

The standardised mean change for each group was calculated as the difference between post-test and pre-test scores, divided by the pre-test standard deviation with an adjustment for small sample bias [59, 61, 60]. Thereafter, the standardised mean difference (SMD) with 95% confidence intervals for the difference were calculated between the two standardised mean changes values for each study to indicate how much larger (or smaller) the change in the experimental group was (in standard deviation units) when compared to the change in the control group [59, 61]:

$$SMD = C_{Exp}\left(\frac{M_{post,Exp} - M_{pre,Exp}}{SD_{pre,Exp}}\right) - C_{Con}\left(\frac{M_{post,Con} - M_{pre,Con}}{SD_{pre,Con}}\right)$$

Where the *C* (i.e. the correction for small sample bias) is given by:

$$C_j = 1 - \frac{3}{4(n_j - 1) - 1}$$

The SMD magnitude was interpreted as: small (0.20 – 0.49), moderate (0.50 – 0.79) and large (> 0.80) [62].

Determination of the variance

No studies reported the pre- to post-intervention correlations required to determine the variance. Therefore, when the authors did not provide correlations upon our request, standard deviations of the pre- to post-intervention change were used to calculate pre-to-post correlations using the following formula [286]:

$$r_j = \frac{SD_{j,baseline}^2 + SD_{j,final}^2 - SD_{j,change}^2}{2 * SD_{j,baseline} * SD_{j,final}}$$

The corresponding authors were contacted when the standard deviations of the pre- to post-intervention change were not reported. If it was not possible to obtain standard deviation of the pre- to post-intervention change, the median correlation from all other studies for a given outcome was imputed. This ensured that the maximum number of studies were included. Since the experimental and control groups are independent, the corresponding sampling variances were calculated by summing the sampling variances of the two groups [59].

Combining effects and further decisions

When multiple study effects were reported that were not of a direct interest to this review (e.g., separate effects for two or more TS, CS, or RR set structures), a combined effect was computed across the outcome for each group separately (i.e., control and experimental), as outlined by Boronestein et al. [58] for dependent continuous outcomes. This avoided double counting individuals from those studies in the meta-analysis.

While extracting the data from the studies, we noticed that several studies [277, 287, 288, 285] reported the effects of alternative set structures on muscular endurance as assessed by the work completed during repetitions to muscular failure. Therefore, although not originally planned we also meta-analysed the effects of alternative set structures on muscular endurance. Furthermore, while we planned to analyse the effects of alternative set structures on the overall expression of muscular power, which included changes in jump height, sprint and change of direction times as well as velocity and power outputs at submaximal loads, this was not done due to a lack of studies reporting on all these outcomes. Rather, we separately meta-analysed vertical jump performance and velocity and power outputs at submaximal loads due to a large number of studies that reported these outcomes. For vertical jump performance, only unloaded jump assessments were considered while only loaded exercises (both ballistic and strength-oriented) were considered for velocity and power outputs at submaximal loads. If studies reported multiple measures of muscular strength (i.e., using 1RM, MVC, or isokinetic testing), tests with a RM component were used for analysis as these are generally considered more ecologically valid. Similarly, when studies reported changes in both velocity and power outputs at submaximal loads after the intervention, only velocity was used for the analysis. This was done because velocity is: (a) more stable and reliable than power regarding changes in performance [289, 186]; and (b) has a high relationship with fatigue and mechanical impulse, which are highly related to various athletic tasks' performance [13, 15, 290]. In addition, we used mean velocity and power variables for the non-ballistic exercises whereas peak variables were used for the ballistic exercises, where possible. This was done since peak velocity and power variables are pertinent measures for explosive-type resistance training while mean variables are believed to better represent (and are almost exclusively used) velocity though the entire phase of non-ballistic movements [291, 292]. In three studies [285, 293, 284], the unilateral knee extension exercise was employed, and participants' legs were randomly assigned to TS and RR groups. We considered these groups to be independent since previous studies have shown no correlation between legs (left and right) for strength gains after different RT protocols, suggesting that when both limbs are trained, the cross-education effect is minimal [294]. In four studies [295, 275, 213, 281], resistance training volume or intensity were periodised across microcycles (i.e., weeks) and mesocycles (i.e., 4-week blocks). In this case, the average number of repetitions performed, and the average intensity of load was calculated in order to simplify the analyses. When studies did not specify whether the repetitions in the control group (i.e., TS) were performed to muscular failure, the study protocol was classified as "to failure" when some of the participants either failed to complete the protocol or when the combination of the number of repetitions and the load clearly suggested that to be the case (e.g., doing more than 5 repetitions with 85% 1RM).

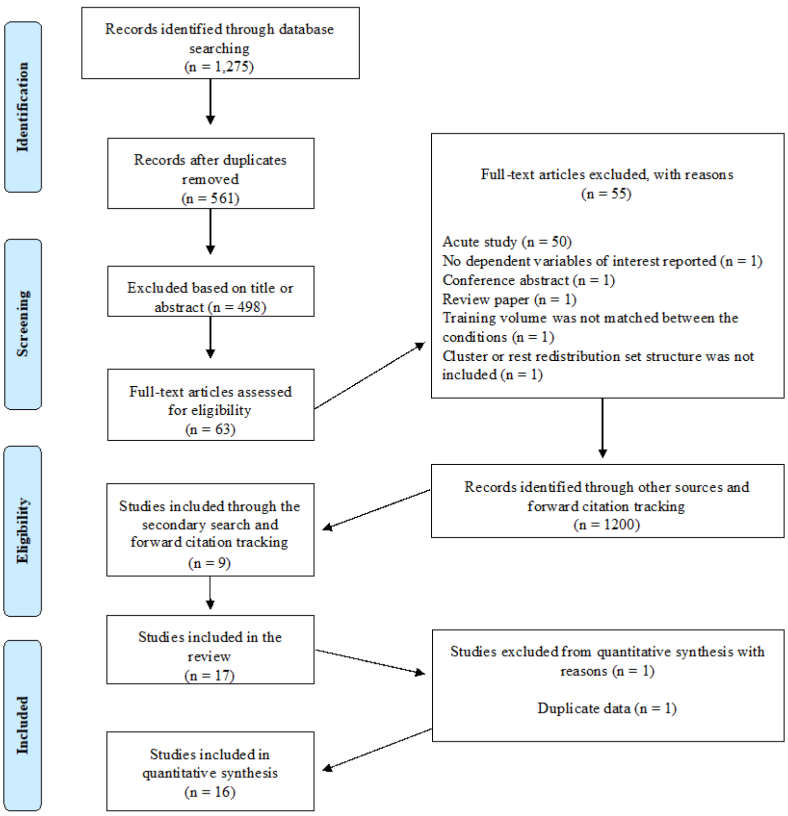
Finally, to support readability, all effects were expressed relative to TS, such that positive values represent outcomes in favour of CS or RR.

9.3 Results

9.3.1 Search results

The primary search yielded 1275 results, of which 8 studies met the inclusion criteria. Forward citation tracking of the included studies as well as monitoring newly published, relevant literature yielded an additional 9 studies that met the inclusion criteria, resulting in 17 studies included in this review. The stages of the search and study selection process is presented in Figure 9-1.

Figure 9-1 Literature search flow chart



Note. n, number of studies.

9.3.2 Study characteristics

The total number of participants pooled across studies was 418 (249 males and 129 females with 40 not specified). However, after thorough inspection of the studies, it was observed that the data from the same participants was used in multiple studies [275, 276, 293, 285]. Therefore, the total number of participants was reduced to 366 (209 males, 117 females, and 40 unspecified). Of the seventeen included studies, two studies included only females [287, 284], five studies [293, 285, 246, 288, 296] included males and females, two studies did not specify sex [295, 283], and the remaining studies included only males. Participants in eight studies had at least 6 months of resistance training experience, in three studies participants had no previous resistance training experience, while prior resistance training experience was not reported in six studies. Mean study duration was approximately 7 weeks (range 4 – 12 weeks). Only four studies specified adherence with the intervention [213, 211, 287, 256] which was generally very high. Ten studies compared RR to TS, and seven studies compared CS to TS. Exercises during training interventions were performed using exclusively weight machines in seven studies, smith machines or free-weights in three studies, while the combination of these training modalities was used in four studies. A more comprehensive description of the participants and the included studies can be found in Table 9-1 and Table 9-2.

Table 9-1 Characteristics of individual study samples.

Study	Participants	Sex: M/F	Age (years)	Height (cm)	Mass (kg)	Training experience (subjective description; years of experience)
Asadi et al. (2016) [283]	TS group: n = 7	Unclear	20 ± 1	180 ± 5	78 ± 4	Physically active sport science students; unclear
	RR group: n = 6	Unclear	21 ± 1	180 ± 3	79 ± 3	Physically active sport science students; unclear
Carneiro et al. (2019) [284]	TS group: n = 8	0/8	63 ± 7[a]	160 ± 1[a]	70 ± 17[a]	Healthy postmenopausal women; unclear
	CS group: n = 8	0/8				Healthy postmenopausal women; unclear
Davies et al. (2019) [246]	TS group: n = 10	5/5	25 ± 7	Unclear	76 ± 10	Resistance trained individuals; 5 ± 8
	CS group: n = 11	7/4	26 ± 7	Unclear	74 ± 10	Resistance trained individuals; 4 ± 4
Dias et al. (2020) [287]	TS group: n = 35	0/35	61 ± 5[a]	156 ± 5[a]	65 ± 13[a]	Physically active elderly women; unclear
	CS group: n = 31	0/31				Physically active elderly women; unclear
Farinas et al. (2019) [288]	TS group: n = 12	8/4	24 ± 5	173 ± 8	71 ± 11	Physically active sport science students; unclear
	RR group: n = 11	8/3	24 ± 2	175 ± 9	75 ± 11	Physically active sport science students; unclear
Rooney et al. (1994) [295]	TS group: n = 13	Unclear	18 – 35[b]	Unclear	Unclear	Healthy young men; unclear
	CS group: n = 14	Unclear	18 – 35[b]	Unclear	Unclear	Healthy young men; unclear
Goto et al. (2005) [277]	TS group: n = 9	9/0	23 ± 1	172 ± 2	65 ± 3	Healthy young men; unclear
	CS group: n = 9	9/0	22 ± 2	170 ± 2	66 ± 2	Healthy young men; unclear
Hansen et al. (2011) [281]	TS group: n = 9	9/0	25 ± 6	189 ± 10	107 ± 7	Elite rugby union athletes; unclear
	RR group: n = 9	9/0	28 ± 5	189 ± 10	100 ± 11	Elite rugby union athletes; unclear
Iglesias-Soler et al. (2016) [285]	TS group: n = 13	7/6	23 ± 5	173 ± 7	67 ± 9	Physically active sport science students; >6 months
	RR group: n = 13	7/6	23 ± 5	173 ± 7	67 ± 9	Physically active sport science students; >6 months
Iglesias-Soler et al. (2017) [293]	TS group: n = 13	7/6	23 ± 5	173 ± 7	67 ± 9	Physically active sport science students; >6 months
	RR group: n = 13	7/6	23 ± 5	173 ± 7	67 ± 9	Physically active sport science students; >6 months

Lawton et al. (2004) [276]	TS group: n = 13	13/0	Unclear	Unclear	Unclear	Junior elite athletes; >6 months
	RR group: n = 13	13/0	Unclear	Unclear	Unclear	Junior elite athletes; >6 months
Morales-Artacho et al. (2018) [211]	TS group: n = 9	9/0	24 ± 6[a]	178 ± 6	77 ± 10	Physically active sport science students; no experience
	CS group: n = 9	9/0	24 ± 6[a]	178 ± 6	77 ± 10	Physically active sport science students; no experience
Nicholson et al. (2016) [212]	TS group: n = 11	11/0	Unclear	Unclear	Unclear	Resistance-trained men; >12 months
	CS group: n = 12	12/0	Unclear	Unclear	Unclear	Resistance-trained men; >12 months
Oliver et al. (2013) [213]	TS group: n = 11	11/0	25 ± 5	180 ± 6	82 ± 12	Resistance-trained men; >2 years
	RR group: n = 11	11/0	25 ± 4	180 ± 4	83 ± 10	Resistance-trained men; >2 years
Rial-Vázquez et al. (2020) [296]	TS group: n = 13	10/3	23 ± 4[a]	177 ± 8	73 ± 11	Physically active sport science students; >3 months
	RR group: n = 11	7/4	23 ± 4[a]	177 ± 8	73 ± 11	Physically active sport science students; >3 months
Cuevas-Aburto et al. (2020) [256]	TS group: n = 12	12/0	21 ± 3	175 ± 5	73 ± 9	Physically active sport science students; unclear
	RR group: n = 13	12/0	20 ± 3	172 ± 5	75 ± 11	Physically active sport science students; unclear
Drinkwater et al. (2005) [275]	TS group: n = 11	15/0	18 ± 0[a]	191 ± 9[a]	86 ± 10[a]	Junior elite athletes; >6 months
	RR group: n = 15	11/0	18 ± 0[a]	191 ± 9[a]	86 ± 10[a]	Junior elite athletes; >6 months

Note. CS cluster set structure, *F* female, *M* male, *N*, number of participants, *RR* rest redistribution set structure, *TS* traditional set structure.

Values are expressed as means ± standard deviations

[a]Combined for both groups

[b]Only range was reported

Table 9-2 Summary of the studies included in the review.

Study	Training protocol (duration; sessions/w; exercise; intensity)	Structure Description Sets x repetitions; inter-set rest; intra-set rest	Control group trained to failure	Adherence	Outcomes; (methods of assessment)
Asadi et al. (2016) [283]	6 weeks; 2 sessions/w; 100 max intensity depth jumps from 45 cm height box per session	TS: 2 x 10; 120 sec; none RR: 2 x 10; 90 sec; 30 sec	No	Unclear	Countermovement jump height (Vertec); Standing long jump height (measurement tape); t-test; 20 m sprint time; 40 m sprint time (all photocell gates)
Carneiro et al. (2019) [284]	8 weeks; 2 sessions/w (no consecutive days); unilateral leg extension (one leg performed TS, while the other leg performed CS); 90% 1RM.	TS: 3 x 4; 90 sec; none CS: 3 x 4; 90 sec; 30 sec	Yes	Unclear	Maximal strength (1RM unilateral leg extension); Thigh CSA (anthropometric equation (thigh circumference − π × skinfold)2/4π); Force-velocity profiles, peak force, velocity and power (linear encoder)
Davies et al. (2019) [246]	8 weeks; 2 upper-body sessions and 1 lower-body session/w for first 4 weeks, 2 upper- body and 2 lower-body sessions/w for last 4 weeks. Set structures were manipulated only for bench press exercise with relative loads ranging from 70-75% of 1RM.	TS: 4 x 5; 300 sec; none CS: 4 x 5; 180 sec; 30 sec	No	Unclear	Maximal strength (1RM bench press); Mean and peak bench press velocity and power (linear position transducer)
Dias et al. (2020) [287]	12 weeks; 2 sessions/w; Bench press, leg press, seated row,	TS: 3 x 8; 120 sec; none RR: 12 x 2; 30 sec; none	No	At least 80%	Maximal strength (10RM Leg press and bench press);

	deadlift, medicine ball throw, plank; 75% of 10RM for strength exercises, whereas medicine ball throw and the plank were performed for maximum distance and maximal hold, respectively				Medicine ball throw distance (measurement tape); Countermovement, squat jump and standing long jump height (contact mat); Muscular endurance (number of repetitions s in 30 sec with 2 kg load)
Farinas et al. (2019) [288]	5 weeks; 2 sessions/w; biceps curl; 10RM load.	TS: 5 x 6; 120 sec and 15 sec; none RR: 30 x 1; 18.5 sec; none	No	Unclear	Maximal strength (1RM biceps curl); Muscular endurance (number of repetitions with 10RM load); Muscle thickness (Ultrasound)
Rooney et al. (1994) [295]	6 weeks; 3 sessions/w biceps curl; 6RM load.	TS: 1 x 6-10; none; none CS: 1 x 6-10; none; 30 sec	Yes	Unclear	Dynamic and isometric maximal strength (1RM biceps curl and strain-gauge force transducer, respectively)
Goto et al. (2005) [277]	12 weeks; 2 sessions/w, lat pulldown, shoulder press, bilateral knee extension; 75% 1RM	TS: 3-5 x 10; 60 sec; none CS: 3-5 x 10; 60 sec; 30 sec	Yes	Unclear	Dynamic, isometric and isokinetic maximal strength (1RM shoulder press and knee extension, with only knee extension being measured isokinetically); Muscle endurance (max number of reps with 70% 1RM shoulder press and knee extension); Muscle CSA

					(magnetic resonance imaging)
Hansen et al. (2011) [281]	8 weeks; 2 sessions/w; front squat, back squat, clean pull, box squat, power clean, jump squat, with set structures being manipulated only for the 2-compound strength and power movements; 80 to 95% 1RM for the squat and clean pull movements during the entire program. In weeks 7 and 8, jump squats at 0-20% 1RM were also performed together with power cleans which replaced the clean pull exercise	TS: 3-5 x 4-8; 180 sec; none RR: 3-12 x 1-6; 120-180 sec; 10-30 sec[a]	Yes	Unclear	Maximal strength (1RM back squat prediction trough the repetitions to failure test with 2-6RM load); Peak velocity, peak power and peak force production during the back squat (portable force plate)
Iglesias-Soler et al. (2016) [285]	5 weeks; 2 sessions/w; unilateral leg extensions (TS with one leg and CS with the other leg); 10RM.	TS: 4 x 8; 180 sec; none RR: 31 x 1; 17.4 sec; none	No	Unclear	Dynamic max strength (1RM leg extension); isometric max strength (leg extension with force cell); Muscular endurance (time to task failure with 50% of MVC); Thigh girth (corrected girth = thigh girth – (π × thigh skinfold)); Rate of force development (during MVC with force cell); Mean propulsive power (linear velocity transducer)

Iglesias Soler et al. (2017) [293]	5 weeks; 2 sessions/w; unilateral leg extensions (TS with one leg and CS with the other leg); 10RM.	TS: 4 x 8; 180 sec; none RR: 31 x 1; 17.4 sec; none	No	Unclear	Force-velocity profiles (linear velocity transducer)
Lawton et al. (2004) [276]	6 weeks; 3 sessions/w (alternate days); 3 1RM intensity was increased by 5% over the last 3 weeks of the training intervention.	TS: 4 x 6; 240 sec and 20 sec; none RR: 8 x 3; 60 sec and 53 sec; none	Yes	Unclear	Maximal strength (6RM bench press); Mean power during bench press throws (linear encoder)
Morales-Artacho et al. (2018) [211]	11 weeks; 2 sessions/w (nonconsecutive days); loaded countermovement squat jumps on a smith machine at 20% of 1RM and abdominal plank.	TS: 6 x 6; 300 sec; none CS: 6 x 6; 240 sec and 30 sec; 30 sec	No	100%	Force-velocity profiles in the counter movement jump, peak force, velocity and power (linear encoder)
Nicholson et al. (2016) [212]	6 weeks; 2 sessions/w; back squat; 85% 1RM	TS: 4 x 6; 300 sec; none CS: 4 x 6; 300 sec; 25 sec	Yes	Unclear	Dynamic (1RM back squat), isometric (1RM back squat test on force plate) and isokinetic strength (dynamometer); Counter movement jump height (force plate)
Oliver et al. (2013) [213]	12 weeks; 2 sessions/w; bench press, back squat; 60 to 75% 1RM.	TS: 4 x 10; 120 sec; none RR: 8 x 5; 60 sec; none	No	95%	Dynamic muscular strength (1RM back squat and bench press); Mean power during back squat and bench press (linear position transducer) as well as during counter movement jumping (determined based on jump height measured using

					Vertec); Lean body mass (DEXA)
Rial-Vázquez et al. (2020) [296]	5 weeks; 2 sessions/w; bench press, back squat, lat pulldown, leg curl; 10RM	TS: 4 x 8; 300 sec; none RR: 16 x 2; 60 sec; none	No	Unclear	Dynamic muscular strength (1RM back squat); Force-velocity profile in the back squat (linear velocity transducer); Maximal propulsive power in the back squat and bench press (linear velocity transducer)
Cuevas-Aburto et al. (2020) [256]	6 weeks; 2 sessions/w; bench press; 75% of 1RM.	TS: 6 x 5; 180 sec; none RR: 30 x 1; 31 sec; none	No	100%	Dynamic muscular strength (1RM bench press); Peak velocity during bench press throws (linear velocity transducer); handball throwing velocity (radar gun)
Drinkwater et al. (2005) [275]	6 weeks; 3 sessions/w (alternate days); 3 1RM intensity was increased by 5% over the last 3 weeks of the training intervention.	TS: 4 x 6; 240 sec and 20 sec; none RR: 8 x 3; 60 sec and 53 sec; none	Yes	Unclear	Dynamic muscular strength (6RM bench press); Mean power during bench press throws (linear encoder)

Note. CS, cluster set structure, *CSA* cross-sectional area, *DEXA* dual-energy x-ray absorptiometry, MVC maximum voluntary contraction, *RM* Repetition maximum, *RR* rest redistribution set structure, *TS* traditional set structure,

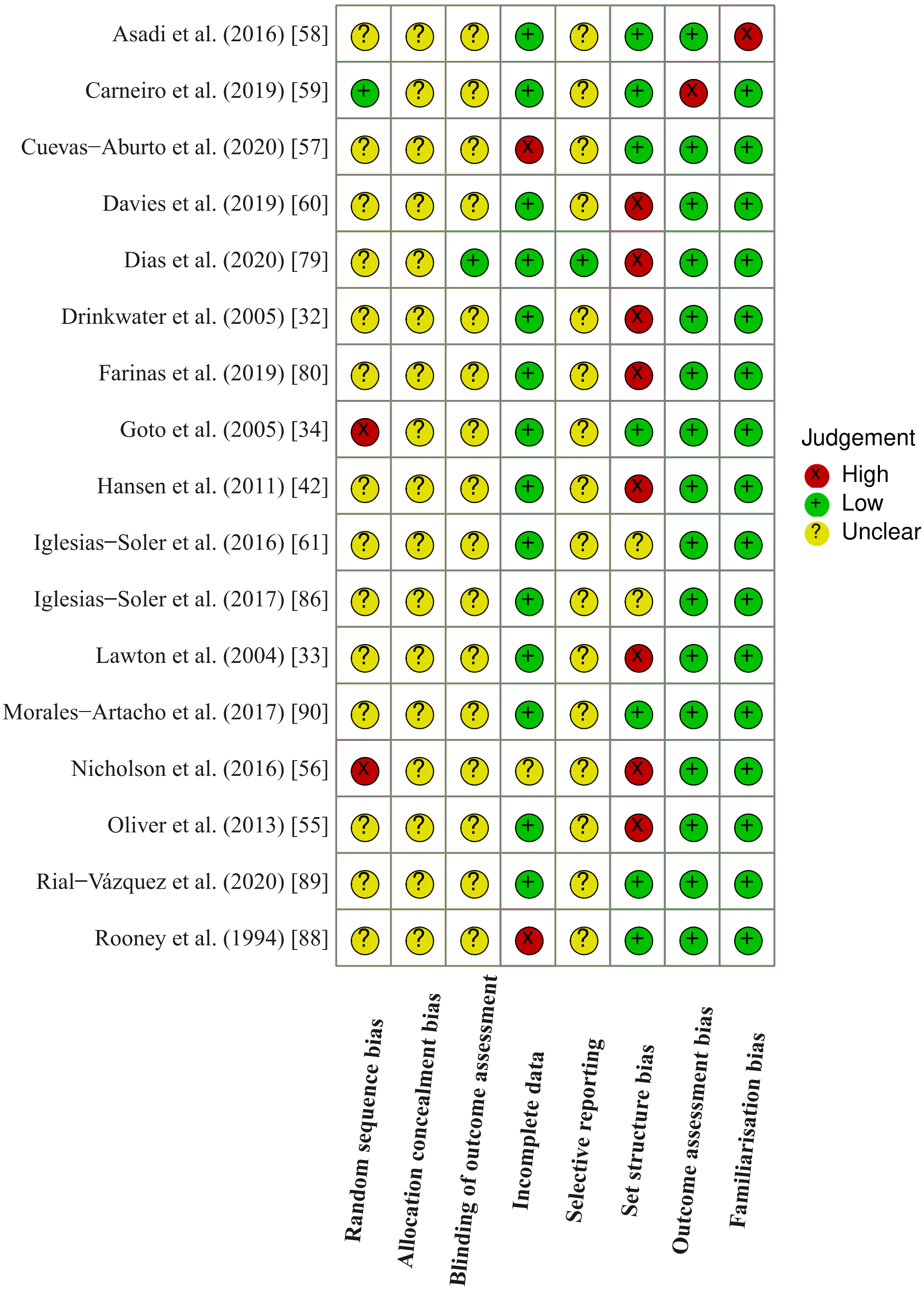
Values are expressed as means ± standard deviations

[a] Only range was reported.

9.3.3 Risk of bias assessment

According to the risk of bias assessment, two studies [277, 212] were at high risk of an order effect bias since they did not report any randomisation. Only one study [284] was classified as low risk, providing sufficient information regarding the method of randomisation. The remaining studies were classified as an unclear risk since they did not provide sufficient information regarding the method of randomisation. No studies provided information regarding outcome blinding procedures. One study [287] attempted to blind the investigators to group allocation and therefore was considered to be at a low risk of allocation concealment bias, whereas all other studies were rated as an unclear risk of bias due to lack of information regarding the allocation concealment. Two studies [255, 295] were rated at a high risk of attrition bias, excluding randomised participants from the analysis without specifying the minimum amount of training sessions required for the participants to be included in the analysis or reporting study dropouts without sufficient reason. One study [212] did not provide sufficient information on the number of participants assessed and included in the analysis after reporting that some of them did not complete the entire intervention and hence, was classified as an unclear risk of attrition bias. No studies, except for one [287], pre-registered their protocols on a publicly available registry platform, so it was unclear whether selective reporting bias was present. One study included in this review pre-registered their protocol [287] and reported the majority (but not all) of the outcomes; however, the outcomes of interest to the present review were reported. Therefore, the study was classified as low risk of selective reporting bias. Eight studies [287, 246, 275, 276, 288, 281, 212, 213] were considered high risk for set structure bias since the participants performed other RT sessions (in which set structures were not manipulated), or because they did not perform all exercises using a single set structure, but rather a combination of set structures (e.g., CS for the back squat, TS for the accessory exercises). Information on set structure was unclear in two studies [293, 285]. Only one study [284] used a linear encoder that was not, to our knowledge, validated in peer-reviewed literature whereas all other studies used established methods, equipment, or instruments to evaluate their outcomes of interest. While four studies [275, 256, 276, 281] did not include a familiarisation session, two of them [283, 295] were classified at high risk of bias for not having a familiarisation session which might have affected the habituation to the study protocols. The rest of the studies performed a test-retest reliability of their assessment procedures, performed an acute study (i.e., one or two sessions) examining the short term effects of their protocol (with all participants) or specifically stated that all participants were accustomed to the study protocols (i.e., performed them in the past). A more detailed risk of bias assessment is illustrated in Figure 9-2.

Figure 9-2 Risk of bias assessment for all included studies.

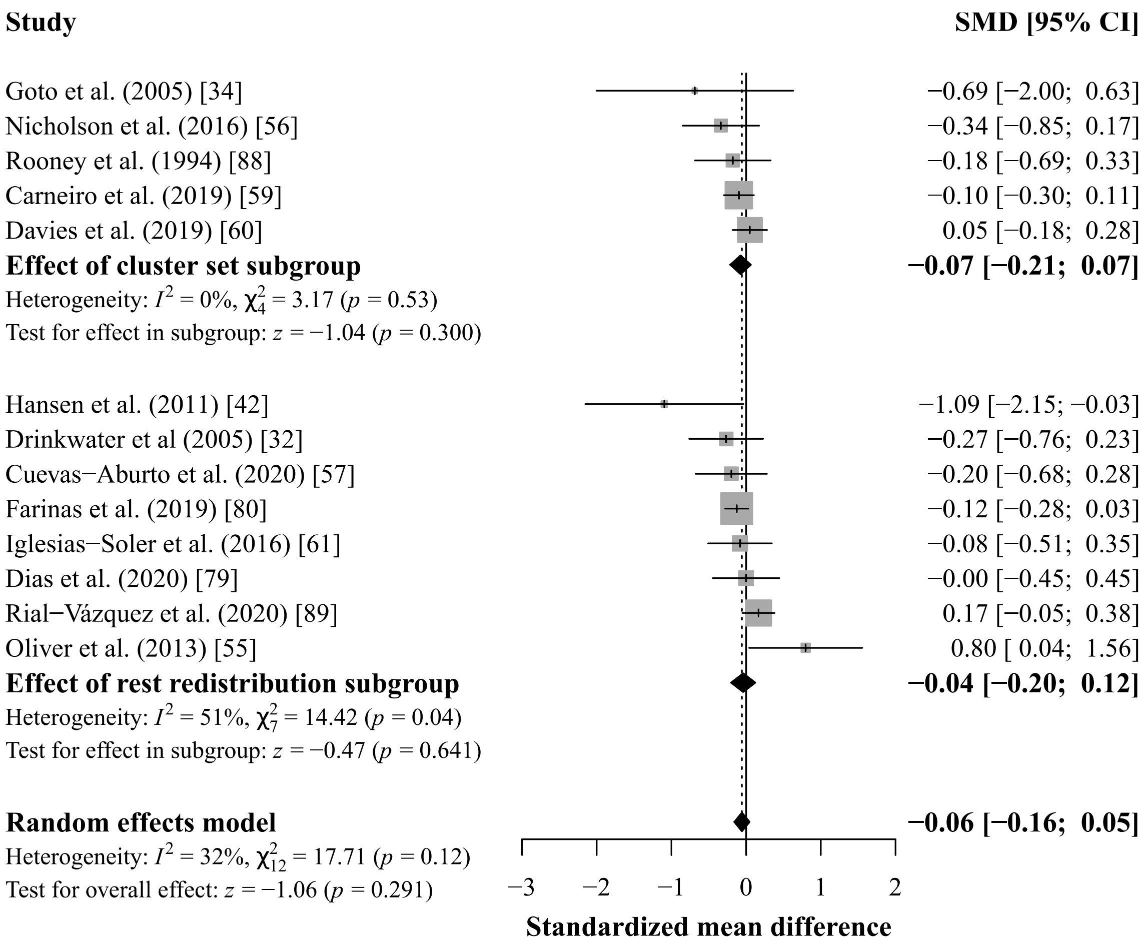


9.3.4 Muscular strength

Sub-group analysis revealed that neither CS (SMD = -0.07 [95% CI: -0.21, 0.07]; p = 0.300; I^2 = 0%; k = 5) nor RR (SMD = -0.04 [95% CI: -0.20, 0.12]; p = 0.641; I^2 = 51%; k = 8) set structures were more effective than TS structures in promoting muscular strength adaptations. Likewise, when the effects from alternative set structures were pooled, there were no significant differences (SMD = -0.06 [95% CI: -0.16, 0.05]; p = 0.291; I^2 = 32%; k = 13) in muscular strength gains compared to TS structures (Figure 9-3). Sub-group results for CS and RR provided moderate whereas pooled results provided high GRADE quality of evidence (Table 9-3).

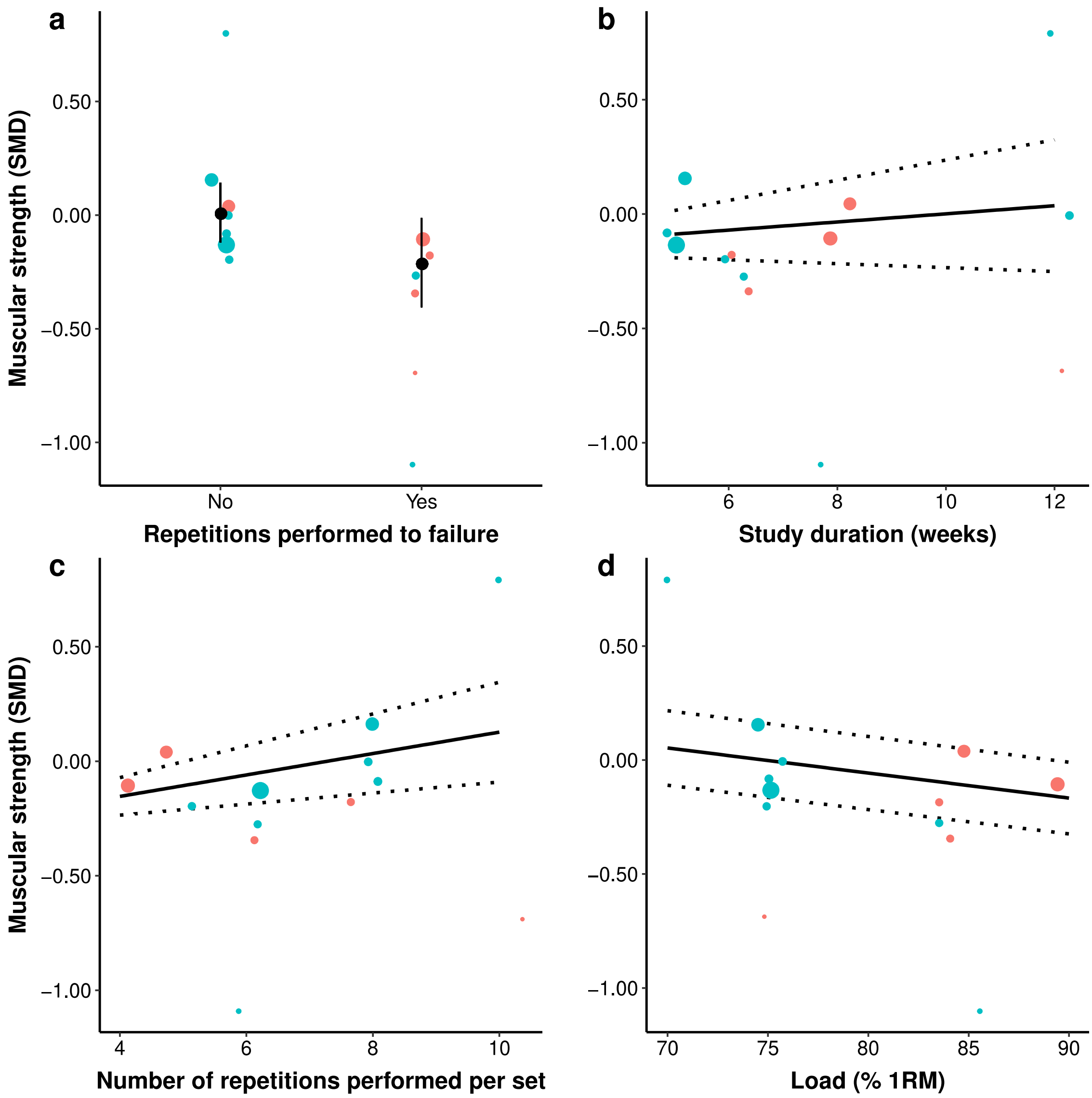
Performing repetitions to muscular failure (b = -0.22 [95% CI: -0.46, 0.16]; p = 0.067), the number of repetitions performed during TS (b = 0.05 [95% CI: -0.02, 0.11]; p = 0.146), the load used (b = -0.01 [95% CI: -0.03, 0.01]; p = 0.249) and study duration (b = 0.02 [95% CI: -0.04, 0.08]; p = 0.526) were not significant moderators of the SMD for muscular strength adaptations (Figure 9-4). Likewise, when analysing RR set structures separately, performing repetitions to muscular failure (b = -0.45 [95% CI: -0.97, 0.07]; p = 0.094) and the study duration (b = 0.03 [95% CI: -0.04, 0.10]; p = 0.397) were not significant moderators of the SMD for muscular strength gains. However, the number of repetitions performed during TS (b = 0.14 [95% CI: 0.05, 0.24]; p = 0.035) and the load used (b = -0.05 [95% CI: -0.10, -0.01]; p = 0.028) were significant moderators of the SMD in muscular strength gains, with higher number of repetitions during TS and lower loads used leading to greater effectiveness of RR on muscular strength gains.

Figure 9-3 Random-effects meta-analysis of the differences in muscular strength gains after resistance training using alternative set structures (i.e., CS and RR) compared to TS. Subgroup analysis based on the effects of CS and RR separately.



Note. CI, confidence interval; CS, cluster set structure; RR, rest redistribution set structure; SMD, standardised mean difference; TS, traditional set structure.

Figure 9-4 Random-effects meta-regression of the differences in muscular strength gains after resistance training using alternative set structures (i.e., CS and RR) compared to TS while controlling for the effects of muscular failure during TS (a), study duration in weeks (b), number of repetitions performed during TS (c) and the load used (d).



Note. Larger data points received greater weighting than smaller data points. Red and blue circles represent studies that compared TS with CS and RR, respectively. Solid (non-vertical) lines represent the estimated relationship, solid vertical lines and dotted lines represent the upper and lower 95% confidence intervals. CS, cluster set structure; RM, repetition maximum; RR, rest redistribution set structure; TS, traditional set structure.

9.3.5 Hypertrophy

Sub-group analysis indicated that neither CS (SMD = -0.93 [95% CI: -3.24, 1.38]; I^2 = 87%; p = 0.429; k = 2) nor RR (SMD = -0.06 [95% CI: -0.26, 0.14]; p = 0.543; I^2 = 0%; k = 3) set structures were less effective in promoting muscle hypertrophy. Pooling the effects from alternative set structures resulted in no significant differences (SMD = -0.03 [95% CI: -0.20, 0.13]; $p = 0.708$; $I^2 = 52\%$; k = 5) in muscle hypertrophy when compared to TS structures. Sub-group results for CS provided low, whereas sub-group results for RR and pooled results provided moderate and low GRADE quality of evidence, respectively (Table 9-3).

9.3.6 Muscular endurance

Sub-group analysis indicated that RR (SMD = -0.37 [95% CI: -0.72, -0.02]; $p = 0.038$; $I^2 = 0\%$; k = 3) but not CS set structures (SMD = -0.42 [95% CI: -1.07, 0.23]; $p = 0.203$; $I^2 = 0\%$; k = 1) were less effective at improving muscular endurance than TS structures. When the effects from alternative set structures were pooled, they were less effective (SMD = -0.38 [95% CI: -0.69, -0.07]; $p = 0.015$; $I^2 = 0\%$; k = 4) at improving muscular endurance compared to TS structures. Pooled results and sub-group results for RR provided moderate GRADE quality of evidence (Table 9-3).

9.3.7 Vertical jump performance

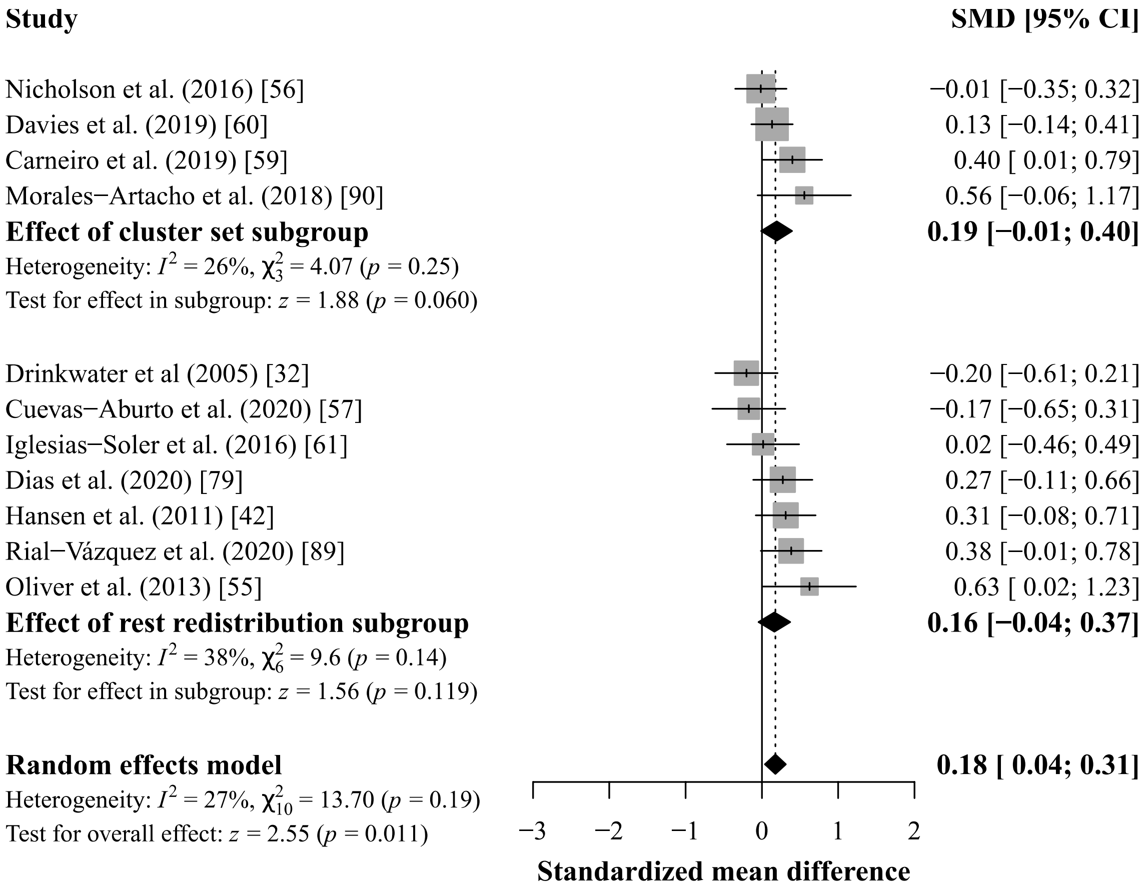
Sub-group analysis revealed that neither CS (SMD = 0.11 [95% CI: -0.37, 0.59]; $p = 0.659$; $I^2 = 0\%$; k = 1) nor RR (SMD = 0.16 [95% CI: -0.09, 0.40]; $p = 0.208$; $I^2 = 0\%$; k = 4) were more effective at improving vertical jump performance compared to TS structures. Likewise, when the effects from alternative set structures were pooled, both alternative and TS structures were equally effective (SMD = 0.13 [95% CI: -0.07, 0.33]; $p = 0.190$; $I^2 = 0\%$; k = 5) at improving vertical jump performance. Pooled results and sub-group results for RR provided moderate GRADE quality of evidence (Table 9-3).

9.3.8 Velocity and power outputs at submaximal loads

Sub-group analysis revealed that neither CS (SMD = 0.19 [95% CI: -0.01, 0.40]; $p = 0.060$; $I^2 = 26\%$; k = 4) nor RR (SMD = 0.16 [95% CI: -0.04, 0.37]; $p = 0.119$; $I^2 = 38\%$; k = 7) were more effective at inducing greater velocity and power outputs at submaximal loads compared to TS structures. However, when the effects from alternative set structures were pooled, significantly greater velocity and power outputs at submaximal loads (SMD = 0.18 [95% CI: 0.04, 0.31]; $p = 0.011$; $I^2 = 27\%$; k = 11) were observed after interventions utilising alternative set structures compared to TS structures (Figure 9-5). Pooled results and sub-group results for CS and RR provided moderate GRADE quality of evidence (Table 9-3).

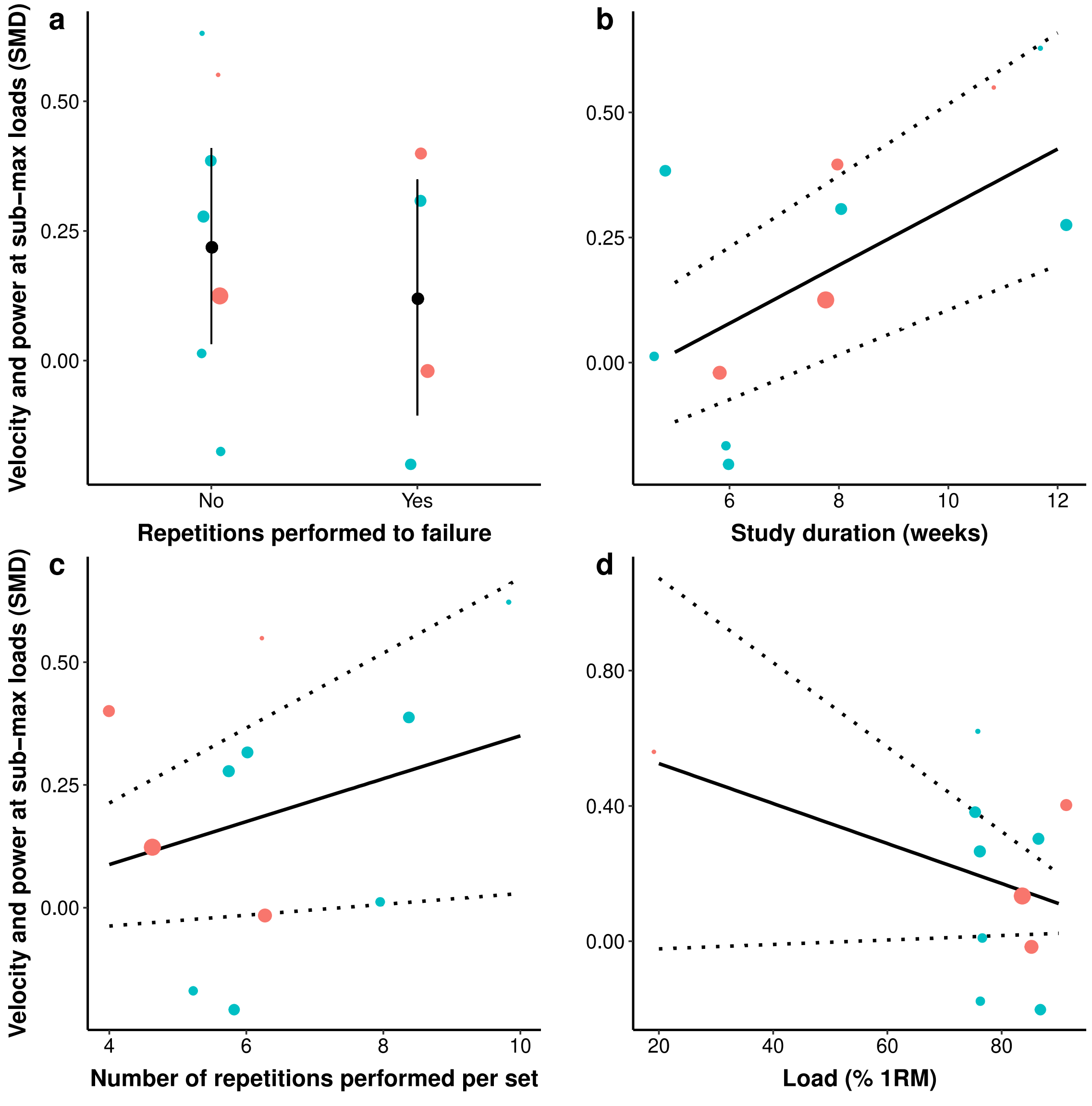
Performing repetitions to muscular failure (b = -0.10 [95% CI: -0.39, 0.20]; p = 0.510), the number of repetitions performed during TS (b = 0.04 [95% CI: -0.06, 0.14]; p = 0.392) as well as the load used (b = -0.01 [95% CI: -0.02, 0.00]; p = 0.236), were not significant moderators of the SMD for enhancing velocity and power outputs at submaximal loads (Figure 9-6). However, study duration was a significant moderator of the SMD (b = 0.06 [95% CI: 0.01, 0.11); p = 0.037) with longer duration studies showing greater effectiveness for alternative set structures in enhancing velocity and power outputs at submaximal loads over TS structures (Figure 9-6). When analysing RR set structures separately, performing repetitions to muscular failure (b = -0.15 [95% CI: -0.63, 0.32]; p = 0.525), the number of repetitions performed during TS (b = 0.12 [95% CI: -0.02, 0.25]; p = 0.087) as well as the load used (b = -0.02 [95% CI: -0.06, 0.03]; p = 0.525) and the study duration (b = 0.05 [95% CI: -0.02, 0.12]; p = 0.175), were not significant moderators of the SMD in enhancing velocity and power outputs at submaximal loads.

Figure 9-5 Random-effects meta-analysis of the differences in velocity and power at submaximal loads after resistance training using alternative set structures (i.e., CS and RR) compared to TS. Subgroup analysis based on the effects of CS and RR separately.



Note. CI, confidence interval; CS, cluster set structure; RR, rest redistribution set structure; SMD, standardised mean difference; TS, traditional set structure.

Figure 9-6 Random-effects meta-regression of the differences in velocity and power at submaximal loads after resistance training using alternative set structures (i.e., CS and RR) compared to TS while controlling for the effects of muscular failure during TS (a), study duration in weeks (b), number of repetitions performed during TS (c) and the load used (d).



Note. Larger data points received greater weighting than smaller data points. Red and blue circles represent studies that compared TS with CS and RR, respectively. Solid (non-vertical) lines represent the estimated relationship, solid vertical lines and dotted lines represent the upper and lower 95% confidence intervals. CS, cluster set structure; RM, repetition maximum; RR, rest redistribution set structure; TS, traditional set structure.

9.3.9 Slope of force-velocity profiles

Sub-group analysis revealed that CS (SMD = 0.30 [95% CI: 0.13, 0.47]; $p < 0.001$; $I^2 = 0\%$; k = 2) but not RR set structures (SMD = 0.17 [95% CI: -0.30, 0.65]; $p < 0.480$; $I^2 = 22\%$; k = 2) promoted greater shifts of the slope of force-velocity profiles towards a more velocity dominant profile compared to TS structures. Likewise, when the effects from alternative set structures were pooled, greater shifts towards velocity dominant profiles were seen (SMD = 0.29 [95% CI: 0.13, 0.44]; $p < 0.001$; $I^2 = 0\%$; k = 4) compared to TS structures. Pooled results and sub-group results for CS and RR provided moderate GRADE quality of evidence (Table 9-3).

Table 9-3 Summary of meta-analysis findings and quality of evidence synthesis.

Outcome	Summary of findings				Quality of evidence synthesis (GRADE)			
	k	n	Effect (95% CI)	Direction of the effect compared to traditional sets	Imprecision	Inconsistency	Risk of bias	Overall quality
Muscular strength								
Cluster set	5	120	-0.07 (-0.21, 0.07)	↔	-1	None	None	Moderate
Rest redistribution	8	230	-0.04 (-0.20, 0.12)	↔	-1	None	None	Moderate
All	13	350	-0.06 (-0.16, 0.05)	↔	None	None	None	High
Hypertrophy								
Cluster set	2	49	-0.93 (-3.24, 1.38)	↔	-1	-1	None	Low
Rest redistribution	3	71	-0.06 (-0.26, 0.14)	↔	-1	None	None	Moderate
All	5	120	-0.03 (-0.20, 0.13)	↔	-1	-1	None	Low
Muscular endurance								
Rest redistribution	3	115	-0.37 (-0.72, -0.02)	↓	-1	None	None	Moderate
All	4	133	-0.38 (-0.69, -0.07)	↓	-1	None	None	Moderate
Vertical jump performance								
Rest redistribution	4	119	0.16 (-0.09, 0.40)	↔	-1	None	None	Moderate
All	5	142	0.13 (-0.07, 0.33)	↔	-1	None	None	Moderate
Velocity and power at sub-max loads								
Cluster set	4	93	0.19 (-0.01, 0.40)	↔	-1	None	None	Moderate

Rest redistribution	7	207	0.16 (-0.04, 0.37)	↔	-1	None	None	Moderate
All	11	300	0.18 (0.04, 0.31)	↑	-1	None	None	Moderate
Slope of the force-velocity profile								
Cluster set	2	49	0.30 (0.13, 0.47)	↑	-1	None	None	Moderate
Rest redistribution	2	50	0.17 (-0.30, 0.65)	↔	-1	None	None	Moderate
All	4	99	0.29 (0.13, 0.44)	↑	-1	None	None	Moderate

Note. CI confidence intervals, *GRADE* Grading of Recommendations Assessment, Development and Evaluation, *k* number of studies, *n* number of participants.

Only outcomes with $k > 1$ are included in this table.

↑ *More effective when compared to traditional set structures*

↔ *Equally effective when compared to traditional set structures*

↓ *Less effective when compared to traditional set structures*

9.4 Discussion

The present systematic review and meta-analysis sought to compare the effects of TS, CS, and RR in promoting various training adaptations. The findings of this review suggest that on a volume-equated basis: 1) set structure manipulation during RT has a negligible impact on muscular strength gains and hypertrophic outcomes; 2) TS is more effective at promoting muscular endurance gains; 3) alternative set structures are more effective at inducing greater velocity and power outputs at submaximal loads; 4) manipulation of the set structure can modulate force-velocity profiles with alternative set structures leading to significant shifts towards velocity-oriented profiles; and 5) while the pooled SMD favoured alternative set structure for vertical jump performance gains, this effect was not statistically significant. Therefore, modifying TS to an alternative set structure (CS or RR) can influence the magnitude of specific muscular adaptations, which further suggests set structure manipulation to be an important consideration for RT program design.

Effects of set structure manipulation on muscular strength, hypertrophy, and endurance

Moderate to high GRADE quality evidence indicates that set structure manipulation during RT has negligible effects on muscular strength gains and hypertrophic (low to moderate GRADE) outcomes when total training volume is equated. More specifically, TS was not more effective than CS or RR at increasing strength or promoting muscle hypertrophy. High levels of effort often experienced during TS are associated with increased metabolic by-product accumulation, motor unit recruitment, and endogenous hormone secretion, all of which have been proposed to contribute to muscle hypertrophy and enhanced muscle strength [267, 297]. Indeed, two studies [277, 281] that reported the greatest advantage of TS over CS and RR used this reasoning to explain their findings. In contrast to this, Oliver et al. [213] found RR to be equally effective in promoting muscle growth as TS, but superior for increasing muscle strength. The explanation for this finding may be found in the study by Burd et al. [297] who demonstrated that maximal electromyographic activity occurred half way through (i.e., repetitions 5–6) the performance of a set of leg extensions using a load corresponding to 70% 1RM. Since Oliver et al. [213] used similar intensity range and divided the number of repetitions performed during TS (i.e., 4 x 10) in half (i.e., 8 x 5) and equated total rest time, this may have resulted in greater neuromuscular activation over consecutive sets compared with TS, further contributing to the greater strength gains in the RR group. That said, there is still an ongoing debate whether significant amounts of fatigue during RT are needed to optimise strength and hypertrophy adaptations.

More recent studies suggest that terminating sets after reaching only moderate levels of effort can lead to similar or greater strength gains when compared to highly fatiguing RT protocols [47, 46, 17]. While training to muscular failure was not a significant moderator ($p > 0.067$) of the differences between TS and alternative set structures in the present review, there was still some indication of greater effectiveness of alternative set structures on strength gains when TS are performed to failure. In addition, based on the available evidence [298], stopping several repetitions short of failure when training with moderately heavy loads does not seem to compromise hypertrophy, at least when training volumes are equated. Findings of the present review, therefore, support these conclusions since TS (typically performed near or to muscular failure) and CS or RR (typically performed further from muscular failure), were equally effective at promoting muscular strength and hypertrophy adaptations. Although equally effective, it is plausible that the underlying mechanisms for these improvements are different for each set configuration. For instance, it is well established that CS and RR allow for greater velocity and power outputs than TS whereas higher metabolic stress and perceived exertion can be seen after TS [128, 227]. Therefore, the mechanical factors may have more relevance in the adaptations to RT utilising CS and RR whereas metabolic stimuli may be a predominant factor after traditional RT [299].

Moderate GRADE quality of evidence suggests that alternative set structures are less effective at improving muscular endurance than TS. These findings are not surprising since local muscular endurance was examined using the repetitions to failure task with a submaximal load in all studies included in the present review. It is important to note that muscular abilities such as endurance have a significant skill component, meaning that individuals are likely to learn the specific pattern of muscle recruitment associated with performance of a given task [300]. Indeed, in a study by Mattocks et al. [125] one group trained with a repetition range that mimicked the strength test, while the other group trained with a repetition range similar to the endurance test, and subsequently performed better in the muscular endurance test (although, not in all muscle groups).

Therefore, greater muscular endurance adaptations are probably influenced by the greater task-dependent similarities between the testing procedures and TS, rather than CS or RR. It is plausible that muscular endurance adaptations assessed through an intermittent task (e.g., repeated power ability) would be greater after RT using alternative set structures, but this remains to be investigated. Most of the studies examining the effects of set structure manipulation on local muscular endurance have analysed lower-body exercises and found superior effects of TS over CS and RR. Only Goto et al. [277] analysed both a lower-body and upper-body exercise, and reported TS to be more effective than CS only for the knee extension but not shoulder press exercise, suggesting that the differences in local muscular endurance adaptations between TS and alternative set structures might be exercise specific. While previous studies suggested that upper-limb muscles may have a greater trainability than lower-limb muscles that are more involved in daily physical activities [301], it is still unclear why similar results were not observed for both upper- and lower-body exercises. In that regard, future research on this topic is warranted.

Effects of set structure manipulation on velocity and power outputs at submaximal loads, vertical jump performance, and force-velocity profiles

Moderate GRADE quality of evidence shows that alternative set structures induce greater velocity and power outputs at submaximal loads compared to TS. However, these positive effects of alternative set structures were not substantial (SMD = 0.18). In addition, when examining the selective effects of CS and RR, the sub-group analysis revealed that the positive effects of CS and RR over TS were not significant ($p < 0.05$). This is surprising since CS and RR improve acute energy restoration and better maintain performance than TS, and thus are thought to be beneficial for movement velocity and muscular power gains [24, 128]. While it may be tempting to conclude that CS and RR are equally effective in enhancing velocity and power as TS, it must be noted that considerably lower number of studies included in each sub-group analysis may have affected the results. This contention is supported by the pooled results of the present review, and by a recent meta-analysis [128] which compared the acute effects of TS, CS, and RR on velocity and power outputs, and concluded that both CS and RR were superior to TS, with CS providing even larger effects on acute mechanical performance enhancement. Since the present meta-analysis included a considerably lower number of studies (11 vs 19) than that on the acute effects of TS, CS and RR, it is plausible that lower statistical power caused the discrepancy between the findings. In addition, careful inspection of the two studies [213, 211] which have shown the greatest effects of CS and RR on velocity and power adaptations might explain our findings further. Interestingly, both Oliver et al. [213] and Morales-Artacho et al. [211] examined velocity and power outputs at submaximal loads that closely mirrored those used during the training intervention, whereas other studies either used less specific testing conditions, or tested against a range of specific and non-specific submaximal loads which may have skewed the results. According to the velocity specificity principle [126, 302], high-velocity training elicits greater increases in strength and power at high-movement velocity than at low-movement velocity, whereas low-velocity training develops strength and power at low-movement velocity with little effects on high-velocity strength and power, indicating the velocity-specific adaptations to RT. Although RT also causes increases in strength and power above and below the training velocity, the transfer diminishes as the testing velocity deviates from the velocity of training [303, 304]. This principle is even more relevant in this review considering that only a few included studies used a periodised approach to training while the rest of them applied little to no variation during the training intervention. Current evidence suggests [305, 306] that no or only minimal transfer effect can be expected when training specificity is offset by testing on a neutral instrument. Therefore, it may be that using a less specific condition (in this case intensity of load) to assess mechanical performance improvement during RT, might also compromise the evaluation of the resultant training adaptations.

Neither the presence of muscular failure during TS, the number of repetitions performed in a set, nor the load used were significant moderators of the differences between TS and alternative set structures for velocity and power adaptations. However, study duration was a significant moderator for the effectiveness of alternative set structures with longer duration studies promoting greater velocity and power outputs at submaximal loads compared to TS. Although interesting, this finding likely represents a type I error for the following reasons: the study [211] which reported the greatest effect of CS over TS, although lasting 11 weeks in total, manipulated set structures only in the last training block (i.e., 3 weeks), and we found no significant association between the effects of alternative set structures and the study duration when analysing RR separately (i.e., while excluding the afore-mentioned study [211]). Therefore, we suspect this analysis represents a false positive finding given the non-significant effects of the study duration when a generally higher number of studies that compared TS and RR were analysed separately. Finally, it must be noted that, although significant, only small effects were observed in favour of alternative set structures over TS for inducing greater velocity and power adaptations. Nevertheless, even small improvements in performance in some sports may translate to meaningful differences in competitive outcomes [307, 308].

Moderate GRADE quality of evidence suggests that altering the set structure to include shorter but more frequent rest periods has marginal positive effects on vertical jump performance improvement since TS, RR, and CS were all equally effective. However, effect sizes in 4 of 5 studies, as well as examination of the confidence intervals, indicate a likely benefit in favour of alternative set structures on vertical jump performance gains. This discrepancy could likely be attributed to the lack of training specificity. Briefly, both studies that reported the smallest effects in favour of alternative set structures over TS on jumping performance did not include vertical jumps in the training program. These studies also followed a fixed (i.e., non-periodised) and highly demanding RT program. While implementing vertical jumps in a well-rounded RT program is likely to elicit the greatest improvement in vertical jump performance, it seems that training variation and specificity of load might also affect the resultant vertical jump performance adaptations [309]. This is probably also relevant to other physical capacities such as sprinting, horizontal jumping, change of direction and throwing since the only two studies [283, 256] which looked at these outcomes reported marginal improvements after RT regardless of the set structure. However, the results were also probably affected by the lack of training specificity since these performance-related outcomes were not a part of the training intervention. Therefore, future studies examining the effects of alternative set structures on various sport performance-related outcomes should take a periodised approach while incorporating them into a RT program to better balance stimulus and fatigue and prevent this from being a possible confounder.

Moderate GRADE quality of evidence indicates the ability of alternative set structures to modulate force-velocity profiles of the individuals. More specifically, alternative set structures induced significant shifts of the slope of force-velocity profiles towards being more velocity-oriented compared to TS. This finding is not surprising considering effects sizes for velocity and power outputs at submaximal loads and vertical jump performance gains all favoured alternative set structures and that muscular strength adaptations did not show an effect of set structure. Greater velocity and power adaptations at submaximal loads, vertical jump performance gains and consequent shifts towards a velocity-oriented force-velocity profile after utilising alternative set structures are consistent with the principle of specificity, which dictates that the more closely a training program replicates the requirements of a given outcome, the greater the transfer of the training to that outcome [310]. However, Iglesias-Soler et al. [293] brought an additional matter worthy of discussion while reporting greater shifts towards velocity-oriented profiles after RT using TS rather than RR. In that study [293], the intended velocity was always maximum, although the actual training velocity was always higher during RR than TS, which led authors to speculate that the intended velocity matters more than the actual training velocity when it comes to the changes in the force-velocity relationship. However, this training study consisted of only 10 sessions and used a unilateral leg extension exercise only with a constant load (75% of 1RM) throughout all sessions. In addition, each individual served as their own control since opposite legs performed RT using different set structures (i.e., TS or RR). While this approach minimises the biological variability that may affect training outcomes, the authors acknowledged that the cross-education effect phenomenon, although minimal and probably negligible, could have occurred in their study [293]. In that regard, the cross-education effect, together with previously mentioned factors (i.e., low number of sessions and the constant load used) may have caused similar adaptations between limbs despite differing training protocols [288]. Thus, it is presently unclear whether intended or actual velocity is the most important stimulus for shifting a force velocity profile to be more velocity oriented. Therefore, an avenue for future research is to identify which confounding factors can affect the ability of alternative set structures to modulate force-velocity profiles.

Implications for training and research

Overall, the findings of this review suggest that altering the set structure during RT does not affect increases in muscle strength and size. However, the training loads and volumes were matched in the experimental groups of each study included in this review.

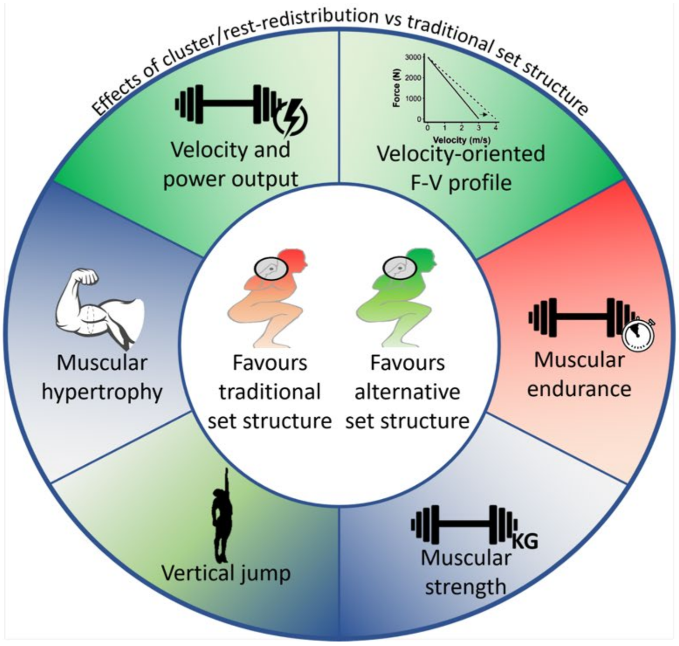
In that regard, and considering the mechanical advantage and lower metabolic stress and perceived exertion associated with CS and RR compared to TS, it is reasonable to assume that participants in CS and RR groups may have been able to tolerate greater training loads, perform more repetitions in a training set, or both. In fact, Iglesias-Soler et al. [250] examined the maximal number of repetitions that could be performed using RR and TS. In that study, participants performed 3 sets of squats to failure using a 4RM load using TS with 3 minutes of inter-set rest. During RR, participants performed multiple sets of one repetition with the same load until the point of exhaustion. In this case, rest between repetitions was calculated based on the ratio of the total recovery time during TS to the individual number of repetitions completed during TS minus one. RR allowed participants to complete about 5 times as many repetitions as the TS protocol (RR = 45.5; TS = 9.3 repetitions). Similarly, Iglesias-Soler et al. [311] showed that CS can be an effective tool for increasing training volume and intensity. In this study [311], participants performed repetitions to failure using TS and using CS consisting of 30 seconds of rest between every repetition. As a result, a greater number of repetitions was performed when CS was used in the bench press and biceps curl exercises, although the load for CS condition was considerably heavier (90% and 70% 1RM for CS and TS, respectively). Going further, Tufano et al. [201] expanded on these findings while showing that CS can allow for greater loads to be lifted without decreasing relative movement velocity when compared to TS, which the authors summarised as greater training stress with similar degrees of relative fatigue. Since dose-response relationships exist between RT volume and both muscle strength gains [121] and increases in muscle growth [3], these data collectively suggest that alternative set structures might be more effective at inducing these adaptations than TS if they are designed to include greater training loads and number of repetitions during RT. Indeed, Nicholson et al. [212] found that a group using a CS structure with greater loads increased their strength slightly more (13.35 ± 2.13%) than volume-equated TS (12.16 ± 2.76%) and CS (11.14 ± 3.35%) groups following a 6-week training period while still experiencing lower or similar levels of metabolic stress and decline in movement velocity. However, these potential advantages of alternative set structures are largely inferred from cross-sectional studies [311, 250, 201]. Therefore, exploring the long term effects of CS and RR including greater loads or number of repetitions compared to TS on strength gains and muscle growth appears to be an attractive avenue for future research.

Local muscle endurance adaptations were greater after using TS rather than CS and RR structures during RT. However, the considerable amount of mechanical, metabolic and perceptual markers of fatigue often associated with TS challenges the rationale of using TS during RT in order to improve local muscle endurance. For instance, performing a high volume of repetitions during RT may deteriorate movement technique due to acute fatigue [242, 312]. A strategy for achieving task outcomes in the presence of fatigue often associated with movement reorganisation involves shifting muscle recruitment away from fatigued muscles to others to compensate [313, 314]. This phenomenon, observed during the successive performance of physical tasks to fatigue [314, 313], suggests that, to maintain global task performance, the neuromuscular system shifts movement contributions away from the prime movers that fatigue earliest and towards other muscle groups still intimately involved in movement outcome. In that regard, it has been shown that weightlifting technique can be maintained to a greater extent with CS as opposed to TS [242], while the contribution from the joints responsible for producing power in the back squat exercise was altered less during RR than TS [253]. While this suggests that alternative set structures may be more effective for skill acquisition and subsequently performance enhancement, more longitudinal studies are needed to substantiate these claims. Finally, RT can be used to improve local muscular endurance via high repetition sets at a close proximity to failure. However, this type of RT is sometimes also used to improve overall work capacity, which occurs as a result of the large number of repetitions completed [216, 1, 2]. However, work capacity can be improved more directly through aerobic training modalities such as running [315], while also avoiding potentially maladaptive RT movement patterns [253, 242] that can occur as a result of performing a high number of repetitions within sets in a consecutive fashion. Therefore, the support for using TS during RT for the sole purpose of improving muscle endurance is tenuous.

The current findings indicate that alternative set structures are generally more effective than TS at promoting velocity and power adaptations, vertical jump performance and consequent shifts towards velocity-oriented force-velocity profiles after RT, whereas increases in muscle strength and size will not be affected by the set structure choice. In that regard, it is a viable recommendation to use alternative set structures during various training phases such as strength-endurance, maximal strength, strength-speed, and speed-strength. For example, a strength-endurance phase often requires a high volume of repetitions in order to increase overall work capacity and stimulate increases in muscle cross-sectional area of an athlete [216, 2]. Since CS and RR can allow for higher volumes of work while preventing potential fatigue-induced deterioration in form, they may be preferable to TS structures. Furthermore, during a maximal strength phase, athletes often shift their training focus to exercises that emphasise force production. In that regard, alternative set structures may allow for greater loads to be lifted with lower or similar levels of metabolic stress and declines in movement velocity compared to TS; thus, training the high-force end of the force-velocity spectrum more efficiently. Finally, both strength-speed and speed-strength phases aim to increase rate of force development while lifting relatively heavy loads as quickly as possible. Here as well, CS and RR can encourage higher velocity and power outputs, since fatigue can quickly manifest when repeatedly performing explosive movements under external load using TS [128, 24], potentially attenuating training adaptations. This is further supported by recent studies where alternative set structures allowed for a greater number of repetitions to be performed before reaching a certain velocity [116] or power loss threshold [160]. However, in some instances, the objective of RT requires a multifaceted approach to training in which hypertrophy, strength, and velocity and power outputs are all considered throughout a microcycle. This is especially prudent in team sports where frequent matches throughout the season and extended competitions periods (e.g., entering play-offs or playing Champions League) can alter the length of the preparatory period and its specific phases [316]. In that regard, alternative set structures might be a viable option for those facing time-constraints since, with a proper distribution of rest during RT, it is possible to have similar (or greater) workload in training without sacrificing velocity and power outputs [201, 311, 212, 250], leading to similar hypertrophic and strength changes with greater increases in velocity and power. Nevertheless, a previous meta-analysis found that alternative set structures are highly effective at reducing acute metabolic stress and perceptual exertion induced by RT when compared to TS, further suggesting their ability to accelerate the rate of recovery following RT [128]. Broadly speaking, this feature of alternative set structures would be important during in-season training when the weekly scheduling of training is dictated by the dual need to maintain (or even improve) physical qualities of the players and avoid excessive residual fatigue at the end of the week in preparation for the next match

[316]. In addition, athletes who train multiple times a day and who need to manage RT fatigue for both event performance and sport specific training sessions [263, 97, 17] might also benefit from alternative set structures. For these reasons, CS or RR structures provide coaches and athletes with a multitude of options to design their training to better manage fatigue while inducing desired adaptations. Collectively, alternative set structures can be manipulated in various ways that encourage different chronic training adaptations (Figure 9-7), not just to result in less fatigue as demonstrated by previous individual studies and meta-analyses.

Figure 9-7 Summary of chronic adaptations to resistance training using traditional and alternative (i.e., cluster and rest redistribution) set structures.



Note. Outcomes shaded in blue were not significantly different between the set structures. For the outcome shaded in green and blue (i.e., vertical jump), the results were in favour of alternative set structures compared to the traditional set structure, but these effects were not significant.

Limitations and considerations

Several aspects of this review should be considered when interpreting the findings. First, analyses on hypertrophy, muscle endurance, vertical jump performance, and the slope of force-velocity profiles included a small number of studies with a combined number of participants ranging from 99 to 142. However, it should be considered that only small to moderate levels of heterogeneity were observed, suggesting that the results were broadly consistent (i.e., stable). Second, the considerably lower number of female participants in most analyses limits the generalisability of our findings to female participants, and more research should include females when possible. Third, while we performed meta-regression to examine how muscular failure, number of repetitions, study duration, and the load used during TS impacted the differences in the effectiveness between alternative set structures and TS, the number of included studies only allowed this to be performed for strength, velocity and power outcomes. In addition, while we attempted to compare the effectiveness of CS and RR set structures against each other, a relatively small (and disproportionate) number of studies prevented us from doing so. Therefore, more research is needed on the selective effects of CS and RR on various training adaptations. Fourth, some studies did not report all information required for meta-analysis and we therefore extracted the required information from figures or estimated the information (e.g., pre-post assessment correlations) based on other studies. This likely introduced some error and we therefore urge researchers to report standard deviations of the difference scores (and or pre-post assessment correlations) when reporting the results of the training intervention studies. Similarly, only four studies reported adherence with the intervention, hence future studies should ensure that adherence rates for all groups are presented. Fifth, almost half of the studies included in this review were considered to be at high risk of set structure bias since the participants were performing other standardised RT sessions or because they were not instructed to perform all exercises during an intervention using a single set structure, but rather a combination of set structures (e.g., CS or RR for the back squat, TS for the accessory exercises). While this likely increased ecological validity of the findings, it also meant that findings could not be solely attributed to the true effects of set structure manipulation. Finally, some studies did not include specific exercises or intensities during the training, despite being assessed at the end of the intervention (e.g., vertical jumps were not included in training, but their improvement was assessed). This could have caused an underestimation of the actual differences between TS and alternative set structures for certain outcomes.

9.5 Conclusion

This systematic review and meta-analysis found that set structure manipulation during RT has a negligible impact on muscular strength gains and hypertrophic outcomes. However, it should be noted that training intensities and volumes were equated between the set structures in all included studies. Since alternative set structures could allow for greater training loads and volumes when compared to TS, future studies should explore the long-term effects of CS and RR including greater loads or number of repetitions compared to TS on strength gains and muscle growth. While using CS and RR during RT generally led to greater vertical jump performance when compared to training using TS, the difference between performance gains was not significant. This was likely caused by the training specificity issues observed in many studies since vertical jump was rarely a part of the RT protocols. Alternative set structures induced greater velocity and power outputs at submaximal loads than TS and were also able to modulate force-velocity profiles towards being more velocity-oriented. TS had more favourable effects on local muscle endurance improvement when compared to CS and RR. However, since a considerable amount of mechanical, metabolic and perceptual markers of fatigue is often experienced during TS, and because there are other, more effective ways of improving work capacity, the larger improvement in muscular endurance during TS compared to CS and RR may be of limited practical relevance. Collectively, the findings of this review indicate that alteration of TS to alternative set structure (CS or RR) is expected to influence the magnitude of specific muscular adaptations which further suggests set structure manipulation to be an important consideration for RT program design.

Chapter 10: Using cluster and rest redistribution set structures as alternatives to resistance training prescription method based on velocity loss thresholds

Preface

In Chapters 8 and 9, it was demonstrated how both cluster and rest redistribution set structures are effective in alleviating acute mechanical, metabolic, and perceptual markers of fatigue during resistance training, and thus effective at inducing positive training adaptations. With these points in mind, it is possible that both cluster and rest redistribution set structures could be used as an *a priori* alternative to commonly used velocity loss thresholds. Therefore, this Chapter expands on the previous two chapters and answers the question of whether cluster sets and rest redistribution can be used as a free alternative to resistance training prescription with velocity loss thresholds. Compared to previous Chapters, exercises in this Chapter were performed in a Smith Machine. This was a necessary adjustment as the participants recruited in the study were habitually performing exercises in the Smith machine, and did not have much experience with the free-weight, compound exercises such as the back squat and bench press. Therefore, to ensure the participants' safety and at the same time validity of the findings, participants performed exercises in a Smith machine.

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10.1 Introduction

The beneficial effects of resistance training (RT) on muscular strength, power, speed, endurance, balance, coordination, and hypertrophy are widely recognised [1, 2]. In addition, RT is often used for injury prevention and rehabilitation purposes and has an important role in general well-being due to numerous beneficial effects on health and quality of life [31, 32]. However, adaptations to RT may differ depending upon several factors such as the choice and order of the exercises, training intensity, volume, frequency, rest interval duration, set structure, and velocity of the repetitions [3, 196, 197, 217, 128, 56]. Of these, training volume and intensity have received the majority of attention in the literature [3, 33]. On that note, exercise intensity during RT has traditionally been determined as the load lifted relative to the one-repetition maximum (%1RM) while set volume has frequently been prescribed according to a theoretical maximum number of repetitions per set that can be performed against a given %1RM until reaching muscular failure [317]. Although this way of prescribing training loads and volume is relatively simple and practical and can be managed with relative ease with large groups of people, it does not account for physiological and psychological stressors that can affect an individual's day-to-day performance [318]. For instance, maximal strength can fluctuate daily when an individual is fatigued or significantly increase within a few weeks due to training adaptation [37]. Furthermore, the number of repetitions that can be completed against a given %1RM has been shown to be both individual- and exercise-specific [12, 15]. To combat these issues, the velocity-based training (VBT) approach to RT has been shown as a highly effective and reliable methodology for RT monitoring and prescription [13, 15].

Among other advantages, VBT allows for the objective assessment of the neuromuscular fatigue incurred during a set by monitoring the velocity loss (VL) of the repetitions [15]. This is because performing multiple repetitions in a consecutive fashion without rest between repetitions (i.e., traditional sets [TS]) inevitably results in fatigue accumulation, especially when large number of repetitions are performed, and the loads used [128]. In addition, monitoring VL reached in each set serves as a precise method of quantifying the level of effort (i.e., repetitions performed with respect to the maximum number that can be completed) [15]. Since level of effort is an important factor in determining the acute responses [262] and subsequent adaptations to RT [17], many studies using VBT approaches to RT have examined the effects of training with different magnitudes of VL on maximal strength, hypertrophy, muscle endurance and performance of athletic tasks. In brief, higher VL (> 20%) maximised hypertrophic adaptations but resulted in a significant reduction in the IIX muscle fibre phenotype [17, 47] whereas lower VL (≤ 20%) resulted in similar improvements in muscle strength and endurance as well as performance of sport-specific tasks such as vertical jumping and sprinting [17]. However, Pareja-Blanco et al. [47] recently showed that here might be an upper and lower VL threshold that should be prescribed during RT to induce optimal training adaptations. It was concluded that moderate VL thresholds (i.e., VL10 and VL20) should be chosen to optimise adaptations to RT since VL0 seemed to induce levels of fatigue that were too low to maximise adaptations, whereas VL40 did not promote further muscle strength and hypertrophy compared to VL20.

Despite the benefits of monitoring repetition velocity during RT, doing so requires the use of valid and reliable velocity measuring devices (e.g., linear position transducers). While the cost of these devices has decreased in recent years, they are still not affordable to many. Even if velocity measuring devices are available, their use with groups of people can be an impractical task (e.g., team sports, group sessions). In that regard, more heuristic approaches to controlling movement velocity during RT could prove beneficial. Cluster sets (CS), where intra-set rest periods are implemented in addition to the pre-existing inter-set rest periods, are a straight-forward method to reduce fatigue while allowing higher velocity repetitions to be performed during RT [128]. However, CS extend total training time relative to TS which might not always be feasible from a practical standpoint. A more time efficient alternative to CS is to simply redistribute the total rest time of TS structures to include shorter and more frequent rest intervals. Just like CS, this set structure, known as rest redistribution (RR), has been shown to be effective – albeit to a lesser extent – in alleviating acute mechanical, metabolic, and perceptual markers of fatigue during RT [128], and thus effective at inducing positive training adaptations [56]. With these points in mind, it is possible that both CS and RR set structures could be used as an *a priori* alternative to commonly used VL thresholds. Indeed, Tufano et al. [25] observed that 12-second inter-repetition rest periods allowed for 36 consecutive back squat repetitions to be performed without dropping below VL20 while examining the effects of CS and RR on mechanical performance whereas Jukic & Tufano [116] recently showed that RR allowed almost all repetitions (~ 17.5 out of 18) in a clean pull exercise to be performed with less than 20% VL regardless of the load used across three sets. However, these studies used either CS or RR protocols in isolation, did not have a TS protocol, and used only lower body exercises in their protocols. Since both CS and RR could affect RT performance differentially [128, 56] with these effects often being exercise specific [227], it would be beneficial to examine both CS and RR as an alternative to VL thresholds (e.g., VL20) across multiple sets and exercises within the same study.

To shed light on whether CS and RR could be used as an *a priori* alternative to VL, we examined the effects of TS, CS and RR on a) VL reached during back squat (SQ) and bench press (BP) exercises across multiple sets; and b) the number of instances at which VL20 was not exceeded. Based on previous research [116, 128, 56], we hypothesised that: a) lower VL will be experienced during CS and RR compared to TS during both SQ and BP across all sets (CS < RR < TS); and b) Both CS and RR would allow for the greatest number of repetitions to be performed above the VL20 threshold (CS > RR > TS) and could potentially serve as an *a priori* alternative to VL20 thresholds.

10.2 Methods

10.2.1 Participants

Thirty-one resistance-trained men volunteered to participate in this study (mean ± standard deviation [SD]: age = 21.3 ± 2.3 years [range = 18-30 years]; body mass: 78.4 ± 12.9 kg; body height = 1.76 ± 0.07 m; SQ 10RM = 78.5 ± 12.7 kg; BP 10RM = 65.9 ± 13.7 kg). To be eligible for this study, participants had to be free from any musculoskeletal injury and familiarised with RT while having at least 1 year of experience in performing BP and SQ exercises with a proper technique. During the study, participants were instructed to avoid any strenuous exercise. Written informed consent was obtained after the participants received an oral explanation of the purpose and potential risks of the study. All procedures were conducted in accordance with the Helsinki Declaration and approved by the University of Granada's Ethics Committee (IRB approval: 935/CEIH/2019).

10.2.2 Study design

A randomised cross-over design was used to examine the effects of different set configurations on velocity loss and to determine whether alternative set structures (i.e., CS and RR) could be used as an alternative to 20% velocity loss threshold during strength-oriented RT sessions. For this purpose, participants reported to the laboratory on 4 occasions within a 2-week period. During the first visit, the 10RMs during SQ and BP exercises were determined. Thereafter, participants reported to the laboratory on three occasions (i.e., experimental sessions) during which they performed BP and SQ exercises using different set structures. All experimental sessions were performed in a randomised order with 48 to 72 hours of rest between sessions. Barbell velocity was collected during all repetitions. Throughout the sessions, strong verbal encouragement and visual velocity feedback were provided to ensure that participants performed the concentric phase of the exercises with the maximal intent. All sessions for the same participants were held at the same time of day (± 1 hour) to minimize the effects of the circadian rhythm on physical performance.

10.2.3 Ten-repetition maximum session: Day 1

Before the commencement of the incremental loading test, participants completed a standardised warm-up consisting of running at a self-selected low intensity pace for 5 min, and dynamic stretching for 5 min. Thereafter, an incremental loading test was performed to determine the load associated with a mean velocity of 0.70 $m \cdot s^{-1}$ and 0.55 $m \cdot s^{-1}$ (≈ 10RM, 80% of 1RM) for SQ and BP, respectively. The first external load in both exercises was the unloaded barbell of the Smith machine (20 kg), and weight discs were added until reaching the mean velocities described above. Thenceforth, participants were instructed to perform a set of repetitions to failure against these loads to determine their 10RM. If it was clear that the participant was able to perform less or more than 10 repetitions with a given load, the set was immediately terminated, and 5 minutes of rest was provided before the next 10RM attempt with a modified load. The magnitude of the load change was decided based on the mutual consensus between the participants and the experienced researcher. The 10RM load was determined in no more than 3 attempts for all participants. During the SQ exercise, participants were required to squat until the top of their thighs were parallel to the floor without pausing at the bottom. In addition, participants were instructed to self-select their grip width [319, 320] and perform the BP exercise such that the bar was pressed concentrically immediately after touching the chest without a pause.

10.2.4 Experimental sessions: Days 2-4

Following the 10RM session, participants returned to the laboratory on another three separate occasions during two consecutive weeks. During these sessions, participants had to perform SQ and BP against the 10RM load using *traditional* (TS; 3 sets of 6 continuous repetitions with 3 minutes of inter-set rest), *cluster* (CS; 3 sets of 6 repetitions with 30 seconds of intra-set rest every 2 repetitions and 3 minutes of inter-set rest), and *rest redistribution* (RR; 9 sets of 2 repetitions with 45 seconds of inter-set rest) set structures with 10 minutes of rest between the SQ and BP exercises. Sessions were separated by 48 to 72 h of rest and were performed in a randomised order with exercises performed in the same order during all three sessions. Each experimental session was preceded by the standardised warm-up followed by 10 bodyweight SQ, 5 SQ with 50% of 10RM load, 2 SQ with the 10RM load, 10 push-ups, 5 BP with 50% of the 10RM load, and 2BP with the 10RM load.

10.2.5 Data acquisition

All repetitions in the present study were performed in a FFittech Smith Machine (Taiwan, China) which did not have a counterweight system and with the weight of the unloaded barbell being 20 kg. Mean velocity of all repetitions was recorded using a dynamic measurement system (T-Force System; Ergotech, Murcia, Spain). This system consists of a linear velocity transducer interfaced to a computer by means of a 14-bit analog-to-digital data acquisition board and custom software. Instantaneous velocity was sampled at 1000 Hz and smoothed using a 4th order low-pass Butterworth filter with no phase shift and 10 Hz cut-off frequency. Reliability of this system has been reported elsewhere [321, 13] and its cable was vertically attached to the right side of the barbell, between the hands and the loaded barbell sleeves, with the Velcro strap.

10.2.6 Statistical analysis

All raw data on velocity loss were normally distributed as determined by graphical inspection and the indicator value range for skewness and kurtosis [322, 323, 145]. Descriptive data are presented as medians and interquartile ranges unless otherwise stated. To examine the effects of different set structures on VL during each set, linear mixed effects models were used. For this purpose, velocity loss served as an outcome measure whereas set structure (three levels) was treated as a fixed effect. In addition, set number (three levels) and exercise (two levels) were also included as fixed effects and modelled as an interaction with the set structure.

The same approach as described above was also used to test whether CS and RR set structures maintained barbell velocity at less than a 20% loss. However, for this purpose, generalised mixed effects models were used. Since the number of instances at which participants stayed above 20% VL threshold was the outcome variable in this case, a binomial error distribution was specified with a logit-link function to predict the odds of staying above 20% velocity loss threshold as a function of the set structure and interactive effects of the exercise and set number (fixed effects).

For all models, participants were treated as random effects, while random slopes were also introduced in the models as long as their addition did not result in a convergence error. Therefore, due to the inclusion of both fixed and random effects, restricted maximum likelihood estimation was used for evaluation of the models. Furthermore, their contribution — and the contribution of modelled interactions among predictors — to the explanatory power of any of the explored models was examined using a likelihood ratio test, deviance statistic and Akaike information criterion score before selecting the final model in order to obtain the best-fit model while maintaining model parsimony. The final linear mixed-effects model included interaction between the set structures, exercises and set numbers as fixed effects and participants included as random effects. However, the final generalised mixed-effects model was identical except also including a random slope for set structures. For linear mixed-effects models, estimated marginal means and 95% confidence intervals were calculated and presented with comparisons made using post-hoc Holm-Bonferroni adjustments. For generalised mixed-effects models odds ratios as well as predicted probabilities were evaluated and presented to aid interpretation of the findings.

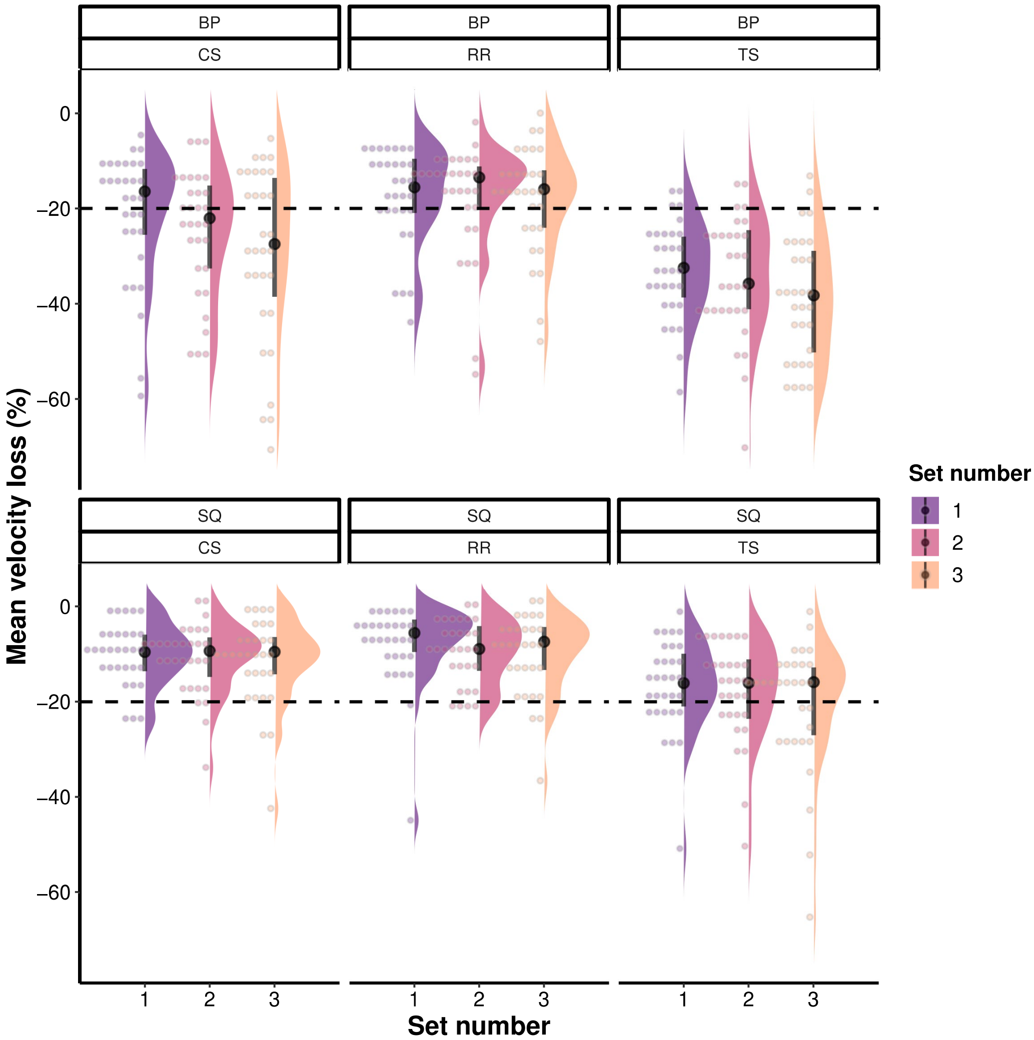
Since regression-based models can be sensitive to variables that are correlated, the variance inflation factors for all predictor parameters used in the linear mixed-effects model were inspected to check for multi-collinearity. In addition, autocorrelation diagnostics were performed to confirm the independence of the observations. For linear models, a Gaussian distribution was assumed, and the approximate normal distribution of model residuals was checked to confirm goodness of fit. To ensure the assumptions of the model were met, the plotted residuals were also checked to ensure homoscedasticity prior to utilising the results of the model. To validate the assumptions of the generalised mixed-effects model, tests for uniformity of residuals, under and over dispersion, outliers and zero-inflation were performed using simulation-based approach (which works comparably to parametric bootstrapping – see [176]), which confirmed the absence of significant problems with the model fit.

All statistical analyses were conducted in R language and environment for statistical computing using *lme4*, *emmeans*, and *ggeffects* packages while model assumptions were checked using *performance* and *DHARMa* packages (4.0.5, R Core Team, Vienna, Austria).

10.3 Results

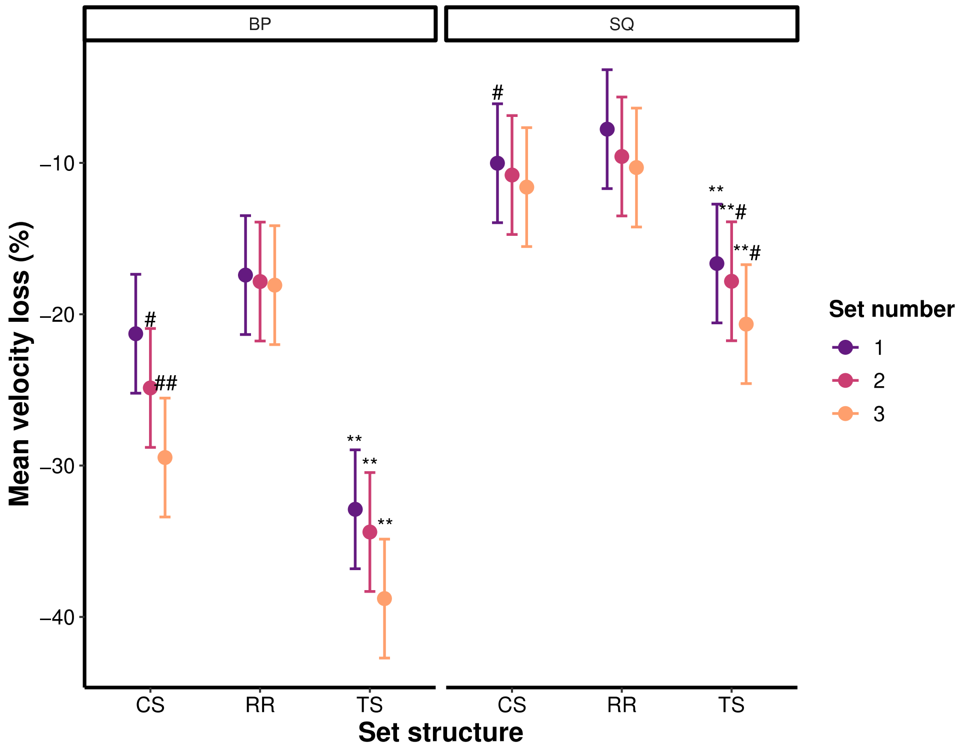
For descriptive purposes, raw data with medians and interquartile intervals as well as their distribution is presented in Figure 10-1. Results from the linear mixed-effects model (interactions and main effects) are described in the text, whereas estimated marginal means with 95% confidence intervals and pairwise comparisons are illustrated in Figure 10-2. The final linear mixed-effects model on the velocity loss experienced during TS, CS and RR revealed a non-significant interaction between the set structure, set number, and exercise ($F = 0.793$; $p = 0.530$). Similarly, exercise x set number and set structure x set number interactions did not reach statistical significance ($F = 0.693$ – 0.772; $p = 0.500$ – 0.544). However, set structure x exercise interaction was significant ($F = 9.846$; $p = 0.0005$). In addition, significant main effects of set structure ($F = 97.811$; $p < 0.0001$; TS > CS > RR), exercise ($F = 281.153$; $p < 0.0001$; BP > SQ) and set number ($F = 7.770$; $p = 0.0005$; Set 3 > Set 2 > Set 1) were observed for the amount of VL reached.

Figure 10-1 Medians and interquartile ranges (i.e., middle 50% of the data between 75th and 25th percentiles) for mean velocity loss across all set structures, exercises and training sets.



Note. The dashed line represents a 20% velocity loss threshold whereas each dot represents one data point (3.22% of the whole data) and together with density represents the distribution of the data. BP, Bench press; CS, Cluster set structure; RR, Rest redistribution set structure; SQ, Back squat; TS, Traditional set structure.

Figure 10-2 Estimated marginal means with 95% confidence intervals for the mean velocity loss across all set structures, exercises, and training sets.



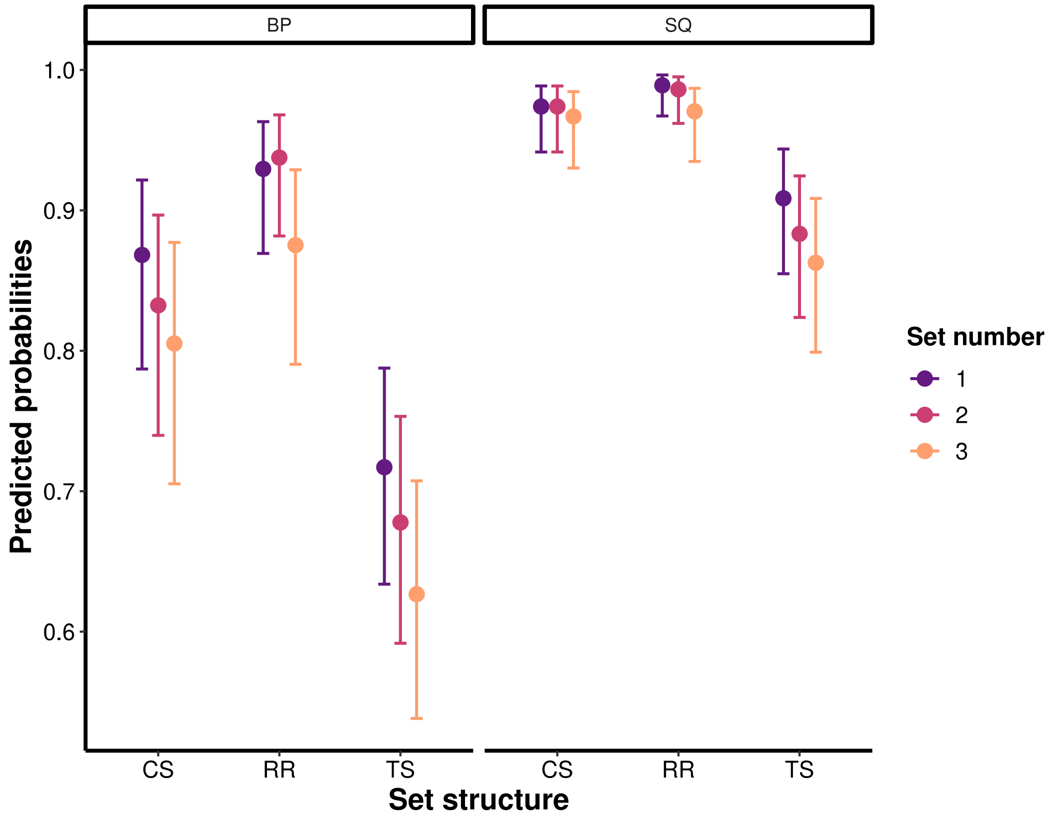
Note. BP, Bench press; CS, Cluster set structure; RR, Rest redistribution set structure; SQ, Back squat; TS, Traditional set structure; **Significantly greater decline than CS and RR ($p < 0.001$); **#Significantly greater decline than CS ($p < 0.05$) and RR ($p < 0.001$); #Significantly greater decline than RR ($p < 0.05$); ##Significantly greater decline than RR ($p < 0.001$).

The final generalised linear mixed-effects model for the number of instances participants were able to stay above the 20% VL threshold revealed no significant set structure x exercise x set number, exercise x set number, set structure x exercise, and set structure x set number interactions ($\chi^2 = 0.015 – 4.417$; $p = 0.959 – 0.110$). However, significant main effects of set structure ($\chi^2 = 45.356$; $p < 0.0001$; RR > CS > TS), exercise ($\chi^2 = 162.987$; $p < 0.0001$; SQ > BP), and set number ($\chi^2 = 14.813$; $p = 0.0006$; Set 1 > Set 2 > Set 3) were found for staying above the 20% VL threshold. Specific comparisons (odds ratios) are presented in Table 10-1. Predicted probabilities for staying above the 20% VL threshold broken down by the set structure, exercise and set number are illustrated in Figure 10-3.

Table 10-1 Pairwise comparisons between different set structures for the odds of staying above 20% velocity loss threshold broken down by exercise and training set.

	Description		Statistics			
Comparison	Exercise	Set number	Odds ratio	SE	Z score	p value
CS / RR	Bench press	1	0.500	0.181	-1.914	0.056
CS / TS	Bench press	1	2.600	0.792	3.138	0.003
RR / TS	Bench press	1	5.205	1.946	4.412	0.000
CS / RR	Back squat	1	0.413	0.273	-1.339	0.180
CS / TS	Back squat	1	3.767	1.783	2.802	0.010
RR / TS	Back squat	1	9.126	5.625	3.587	0.001
CS / RR	Bench press	2	0.330	0.120	-3.060	0.004
CS / TS	Bench press	2	2.360	0.688	2.947	0.004
RR / TS	Bench press	2	7.145	2.711	5.183	0.000
CS / RR	Back squat	2	0.525	0.327	-1.036	0.300
CS / TS	Back squat	2	4.948	2.285	3.462	0.001
RR / TS	Back squat	2	9.431	5.335	3.967	0.000
CS / RR	Bench press	3	0.589	0.187	-1.670	0.095
CS / TS	Bench press	3	2.463	0.697	3.183	0.003
RR / TS	Bench press	3	4.180	1.419	4.214	0.000
CS / RR	Back squat	3	0.888	0.454	-0.233	0.816
CS / TS	Back squat	3	4.646	1.985	3.596	0.001
RR / TS	Back squat	3	5.234	2.420	3.581	0.001

Figure 10-3 Predicted probabilities with 95% confidence intervals for staying above 20% velocity loss threshold for all set structures, exercises, and training sets.



Note. For specific comparisons, please refer to Table 10-1. BP, Bench press; CS, Cluster set structure; RR, Rest redistribution set structure; SQ, Back squat; TS, Traditional set structure.

10.4 Discussion

The purpose of this study was to examine the effects of CS, RR, and TS on neuromuscular performance and to determine the viability of using CS and RR as alternatives to prescribing VL20% thresholds across multiple BP and SQ sets. The main findings of this study revealed that a) the inclusion of 30 second intra-set intervals during CS, and creating shorter but more frequent rest periods during RR prevented the VL experienced during TS with RR being the most effective set structure for this purpose; b) these effects were more pronounced during BP than SQ (i.e., the magnitude of VL was lower); c) both CS and RR allowed the vast majority of repetitions to be performed above VL20%; and d) velocity was better maintained above VL20% during the BP compared to SQ during CS and RR, with RR also being more effective than CS for maintaining velocity during the BP exercise. Taken together, data from the current study show that CS and RR are effective at reducing the overall fatigue-induced decrease in velocity compared with TS while also allowing the vast majority of repetitions to be completed above VL20% – though the magnitude of these effects are likely to be exercise-specific.

As expected, significantly lower VL was observed during both CS and RR when compared to TS, regardless of the exercise and the set number – a finding that is in agreement with the literature [128]. However, our first hypothesis was only partially supported since, although both CS and RR were effective at reducing VL experienced during TS, RR was more effective than CS. The way in which CS and RR set structures were constructed could potentially explain the greater effects of RR over CS on VL. Namely, RR set structure consisted of 9 sets of 2 repetitions with 45 seconds of inter-set rest whereas CS consisted of 3 minutes of rest after every set of 6 repetitions which was interspersed by 30 seconds of rest after every 2 repetitions. Due to this setup, inter-set of RR (45 seconds) can be aligned and compared with the intra-set rest of CS (30 seconds). In this regard, longer rest periods after every 2 repetitions during RR than CS might have allowed better energy substrate restoration, while only 30 seconds of rest during CS caused some residual fatigue to be carried over from the previous set of 2 repetitions, subsequently resulting in greater VL compared to RR (see Appendix F Ch. 10 File I and Appendix F Ch. 10 File II for visualisation). However, although plausible, this is speculative since energy substrate restoration was not measured in the present study. Regardless of the mechanism behind this finding, it must be noted that RR set structures are also more efficient as they do not extend total training time like CS, but still attenuate neuromuscular fatigue (and seemingly to a greater extent than CS, at least in the present study). This is particularly important for practitioners who are often time constrained. Furthermore, the magnitude of the effect of CS and RR on VL, when compared to TS, was lower for the SQ than the BP exercise since much lower VL was experienced during TS, and subsequently CS and RR, in the SQ than the BP exercise. Therefore, when considering the findings from the present study, findings from a recent meta-analysis [227], and distinct neuromuscular and perceptual fatigue profiles reported in the literature for upper- and lower-body muscles [324, 209], the effects of CS and RR on the overall neuromuscular performance might be exercise specific.

Although reducing neuromuscular fatigue, as quantified by VL incurred in a training set during resistance training, is a very beneficial feature of CS and RR set structures, the VL experienced might still be unnecessarily high (i.e., higher than 25%) which could result in sub-maximal training adaptations [17, 47]. In this regard, a significant body of literature now suggests terminating training sets after VL20-25% has been reached. The rationale behind this suggestion is based on the findings from longitudinal studies which collectively show how VL20-25% is the most efficient VL threshold as it induces hypertrophic adaptations [47], allows for positive neuromuscular adaptations [47], preserves the expression of the fast twitch muscle fibres with considerably lower training volume being performed compared to higher VL thresholds [17]. However, valid and reliable measuring devices are needed to prescribe sets using VL which are still not affordable to many, and therefore making this training methodology inaccessible to many. The present study shows the viability of both CS and RR to potentially serve as cost-free alternatives to VL20% resistance training prescription. Specifically, the participants were able to perform the vast majority of repetitions during both CS and RR with less than 20% VL compared to TS. Therefore, CS and RR were effective not only at allowing for higher absolute velocities during the whole training session (average velocity across sets), but also at minimising the degree of fatigue (i.e., velocity loss) experienced at the end of each training set. The present results agree with the findings from the only two other studies – to our knowledge – that have taken a similar approach to assess the ability of CS and RR to maintain velocity above certain thresholds [25, 116]. However, those studies used either CS or RR protocols in isolation, did not have a TS protocol, or used only lower body exercises. Therefore, the present study expands on previous findings demonstrating that the effects of CS and RR, compared to TS, were more pronounced during the BP exercise, with RR also being more effective than CS in maintaining repetition velocity above VL20%. As stated, the greater effects of RR compared to CS could be attributed to how these set structures were constructed (i.e., longer more frequent rest periods during RR). However, the greater benefits of both CS and RR during the BP could likely be explained by the smaller muscle groups involved in this exercise – which results in more localised fatigue – compared with the SQ where the fatigue is distributed among a greater amount of muscle mass. The relative position of the sticking region in these exercises may also explain these VL differences, as the SQ allows more time/distance for force generation after such region. This probably also explains why overall VL was greater in the BP compared to SQ exercise. In turn, participants managed to maintain repetition velocity in the SQ exercise even during TS (~ 21%), although their velocity maintenance was still considerably higher during CS and

RR (~ 10%). In this regard, it can be concluded that CS and RR will provide greater benefits for the BP exercise due to the greater localised fatigue that is typically experienced in this compared to the SQ exercise, but also that CS and RR will allow for the extremely high velocity maintenance in the SQ exercise. Thus, practitioners should be aware that the same VL threshold (or the use of the same CS or RR setup) may produce divergent training adaptations when used for different exercises. With that said, the use of CS and RR during resistance training can be of a great practical value as it can produce similar outcomes as prescribing VL20% [17, 47] while avoiding the financial and potential logistical constraints associated with the use of velocity tracking devices.

Limitations and directions for future research

The results of this research expand on previous studies investigating the effects of CS and RR on resistance training performance, and their use as cost-free alternatives to resistance training prescription via VL thresholds. However, it should be noted that our findings do not necessarily transfer, at least not to the same extent, to other exercises, and free-weight alternatives of BP and SQ exercises since our participants performed BP and SQ exercises in the Smith machine. In addition, since our participants were only recreationally trained these findings may not be generalisable to athletic or sedentary populations. Therefore, future studies should investigate the effects of CS and RR on resistance training performance in other populations as well as other commonly used exercises during resistance training. Finally, we only looked at the effects of CS and RR on VL20% with a single load, set and repetition scheme. Future research should investigate different set, repetition and loading schemes of CS and RR and their association with different VL thresholds. Doing so will provide sport professionals who don’t have access to VBT devices additional options for mimicking the benefits of VBT in a more practical way.

10.5 Conclusions

The use of CS and RR attenuated VL experienced during TS across multiple sets of both BP and SQ exercises. In addition, the use of CS and RR allowed for the vast majority of the repetitions to be performed above VL20%. These beneficial effects of CS and RR were greater in the BP exercise likely due to the smaller muscle groups involved in this exercise, thus resulting in more localised fatigue accumulation compared to the SQ exercise. While this suggests that the magnitude of the effect might be exercise-specific, velocity maintenance in the SQ exercise is still expected to be considerably greater during CS and RR than TS. Importantly, for the purpose of maximising mechanical outputs in the shortest time period, RR emerged as the most efficient set structure among the three since it allowed for the lowest VL among the three set structures, and greatest number of repetitions to be performed above VL20% without extending the total training time – which was the case during CS. Collectively, while both CS and RR are effective tools for reducing the overall fatigue experienced during resistance training, they also allow repetition velocity to be maintained above VL20%. Therefore, the beneficial effects of terminating training sets after VL20% demonstrated in prior literature can be achieved by using CS and RR, while avoiding the financial and logistical constraints associated with the use of velocity tracking devices.

Chapter 11: General summary, practical applications, and directions for future research

11.1 General summary

The overall purpose of this thesis was to examine current and novel velocity-based approaches to RT monitoring and prescription while also considering the potential effects of sex, training history, relative strength, and personality traits on the accuracy of these monitoring and prescription tools. Research stemming from this thesis also addressed financial constraints associated with a velocity-based approach to RT monitoring and prescription by 1) exploring the accuracy of more affordable velocity monitoring devices; and 2) identifying no-cost alternatives to RT prescription using VL thresholds. In addition to addressing identified gaps within the literature, the findings from this thesis were intended to have an immediate impact on the practice of those who work with athletes and recreational trainees. To achieve this, three secondary and six primary research projects were conducted, giving rise to four distinct, yet connected themes of this thesis.

Before tackling the above-mentioned purposes of this thesis, it was necessary to describe the evidence-based benefits and shortcomings of the velocity-based approach to RT monitoring and prescription (Chapter 1). Thereafter, an emphasis was placed on the unknowns and potential shortcomings of the velocity-based approach to RT monitoring and prescription. More specifically, in Chapter 2, a systematic review and meta-analysis on the acute and chronic effects of implementing VL thresholds during RT were conducted. Despite concluding that VL thresholds can modulate the acute and chronic responses to RT, several methodological limitations with the implementation of this method in practice were identified, and no-cost alternatives were discussed. In addition, potentially superior velocity-based RT monitoring and prescription methods were proposed. Therefore, the data from this Chapter served as a basis for the following Chapters with the aim of identifying and explaining individual responses to different VL thresholds, and later, identifying potentially superior velocity-based RT monitoring and prescription methods and the alternative means of implementing VL thresholds during RT.

After covering the theoretical and practical aspects of the velocity-based approach to RT monitoring and prescription, before addressing the issues with VL thresholds raised in Chapter 2, it was important to consider what velocity-monitoring devices were going to be used in subsequent Chapters and whether new, more affordable, wireless devices are sufficiently reliable for use in practice. In Chapter 3, the reproducibility and sensitivity of PUSH2 and Vmaxpro and GymAware were evaluated. Overall, GymAware was the most reliable and sensitive device for detecting the smallest changes in RT performance, regardless of the velocity metric used. Considering this, data collected from GymAware was used to address the research aims of the subsequent studies within this thesis.

With the most reliable and sensitive devices established, the next step was to explore some of the methodological issues with VL thresholds raised in Chapter 2. In Chapter 4, substantial inter-individual variability in the amount of work that can be completed until reaching a given VL threshold was confirmed and potential factors responsible for this variability were identified. Additionally, the utility of a frequently advocated VL-$\%_{repetitions}$ relationship for RT set volume prescription was evaluated in Chapter 5. Perhaps not surprisingly, when VL-$\%_{repetitions}$ relationships were modelled for each individual rather than the entire group of people, the goodness of fit of VL-$\%_{repetitions}$ relationships drastically improved. However, despite the improved goodness of fit of individual VL-$\%_{repetitions}$ relationships, the ability of both general and individual VL-$\%_{repetitions}$ relationships to predict $\%_{repetitions}$ in a subsequent testing session was poor and always led to prediction errors higher than 10%. Therefore, VL-$\%_{repetitions}$ relationships do not seem to provide any additional benefits for RT monitoring and prescription compared to more traditional, no-cost methods such as those using 1RM and XRM assessments of RPE scales.

After confirming issues with using VL thresholds in practice, two novel velocity-based approaches to monitoring and prescribing RT were examined in Chapters 6 and 7. It was found that modelling individual XRM- or RIR-velocity relationships are valid means of monitoring and prescribing RT intensity of load and set volume while also controlling for the level of effort experienced in a set. Thus, XRM- and RIR-velocity relationships are not only superior RT monitoring and prescription tool compared to using VL thresholds, but can also be used in lieu of traditional RT methods to monitor, prescribe and adjust both the training load and set volume more accurately, potentially allowing for more efficient adaptation and better fatigue management.

Although RIR- and XRM-velocity relationships might seem identical on the surface, both may have unique applications. For instance, compared to only 3 data points provided by the XRM-velocity relationship, the RIR-velocity relationship provides the entire spectrum of RIRs and associated velocities and is therefore more nuanced and precise (as evidenced by lower error rates). The RIR-velocity relationship can also be useful as it does not require any cognitive effort for set termination (e.g., the individual does not have to count the number of repetitions completed to know when to stop). In this regard, an individual using the RIR-velocity relationship can solely focus on lifting with maximal intent and perhaps velocity feedback and thus increase the efficiency of these cognitive tasks. In contrast, if the individual does not prefer to have constant velocity feedback due to distraction issues, but internally counting repetitions and lifting with maximal intent is not a problem, then the XRM-velocity relationship might be preferred, with the cost of slightly decreased precision.

In the final theme of this doctoral work, the aim was to identify potential alternatives to VL thresholds during RT. Despite the methodological issues with VL thresholds demonstrated in Chapters 2, 4, and 5, this was important for two reasons. Firstly, in Chapter 2, it was found how terminating training sets after reaching low to moderate VL thresholds optimises RT-induced training adaptations, especially those related to muscle strength, power, and endurance as well as the performance of athletic tasks such as jumping and sprinting. Secondly, getting these benefits requires the use of valid and reliable velocity monitoring devices. While the cost of these devices has decreased in recent years, some of which were examined in Chapter 3, they are still not affordable to many. Even if velocity measuring devices are available, their use with groups of people can be impractical. Therefore, more heuristic approaches to maintaining high movement velocity during RT such as using CS and RR set structures could prove beneficial.

In Chapters 8 and 9, the acute and chronic effects of using CS and RR set structures during RT were thoroughly reviewed and quantified. With two systematic reviews and meta-analyses confirming the benefits of using CS and RR on acute RT performance and fatigue responses as well as chronic RT-induced training adaptations and performance of athletic tasks, the final hurdle was to directly answer the question of whether CS and RR can be used as alternatives to RT monitoring and prescription method using VL. This question was addressed in Chapter 10 and it was found that CS and RR compared to TS set structures attenuated VL across multiple sets of both bench press and back squat exercises. Additionally, and perhaps more importantly, both CS and RR allowed the vast majority of repetitions to be performed above 20% VL during both exercises. Therefore, the beneficial effects of terminating training sets after reaching low to moderate VL demonstrated in Chapter 2 could likely be achieved by using CS and RR, while avoiding the financial and logistical constraints associated with the use of velocity monitoring devices.

Taken together, methodological issues and potential confounding factors associated with the use of VL thresholds in practice were identified in this thesis. Additionally, two novel velocity-based approaches to RT monitoring and prescription were examined and their validity was confirmed. Since it remains challenging for financially or logistically constrained practitioners to utilise a velocity-based approach to RT monitoring and prescription, the accuracy of more affordable velocity monitoring devices and no-cost alternatives to RT prescription using VL thresholds were explored and identified. Therefore, the data from this thesis highlight some good and bad aspects of the velocity-based approach to RT monitoring and prescription and potential alternatives.

11.2 Practical applications

This thesis was intended to directly influence the practice of sport scientists, strength and conditioning coaches, physiotherapists, and athletic trainers who already use, plan to use or are logistically constrained to implement the velocity-based approach to RT monitoring and prescription in their work. In this regard, several practical applications were identified:

1. A graded relationship exists between VL experienced during a set and acute training volume, neuromuscular, metabolic, and perceptual responses to RT with factors such as type of exercise, loads used, and individual characteristics of a trainee seeming to modulate these relationships. Therefore, practitioners can

use VL to monitor RT-induced acute fatigue but should be aware of the high inter-individual variability in acute responses.

2. As higher VL experienced during RT could interfere with the ability to rapidly produce force, cause a reduction in the expression of fast-twitch muscle fibres, and prolong recovery from resistance training, low to moderate VL (e.g., 20%) could be recommended to optimize strength and power training adaptations as well as the performance of sport-specific tasks. However, if hypertrophy is also the goal, more of the prescribed sets could utilise moderate VL thresholds, or more total sets with low to moderate VL could be performed.
3. When considering what devices should be used in practice, MV and PV from GymAware and MV from Vmaxpro devices can be recommended for RT monitoring and prescription due to their low magnitudes of error; thus, allowing for sensible detection of meaningful changes in neuromuscular status and functional performance during RT. In contrast, caution should be exercised when using PUSH2 in practice due to their comparatively higher, unacceptable measurement error and generally low sensitivity to detect changes in RT performance.
4. VL thresholds cannot be used to reliably control the amount of work completed during RT, but rather as a general variable quantifying the amount of fatigue experienced by an individual. When VL thresholds are used for fatigue monitoring purposes, the responses should be interpreted on a case-by-case basis since load, sex, training status, history, and personality traits can all influence, at least to some extent, the variability in responses to different VL thresholds.
5. Regardless of whether individual or general VL-$\%_{repetitions}$ relationships are used for RT monitoring and prescription, they lack accuracy and stability in time. Thus, VL-$\%_{repetitions}$ relationships are not expected to be more beneficial compared to more traditional, no-cost methods and hence should not be used for monitoring and prescribing RT with free-weight exercises.
6. Individualised XRM-velocity relationships provided twice as high goodness of fit and were able to predict XRM in a subsequent testing session with acceptable accuracy compared to general XRM-velocity relationships. Although sex, training status and history, and personality traits did not affect the goodness of fit of

individual XRM-velocity relationships or their prediction accuracy, some individual XRM-velocity relationships might still yield unacceptable prediction errors. Therefore, XRM-velocity relationship accuracy should be evaluated on a case-by-case basis. Nevertheless, an individual XRM-velocity relationship can be established with a simple linear regression model using the maximal velocity of three sets to failure with 90, 80 and 70% of 1RM and the corresponding number of repetitions performed to failure. This allows practitioners to prescribe RT loads matching an intended XRM by recording only the fastest velocity of the set (usually within the first 3 repetitions) with a given load and predicting, with reasonable accuracy, an individual's XRM.

7. Individualised RIR-velocity relationships provided twice as high goodness of fit and were always able to predict RIR in a subsequent testing session with acceptable accuracy compared to general RIR-velocity relationships. Additionally, sex, training status and history, and personality traits did not affect the goodness of fit of individual RIR-velocity relationships or their prediction accuracy Therefore, practitioners are encouraged to create RIR-velocity profiles for each individual separately to leverage the accuracy of this RT monitoring and prescription method in practice.
8. Using RIR-velocity relationships in practice could further be simplified by establishing a single relationship which covers a range of loads (e.g., 70 to 90% of 1RM), rather than having a profile for each load separately. This allows selection of the loads based on the "starting velocity" (i.e., the velocity associated with an intended load that can be lifted a given number of times) and termination of the sets when the "stopping velocity" (i.e., velocity associated with an intended RIR) is reached.
9. Both CS and RR seem to be very effective at reducing mechanical fatigue, perceptual exertion, and metabolic stress during and after RT, and thus inducing positive training adaptations more efficiently compared to performing many repetitions in a consecutive fashion (e.g., doing a set of 8 repetitions without any inter-repetition rest). Therefore, a simple and effective way for practitioners to offset acute fatigue and maintain high-movement velocities during RT would be to add pre-planned rest intervals within a set alongside normal inter-set rest periods, thereby breaking sets into small clusters of repetitions (i.e., CS). If time-

constrained, practitioners should consider the more time-efficient alternative of RR set structures whereby the total rest time planned for a given exercise is simply redistributed to include shorter and more frequent rest intervals between sets.

10. On top of being effective at alleviating acute fatigue responses and inducing positive training adaptations, both CS and RR are likely to allow the majority of the repetitions in a set to be performed above 20% VL. Therefore, practitioners could leverage the beneficial acute and longitudinal effects of terminating RT sets after reaching low to moderate VL thresholds, while avoiding the financial and logistical constraints associated with the use of velocity monitoring devices. It should be kept in mind that CS and RR can be constructed in many ways which could – together with exercise and load selection – impact the magnitude of their effectiveness on velocity maintenance. Based on the findings presented in this thesis, practitioners should consider implementing 45 seconds of inter-repetition rest after every two repetitions during bench press and back squat exercises with approximately 80% of 1RM to maximise velocity maintenance.

11.3 Directions for future research

A strength of this doctoral work is that most of the findings are of a directly applicable nature to practice. However, largely due to the applied nature of the research and the challenges faced while conducting research during the COVID pandemic, several limitations arose. Specific limitations to each Chapter were in their respective discussion sections. Therefore, directions for future research building upon the research limitations presented in this thesis are summarised below.

1. Future research is required to comprehensively examine the validity of GymAware, PUSH2 and Vmaxpro devices using robust analytical procedures and against a motion capture system. In addition, only MV and PV from these devices were of interest in this thesis. Many practitioners using these devices in practice might be interested in the reliability and validity of other parameters that these devices provide, opening another avenue for future research.
2. VL-$\%_{repetitions}$, XRM- and RIR-velocity relationships should be established for a wide variety of free-weight exercises and with youth, sedentary, and elderly

populations. These factors should also be considered while investigating the effectiveness of CS and RR at managing acute fatigue responses during RT and substituting low to moderate VL thresholds. Therefore, researchers should aim to replicate the findings presented in this thesis while also expanding the range of exercises used and populations included in their studies.

3. The number of females participating in sport science research is generally low. However, this is especially noticeable with research exploring velocity-based approaches to RT monitoring and prescription. Therefore, researchers in future studies should focus on recruiting more female participants, and balancing the number of male and female participants when making comparisons, where possible.
4. The variability in metabolic, neuromuscular, and biomechanical responses to different VL thresholds remains unknown. Therefore, researchers in future studies should quantify the extent to which the demonstrated variability in the amount of work completed until reaching different VL thresholds affects the variability in acute metabolic, neuromuscular, and biomechanical responses to VL thresholds, as well as in longitudinal adaptations.
5. Longitudinal studies are still needed to examine whether XRM- and RIR-velocity relationships remain stable after training adaptations have occurred (e.g., maximal strength increased) and after a period of de-training took place (e.g., 2 weeks of complete rest, relevant to the post-season period in many sports). Additionally, comparing the variability in acute metabolic, neuromuscular, and biomechanical responses between RT prescriptions based on 1) XRM- and RIR-velocity relationships; and 2) different VL thresholds presents an interesting avenue for future research to confirm whether RT monitoring and prescription based on XRM- and RIR-velocity relationships is truly superior.
6. In Chapter 10, the viability of using CS and RR as alternatives to training prescription based on only 20% VL were investigated. This was done as low to moderate VL thresholds, such as 20% VL, are often recommended to optimise RT-induced adaptations while avoiding the potentially negative effects of unnecessary fatigue accumulation using higher VL thresholds. Nevertheless, it is important to note that 20% or any other VL threshold in isolation is not a panacea for RT-induced adaptations. Therefore, another area in need of study is the

periodised use of different VL thresholds over time. For instance, one could plan low to moderate VL phases following high VL in a linear manner or used concurrently in an undulating design. Such a multifaceted approach to training may have merit, especially in high-performance settings where multiple training qualities often must be considered throughout a microcycle or mesocycle.

7. Researchers in future studies should investigate different set, repetition, and loading schemes of CS and RR and their association with different VL thresholds. Doing so will provide practitioners who do not have access to velocity monitoring devices additional options for leveraging the benefits of low to moderate VL thresholds in a more practical way.
8. In Chapter 10, one of the conclusions was that specific constructions of CS and RR set structures are constructed could potentially explain why the effects of RR were greater than CS for velocity maintenance. Specifically, RR consisting of 9 sets of 2 repetitions with 45 s of inter-set rest produced superior velocity maintenance compared to CS consisting of 3 min of rest after every set of 6 repetitions interspersed with 30 s of rest after every 2 repetitions, thus having longer total rest time. However, due to the organisation of CS and RR, the inter-set rest of RR (45 s) was aligned and compared with the intra-set rest of CS (30 s). It was hypothesised that longer rest periods than CS which occurred after every 2 repetitions during RR might have allowed better energy substrate restoration (i.e., ATP and PCr content), while only 30 s of rest during CS caused some residual fatigue to be carried over from the previous set of 2 repetitions, subsequently resulting in greater VL compared to RR. Since energy substrate restoration was not measured in this thesis, researchers in future studies should aim to address this gap in the literature. If energy substrate restoration and the magnitude of the effects of CS and RR for different loads and exercises during RT are indeed linked, practitioners will have the knowledge of how to construct CS and RR set structures to allow the appropriate amount of mechanical and metabolic stress for the intended acute responses and training adaptations long term.

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Appendices

Appendix A *Ethics Approval for Chapters 3 to 7*

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

26 May 2020

Eric Helms
Faculty of Health and Environmental Sciences

Dear Eric

Re Ethics Application: **20/55 Establishment and the reliability of the repetitions in reserve - velocity relationship: the impact of strength levels**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 26 May 2023.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard and that all the dates on the documents are updated.

AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: ivan.jukic@aut.ac.nz; Michael McGuigan; csousa2016@fau.edu; kekwan@aut.ac.nz

Appendix B *Ethics approval for the protocol amendment (Chapters 3 to 7)*

Auckland University of Technology Ethics Committee (AUTEC)

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

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www.aut.ac.nz/researchethics

21 August 2020

Eric Helms
Faculty of Health and Environmental Sciences

Dear Eric

Re Ethics Application: **20/55 Establishment and the reliability of the repetitions in reserve - velocity relationship: the impact of strength levels**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

The amendment to recruitment protocol has been approved for three years until 26 May 2023.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard and that all the dates on the documents are updated.

AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: ivan.jukic@aut.ac.nz; Michael McGuigan; csousa2016@fau.edu; kekwan@aut.ac.nz

Appendix C *Consent form for Chapters 3 to 7.*

AUT
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Consent Form

Project title: ***Establishment and the reliability of the repetitions in reserve – velocity relationship: the impact of strength levels***

Project Supervisor: ***Dr Eric Helms***

Researcher: ***Ivan Jukic***

- O I have read and understood the information provided about this research project in the Information Sheet dated 18/08/2020.
- O I have had an opportunity to ask questions and to have them answered.
- O I understand that I will have to perform incremental loading tests in the free-weight back squat exercise multiple times over the course of a week, which will be followed by another week of testing that will consist of repetitions to failure tests in the same exercise with submaximal loads.
- O I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.
- O I understand that if I withdraw from the study then I will be offered the choice between having any data that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.
- O I agree to take part in this research.
- O I wish to receive a copy of my results (please tick one): YesO NoO
- O I wish to receive a summary of the research findings (please tick one): YesO NoO

Participant's signature : ....

Participant's name : ....

Participant's Contact Details (if appropriate) :

....

....

....

....

Date :

Approved by the Auckland University of Technology Ethics Committee on 21 August 2020; AUTEC Reference number 20/55.

Appendix D *Ethics approval for Chapter 10.*

UNIVERSIDAD DE GRANADA

Vicerrectorado de Investigación y Transferencia

COMITE DE ETICA EN INVESTIGACION DE LA UNIVERSIDAD DE GRANADA

La Comisión de Ética en Investigación de la Universidad de Granada, visto el informe preceptivo emitido por la Presidenta del Comité en Investigación Humana, tras la valoración colegiada del Comité en sesión plenaria, en el que se hace constar que la investigación propuesta respeta los principios establecidos en la legislación internacional y nacional en el ámbito de la biomedicina, la bioteconología y la bioética, así como los derechos derivados de la protección de datos de carácter personal,

Emite un Informe Favorable en relación a la investigación titulada: 'EFECTO DE DISTINTAS CONFIGURACIONES DE ENTRENAMIENTO DE FUERZA SOBRE LA VELOCIDAD DE EJECUCIÓN Y PERCEPCIóN DE ESFUERZO' que dirige D./Dña. JESUALDO DANIEL CUEVAS ABURTO, con NIF 16367550, quedando registrada con el nº: 935/CEIH/2019.

Granada, a 15 de Octubre de 2019.

EL PRESIDENTE
Fdo: Enrique Herrera Viedma

EL SECRETARIO
Fdo: Francisco Javier O'Valle Ravassa

Gran Vía de Colón 48, 2 Planta. 18071 GRANADA
http://investigacion.ugr.es

Appendix E *Consent form for Chapter 10*

FÓRMULA DE CONSENTIMIENTO

D.______________________________________ con DNI._________________, acepta la participación en el estudio titulado ***"Efecto de distintas configuraciones de entrenamiento de fuerza sobre la velocidad de ejecución y percepción de esfuerzo"***.

Las condiciones de participación en el presente proyecto son:
-No presentar ninguna lesión ni problema médico que impida la ejecución de los ejercicios.
-Asistencia e implicación en las sesiones de evaluación.
-No realizar entrenamiento de fuerza previo al día de evaluación/entrenamiento.

He sido informado detalladamente del protocolo de estudio y me han aclarado todas las dudas. También he sido informado de los riesgos que podrían ir asociados a las medidas desglosadas con anterioridad, que en cualquier caso son mínimos dado el carácter de las evaluaciones y procedimientos empleados. Si bien, serán arbitrados y desplegados todos los medios necesarios para evitar cualquier incidencia por medio de la evaluación de la información preliminar relacionada con el estado de salud de los participantes y por cualquier observación de síntomas durante los test y el ejercicio.

En cualquier momento puedo solicitar más información sobre la práctica o los datos correspondientes a las pruebas realizadas.

En cualquier momento tengo libertad para poder retirar mi colaboración en el proceso. Si acepto participar en este estudio, me comprometo a realizar todas las actividades e indicaciones que se indiquen, hasta el término de la presente investigación.

Granada, a______ de _______ del 2019.

Firma:

Datos del firmante:

Responsable del Proyecto:
Amador García Ramos
Dpto. de Educación Física y Deportiva
Universidad de Granada
Contacto: amagr@ugr.es

Appendix F *Supplementary Files for all Chapters in this doctoral thesis*

Supplementary Files for every Chapter in this thesis can be found on the Open Science Framework using this link. More specifically, the link takes one directly to the repository where all Supplementary Files associated with a given Chapter of this thesis are located.