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Objective and Subjective Perspectives in Velocity-Based Training: From Measurement Accuracy to Perceptual and Fatigue Responses

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List of abbreviations

%1RMp	% of perceived repetition maximum
1RM/BW	Repetition maximum/ Body weight
AX-CPT	Ax continuous performance task
BP	Bench Press
BRUMS	Brunel Mood Scale
CC	Control Condition
CCC	Concordance Correlation Coefficient
CI	Confidence Interval
CMJ	Counter Movement Jump
CNS	Central Nervous System
CR-10	10 point Category-Ratio scale
CV	Coefficient of Variation
Ds	Delta Score
EEG	Electroencephalogram
ICC	Intra Class Correlation
LPT	Linear Position Transducer
LVT	Linear Velocity Transducer
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MF	Mental Fatigue
MPV	Mean Propulsive Velocity
MU	Motor Unit
MV	Mean Velocity
MVC	Maximal Isometric Strength
MVT	Minimum Velocity Threshold
Np	Number of Repetitions Perceived
Nr	Real Number of Repetitions that Should Have Been Performed
PBT	Percentage Based Training
PF	Physical Fatigue
POMS	Profile of Mood State

PV	Perception of Velocity
PVC	Perception of Velocity Change
PVL	Perception of Velocity Loss
RFD	Rate of Force Development
RIR	Repetitions In Reserve
RM	Repetition Maximum
ROM	Range Of Movement
RPE	Rate Of Perceived Exertion
RT	Resistance Training
SEE	Standard Error of Estimate
SEM	Standard Error of Measurement
SQ	Squat
V1Rep	Velocity of First Repetition
VAS	Visual Analogic Scale
VBT	Velocity-Based Training
VL	Velocity Loss
Vp	Perceived velocity
Vr	Real Velocity
|Ds|	Absolute Delta Score

Abstract

Velocity-Based Training (VBT) is an objective autoregulation method widely adopted by both researchers and practitioners, consisting of measuring barbell movement velocity through electronic devices. This approach enables the adjustment of training intensity and volume while also serving as a valuable tool to monitor daily readiness and fatigue. In addition to these applications, velocity monitoring allows for the estimation of the one-repetition maximum (1RM) through the creation of load–velocity profiles. Nevertheless, such predictions are not always precise or reliable, particularly in the free weight back squat exercise. Although relatively inexpensive and fairly accurate devices are available, their use can be impractical in certain contexts, especially in team sports, where multiple athletes train simultaneously, requiring several devices at once.

To overcome these limitations, recent research has explored the applicability of perception of velocity (PV) and perception of velocity loss (PVL) as a potential alternative. This subjective parameter enables practitioners to estimate barbell velocity even in the absence of measurement devices. Findings in this emerging field have shown that individuals are able to estimate both the velocity of single repetitions and the velocity loss within a set. Moreover, the development of reliable, low-cost technologies could greatly contribute to the wider implementation and practical usability of VBT.

The present doctoral thesis is organized into two main sections. The first focuses on the reliability of several objective aspects of VBT, encompassing three studies. These works examined the accuracy of 1RM prediction in the back squat for both males and females using the minimum velocity threshold (MVT), evaluated the reliability of a newly developed low-cost device for monitoring barbell velocity, and investigated the effect of mental fatigue on VBT-based resistance training sessions, including potential sex-specific responses. Thanks to these studies, it has been possible to highlight that sex-specific differences, which

are often under investigated in the literature, are crucial for the appropriate prescription of training, even when a velocity-based approach is employed

The second part of the thesis aims to expand current knowledge on PV and PVL. Through a series of studies, several key aspects of these subjective measures were explored. The findings demonstrated that both PV and PVL are stable parameters, not only over time, since accuracy remained stable even four weeks after familiarization, but also under conditions of both physical and mental fatigue. Furthermore, a new exercise-specific PV scale for the bench press was developed and validated. Finally, a study addressing the mechanistic basis of PV investigated the role of visual input on accuracy, revealing that the absence of visual feedback increases error variability, particularly leading to greater underestimation of actual barbell velocity. Overall, the evidence gathered throughout this doctoral work supports the notion that PV and PVL are stable and reliable parameters for training prescription, especially when applied at higher loads (around 80% 1RM) and with velocity loss thresholds exceeding 20%.

Chapter 1: Introduction and prescription of Resistance Training

1.0 Resistance Training: Performance and Health Benefits

Resistance training (RT) is currently regarded as one of the most effective and versatile exercise modalities in both athletic and clinical contexts[1–5]. Originally designed as a tool primarily for athletes, its scope of application has progressively expanded, and it is now widely recommended for the general population, including children, adolescents, adults, and older individuals[4,6]. This evolution is supported by a growing body of evidence demonstrating its safety and efficacy in enhancing performance, promoting health, and preventing various chronic conditions[7–9]. Within sports domain, RT represents a cornerstone of athletic preparation. Progressive overload training induces neuromuscular adaptations that result in improvements in maximal strength[10], power[11], and the ability to generate force rapidly[12], qualities that are critical across a wide range of disciplines. Beyond strength- and power-oriented sports, RT has also been shown to benefit endurance and team sports by enhancing movement efficiency (i.e. lowering energetic cost)[13], motor coordination[14], and joint stability[14]. These adaptations contribute not only to improved athletic performance but also to the prevention of injuries[15]. Parallel to its role in athletic performance, an increasing body of research highlights the health-related benefits of RT. Regular participation in resistance-based programs promotes reductions in fat mass and improvements in body composition[16], along with an increase in resting metabolic rate[17]. From a cardiovascular perspective, RT has been associated with improvements in blood pressure regulation[18]. At the metabolic level, it enhances insulin sensitivity[19], glucose tolerance[20], and overall glycemic control, positioning RT as an effective preventive intervention against type 2 diabetes[20]. Additional benefits include improved musculoskeletal health:

increased bone mineral density[21] and the attenuation of sarcopenia[22] make RT particularly valuable in later stages of life, contributing to healthier and more functional aging[23]. Equally important are the psychological outcomes, as RT has been linked to improvements in mood[24], self-esteem[24], and cognitive function[25].

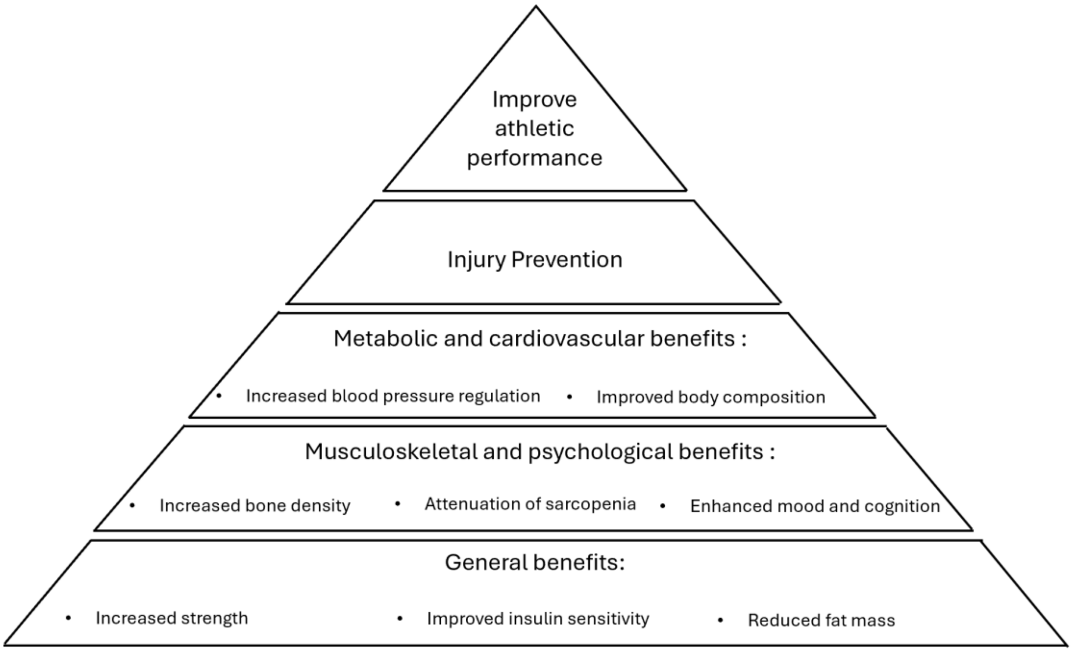

Figure 1: Benefits attainable through adherence to structured resistance training (RT) programs

1.1 How to manage Resistance Training programs: Principles and fundamentals

In order to achieve the aforementioned benefits and adaptations associated with RT, it is essential to ensure accurate prescription and execution of training programs, along with adherence to the fundamental principles of RT and the appropriate management of its key variables[1,26]. The core principles can be summarized into four main categories: progressive overload, specificity, variation, and individualization.

- The principle of progressive overload states that training demands must increase progressively in response to the adaptations elicited by previous training stimuli, in order to promote further improvements[27]. This overload can be applied through several strategies, including increasing training frequency, intensity, or volume, or by reducing recovery intervals.
- The principle of specificity highlights that training-induced adaptations are directly related to the nature of the stimulus provided[28]. Consequently, when designing a training program, it is crucial to consider the metabolic, biomechanical, and psychological demands associated with the intended outcome, ensuring that the exercises and methods employed align with the target goal.
- The principle of variation is equally important, as it prevents stagnation in adaptation and helps avoid performance plateaus[29]. To this end, coaches may adjust variables such as the selection of exercises, their order within the session, the execution technique, or the prescribed intensity. However, while variation is necessary, it should never compromise the specificity of the training stimulus.
- Lastly, the principle of individualization underscores that the same training stimulus can lead to different outcomes depending on individual characteristics[30]. Factors such as age, sex, training history, baseline fitness level, and even external variables unrelated to physical activity, such as occupational stress or lifestyle demands, can significantly influence both daily performance and long-term adaptations. For this reason, tailoring training programs to the unique characteristics and needs of each individual is fundamental to maximizing the effectiveness and safety of RT interventions.

As previously discussed, the fundamental principles of RT are intrinsically linked to the appropriate management of its key variables. Among the most relevant parameters to consider in program design are intensity[31], volume[32], density[33], and frequency[34]. Correct manipulation of these variables is essential to optimize adaptations, prevent training plateaus, and ensure both safety and effectiveness of the training process.

Intensity refers to the load lifted during training, which can be expressed in absolute (e.g., kilograms lifted) or relative terms (e.g., percentage of one-repetition maximum, perceived exertion, or velocity-based measures). Intensity plays a critical role in determining the type of adaptation achieved: higher intensities typically favor neural adaptations and maximal strength development, while moderate loads performed for higher repetitions may promote hypertrophy and muscular endurance[31].

Volume corresponds to the total amount of work performed, often calculated as the product of sets × repetitions × load. Training volume is a strong determinant of hypertrophic responses and contributes significantly to the accumulation of metabolic stress. However, excessive volume without adequate recovery can increase the risk of overtraining, highlighting the need for careful progression and monitoring[32].

Density represents the relationship between the effective duration of exercise and the total duration of the training session, including rest periods[33]. Manipulating density by adjusting rest intervals can shift the emphasis of the training stimulus: shorter rest periods tend to increase metabolic stress and cardiovascular demand, whereas longer rest intervals allow for greater recovery and the maintenance of higher loads, thus favoring strength and power development.

Frequency indicates the number of training sessions performed within a given time frame, usually expressed per week[34]. Optimal training frequency is influenced by multiple factors, including training status, recovery capacity, and specific goals. For novice individuals, lower frequencies may be sufficient to induce adaptations, while advanced athletes often require higher frequencies or split routines to effectively manage greater training volumes and intensities.

Just as the fundamental principles of RT (progressive overload, specificity, variation, and individualization) must be tailored to the individual, so must the prescription of intensity, volume, density, and frequency. These variables do not act in isolation; rather, their interaction shapes the overall training stimulus and determines the nature and extent of the adaptations achieved.

1.2 Resistance Training Prescription and monitoring: The real limitations of the "traditional approach"

Having clarified the fundamental principles and variables of RT, it is important to address how training is commonly prescribed and monitored in both research and practice. Broadly, RT prescription can follow either "fixed" methods[1] or autoregulatory methods[35–37]. Fixed methods, often referred to as the "traditional approach," remain the most widely used in both athletic and clinical contexts. This method prescribes intensity based on a percentage of the one-repetition maximum (%1RM), while training volume is predetermined according to the specific goals of the athlete or patient[1]. The advantages of this approach are evident: it requires no specialized equipment and is strongly supported by a large body of literature that provides well-established guidelines for selecting intensities and volumes according to desired adaptations (e.g., hypertrophy, strength, power, or endurance). However, the traditional %1RM-based approach also presents two main limitations:

1. The accurate prescription of intensity
2. Monitoring the daily performance fluctuations

Concerning the accurate prescription of intensity requires determination of the 1RM for each exercise, typically through incremental maximal tests. These tests are time-consuming, particularly when conducted across multiple exercises or with large groups of athletes, and they expose participants to elevated psychophysiological stress and increased risk of injury. Moreover, the 1RM is not a static measure: it fluctuates daily due to factors such as sleep quality, fatigue, and psychological stress, and it changes over time as training adaptations occur. As a result, repeated testing is required throughout the season to maintain accuracy, adding logistical challenges to program design. To address these limitations, research has focused extensively on alternative methods for estimating 1RM that are less time-consuming, less physically demanding, and safer, while still maintaining acceptable levels of validity and reliability. Although direct incremental testing remains the gold standard, two submaximal approaches are frequently reported in the literature:

- Repetition-to-failure prediction models[38]. In this method, the athlete performs repetitions to volitional failure with a given submaximal load. The number of repetitions achieved is then cross-referenced with established conversion charts to estimate the %1RM corresponding to the lifted load, and consequently the absolute 1RM. While supported by a considerable body of evidence, this method has important limitations. First, its accuracy decreases as the number of repetitions performed increases, meaning that estimates are less reliable at lower intensities. Second, inter-individual variability is significant: athletes with different training backgrounds and experience may perform markedly different numbers of repetitions at the same relative load, reducing the generalizability of predictive tables.
- Load–velocity profiling[39–42]. This approach is based on the well-established inverse relationship between load and barbell velocity: as external load increases, lifting velocity decreases in a predictable manner. By plotting multiple loads against their corresponding velocities, a load–velocity relationship can be generated. Among the various load–velocity methods to predict 1RM, those employing the minimum velocity threshold (MVT)[43], which represents the

velocity corresponding to 1RM, have demonstrated the highest reliability and practical applicability, particularly in high-performance settings. Despite its growing popularity and strong theoretical foundation, the load–velocity profiling method is not without limitations. These are particularly evident in free weight and lower-limb exercises such as the back squat, where factors like barbell path variability, technical execution, and inter-individual differences in lifting strategy can influence velocity measurements and reduce the accuracy of 1RM estimations[43]. Further details and a more in-depth discussion on load-velocity profiling and of these limitations will be provided in the following chapter[42].

While 1RM estimation methods may be valuable in specific phases of a training program, primarily as a substitute for direct incremental testing, they are not capable of detecting daily fluctuations in performance. This limitation highlights one of the major shortcomings of the fixed prescription model: the difficulty of monitoring training in real time and accounting for the athlete's actual readiness on a given day[36].

To overcome this challenge, several strategies have been proposed for assessing daily readiness and adapting training loads accordingly. These autoregulatory approaches can be divided into two categories:

1. Subjective methods, based on the athlete's perceived effort or fatigue, most commonly using the Rating of Perceived Exertion (RPE)[37] or Repetitions in Reserve (RIR)[44–46].
2. Objective methods, based on quantifiable data, typically involving barbell velocity and, more generally velocity-based training (VBT), which represents the central focus of this doctoral thesis and the related research work[36,47–49].

1.3 A first step towards autoregulation: The subjective approach

RPE has been defined as "the subjective intensity of effort, strain, discomfort, and/or fatigue that is experienced during physical exercise"[50,51]. The first validated and widely adopted scale was Gunnar Borg's 6–20 scale, introduced in the late 1960s[52]. This instrument was originally designed for aerobic exercise and anchored to heart rate responses, where a score of 6 corresponded approximately to 60 beats per minute at rest, and a score of 20 to ~200 beats per minute, typically representing maximal exertion. This early scale provided a simple, cost-free means of monitoring training intensity in real time and was subsequently adopted across multiple exercise modalities. A major development was the introduction of the 10-point category ratio scale (CR-10), validated initially for aerobic tasks[53] but later adopted in RT[54,55]. The increasing relevance of RPE in RT led to the development of the OMNI-RES scale[37], specifically designed for resistance exercise. This scale ranges from 0 ("extremely easy") to 10 ("extremely difficult") and includes pictorial anchors of a lifter handling progressively heavier barbells. Validation studies demonstrated positive correlations between OMNI-RES ratings and both blood lactate concentrations and total weight lifted[37,56], supporting its utility for prescribing and monitoring training intensity in RT. Another subjective autoregulation strategy, closely related to RPE, is the Repetitions in Reserve (RIR) method[57], which asks athletes to estimate how many additional repetitions they could have performed before reaching failure. Research has shown that RIR scores are strongly and inversely correlated with RPE, particularly in well-trained individuals[58]. However, novice lifters often display lower accuracy in estimating proximity to failure, leading to less reliable application of RIR-based strategies[58]. Recognizing the complementarity of the two approaches, Zourdos and colleagues proposed the RPE–RIR scale, integrating both constructs[59]. In this framework, each RIR value corresponds to a specific RPE rating. For example, prescribing a set of ten repetitions at 8 RPE (≈2 RIR) may allow coaches to standardize perceived effort across athletes more effectively than prescribing ten repetitions at 70% 1RM, which may represent different levels of exertion depending on individual capacity. Evidence suggests that the accuracy of the RIR-based RPE scale is compromised in novice lifters, during sets terminated far from failure, and in moderate- to high-repetition protocols. Nevertheless, when applied in experienced athletes under controlled conditions (low-to-moderate repetitions, close to failure), the RIR-based RPE scale provides a practical and flexible tool for autoregulation in RT.

Chapter 2: Velocity-Based Training: Fundamentals and prescription

2.0 The real deal: An objective autoregulation method: Velocity-Based Training

Before delving into the specific applications of VBT, it is essential to establish a basic understanding of the underlying physiological mechanisms. The theoretical foundation of VBT is rooted in a principle that has been recognized for nearly a century: the inverse relationship between load and muscle shortening velocity[60]. The first systematic investigations of this phenomenon were conducted by Hill, who described the load–velocity relationship in isolated muscle fibers or single myofibrils when tested in vitro[60]. These studies revealed a curvilinear, hyperbolic relationship between load and velocity, with distinct profiles depending on fiber type. While VBT shares this theoretical basis, there are important conceptual and practical distinctions. Unlike Hill's experiments, VBT evaluates the systemic output of multiple muscle groups acting in concert to move an external load. What is measured is not the velocity of individual fibers but the resultant barbell displacement velocity[36], which reflects the integrated neuromuscular performance of the athlete. Because of this, the load–velocity relationship observed in VBT is much more linear in nature. Indeed, numerous studies have demonstrated strong linear correlations between load and velocity, with coefficients of determination (R^2) frequently exceeding 0.95 when modeled with first-order linear equations[61–63]. This linearity provides a robust basis for practical application, as it allows coaches and practitioners to predict performance and adjust loads with high accuracy. Having clarified the theoretical underpinnings of the load–velocity relationship, VBT can now be introduced not only as a method for submaximal approach or monitoring tool, but also as a method of training prescription.

2.1 How to manage Velocity Based Training

The ability to monitor lifting velocity in real time offers a valuable means of assessing an athlete's daily readiness, thereby enabling the adjustment of external load to match the individual's current physiological and neuromuscular state[36,47–49]. However, for the data obtained to be valid and meaningful, it is critical that each monitored repetition is performed with maximal intent, that is, with the explicit effort to move the load as fast as possible during the concentric phase. Without maximal intent, velocity readings underestimate the lifter's true capacity, compromising both monitoring accuracy and training prescription.

The practical utility of VBT can be categorized into three main areas, each exploiting the information obtained from barbell velocity monitoring.

1. The first application, already introduced in earlier sections, concerns the estimation 1RM through submaximal incremental testing[39–42]. By monitoring the velocity of lifts at progressively higher loads, it is possible to predict 1RM without requiring athletes to perform maximal testing, which can be fatiguing, time-consuming, and potentially risky. More detailed insights into this topic and its limitations will be presented in the dedicated chapter.

2. The second application relates to real-time monitoring of athlete readiness[36,47,49,64,65]. By observing barbell velocity during warm-up or preparatory sets, practitioners can assess the daily condition of the athlete and adjust the prescribed load accordingly. This adjustment is achieved by comparing observed values against the individual load–velocity profile, thereby accounting for day-to-day fluctuations in performance capacity. In this context, prescribing velocity targets rather than fixed percentages of 1RM allows for a more individualized training stimulus, ensuring that strength, hypertrophy, or power goals are consistently addressed

despite variability in maximal performance. Once the appropriate load is identified through this method, training is typically prescribed using conventional approaches such as fixed repetitions, sets, or autoregulatory measures like RPE and RIR, rather than continuing to rely on velocity as the primary driver of prescription.

3. Finally, the third application involves the full prescription of training based directly on VBT parameters. Here, velocity is not only used to define intensity but also to regulate training volume[66–70]. Regarding intensity, the load–velocity profile enables practitioners to determine relative load as a percentage of 1RM in a manner that is exercise-specific and influenced by factors such as sex and training experience[42,61,63,71]. For volume regulation, the concept of velocity loss (%VL) is applied. This parameter represents the percentage decrease in barbell velocity from the first repetition of a set, with different %VL thresholds associated with distinct training adaptations. For example, prescribing a 20% VL requires the athlete to continue performing repetitions until barbell velocity drops below 80% of the initial repetition. If the first repetition of a squat is executed at 0.70 m/s, the set would terminate once velocity falls below 0.56 m/s. In this way, %VL provides a dynamic and individualized strategy to prescribe training volume while controlling for fatigue and ensuring specificity of adaptation. The magnitude %VL prescribed and achieved during a set plays a critical role in determining the specific physiological and performance adaptations elicited by RT. Evidence consistently shows that lower %VL values (10%) are associated with reduced metabolic stress and predominantly neuromuscular adaptations, including improvements in maximal strength and neural efficiency.[70] However, such low velocity losses generally produce minimal hypertrophic responses, making them less suitable for goals centered on muscle growth[70]. Moderate velocity losses (approximately 20–30%) appear to offer a more balanced adaptive profile[70]. Training within this range has been associated with significant increases in maximal strength and power output, while simultaneously promoting meaningful hypertrophic

adaptations. As such, this range is often recommended when the goal is to improve multiple performance qualities concurrently. Conversely, high velocity losses (≥40%) have been linked to the most pronounced hypertrophic responses, likely due to the greater metabolic stress and mechanical tension sustained over the course of a set[68,70]. However, these high levels of fatigue have also been associated with detrimental changes in neuromuscular function, such as reductions in rate of force development (RFD). For this reason, protocols involving large %VL thresholds are generally not recommended for athletes whose sport-specific performance depends heavily on rapid force production. Finally, %VL has been shown to correlate strongly with subjective measures of effort. Specifically, higher velocity losses are positively associated with ratings on the OMNI-RES scale, while exhibiting an inverse relationship with RIR[72,73]. In practical terms, as %VL increases, athletes report higher perceived exertion and a lower number of repetitions remaining, further reinforcing %VL as a valuable proxy for monitoring fatigue and internal load during RT[67,69].

2.2 Which velocity are we using and measuring?

Up to this point, the discussion has consistently referred to the term velocity. However, the term velocity can be overly broad, as several different metrics are commonly employed[36]. The three most frequently discussed and investigated in the literature are peak velocity, mean velocity (MV), and mean propulsive velocity (MPV)[74]. The purpose of this section is to clarify the distinctions between these variables and to discuss their practical implications, as well as how they can be reliably measured.

- Mean Velocity (MV).

  MV represents the average velocity of the barbell during the entire concentric phase of a lift. For instance, in a full squat, MV accounts for the complete motion from the bottom position to lockout, averaged across the concentric phase. MV, together with Peak velocity, was among the first metrics investigated in VBT research[36,75] and remains one of the most widely used references in both scientific studies and practical applications.

- Peak Velocity.

  Peak velocity refers to the maximal instantaneous velocity attained during the concentric phase of the lift. Debate has long surrounded the utility of Peak velocity compared to MV and MPV[74]. Evidence suggests that Peak velocity is generally a weaker predictor of performance in controlled dynamic exercises such as squats or presses. Conversely, Peak velocity is considered more reliable when analyzing ballistic movements (e.g., jumps, throws, or Olympic lift derivatives), where maximal acceleration and displacement are critical.

- Mean Propulsive Velocity (MPV).

  MPV was proposed as an alternative to MV. Like MV, it captures the entire concentric phase but excludes the so-called braking phase, in which the barbell is intentionally or unintentionally decelerated and acceleration falls below the gravitational constant.

Studies indicate that MV and MPV are largely interchangeable, with MPV showing slightly greater stability over time[64,76]. This distinction is particularly relevant in novice trainees, whose load–velocity profiles tend to shift substantially during the first weeks of training; these changes are more evident when using MV than MPV[76]. However, after an initial adaptation period, the differences between MV and MPV become negligible. Importantly, although the choice between MV and MPV is somewhat arbitrary, practitioners are advised to consistently use the same metric throughout monitoring to ensure comparability over time.

2.3 How to measure velocity?

Once the velocity variable of interest is selected, accurate measurement becomes essential[36,77,78]. The gold standard for velocity assessment is stereophotogrammetry, which provides highly precise kinematic data. However, this method is impractical for everyday training environments due to cost, time, and laboratory requirements. As a result, various portable technologies have been developed to measure barbell velocity in more ecologically valid settings such as gyms and training facilities. These technologies can be broadly divided into three categories: linear position or velocity transducers, accelerometers, and smartphone applications. Both smartphone applications and accelerometers represent a more affordable and widely available alternative[77–79], with some being free or low-cost. Nevertheless, they currently present notable limitations. Smartphone applications and accelerometer-based devices are often prone to errors, such as 'phantom repetitions'[80] where actual lifts are not detected, leading to data loss or they provide measurements with low and inconsistent accuracy. Some apps provide sufficient accuracy but do not allow real-time monitoring, as video analysis must be completed post hoc[80]. This limitation precludes their use for advanced prescription strategies such as velocity-loss thresholds, which require immediate feedback. Consequently, while smartphone applications and accelerometers may serve as a supplementary tool, they cannot yet be considered reliable standalone solutions for VBT monitoring or prescription. Linear Position Transducers (LPTs) and Linear Velocity Transducers (LVTs) represent the current field-based gold standard for measuring barbell velocity[79,81]. However, substantial variability exists among devices in terms of accuracy, precision, and reliability. Among the commercially available options, the T-Force system (LVT) has shown the highest levels of reliability for constrained movements such as those performed on a Smith machine, whereas GymAware (LPT) is considered the reference tool for free-weight exercises[81].

Despite their robustness, these devices are associated with extremely high costs, often exceeding 2,000 USD per unit. This economic barrier has driven the development of more affordable encoders, with recent models available for approximately 400–500 USD[78]. Nevertheless, while these lower-cost devices demonstrate moderate levels of accuracy and reliability, they still fall short of the gold standard systems[78]. Importantly, the price point remains relatively high when multiple devices are required simultaneously, as is typically the case in team sport environments. For this reason, there is a growing need to investigate and validate the accuracy of low-cost solutions currently available on the market. This issue will be discussed in greater detail in a dedicated chapter. Finally, the limitations of existing technology, together with the high costs of gold-standard devices, have fueled entire line of research exploring the ability of athletes to perceive barbell velocity without instrumentation[82–92]. This emerging field has been a central focus of my research activity and will represent the key theme in the present doctoral thesis.

Chapter 3: Perception of velocity and velocity loss

3.0 Is it feasible to prescribe a VBT program in the temporary absence of specific and reliable instrumentation?

Perception of Velocity (PV) refers to the ability of athletes to estimate barbell displacement velocity during resistance exercise. The first systematic exploration was carried out by Bautista and colleagues (2014)[92], who validated a generic velocity perception scale using the bench press and later applied it to the back squat in elite athletes[91]. In their studies, Bautista et al. investigated athletes' ability to perceive what they defined as the 'average velocity of the set,' referring to the mean velocity of all repetitions performed within a set. Their studies showed that athletes could estimate the average velocity of the set with reasonable accuracy in both exercises[91,92]. Nevertheless, average velocity integrates heterogeneous information, since the velocity of the first or fastest repetition is more closely linked to training intensity, whereas intra-set velocity loss is commonly used as an indicator of training volume. This distinction led to two separate lines of research:

1. One investigating PV as an estimate of intensity, focusing on the first repetition[82–85].
2. The other investigating perception of velocity loss (PVL)[88,90] or perception of velocity change (PVC)[87,89] as an estimate of volume, focusing on the perceived intra-set velocity loss.

3.1 Is it feasible to prescribe a VBT program in the temporary absence of specific and reliable instrumentation: Velocity Perception

Following Bautista's pioneering work, a substantial advancement in the study of PV was provided by Romagnoli and colleagues. Their research shifted the focus from the average velocity of a set, the parameter initially investigated by Bautista, to the mean velocity of single repetitions, with particular attention to the first two repetitions of a set[82–85]. This methodological choice allowed for a better assessment of the athlete's ability to estimate the variable most directly linked to training intensity. A key contribution of Romagnoli's work was the introduction of the Delta Score (Ds)[83,84], an index specifically designed to quantify the accuracy of PV. The Ds is calculated as the difference between the velocity perceived by the athlete (Vp) and the velocity measured via linear encoder (Vr), using the formula Ds = Vp – Vr. This innovation provided an objective and replicable metric to evaluate perceptual accuracy, thereby strengthening the methodological rigor of PV research. Romagnoli and colleagues also developed and validated a squat-specific PV scale[85], distinct from the generic one previously proposed by Bautista[91,92]. This new scale incorporated velocity ranges and exercise-specific verbal anchors, thereby aligning more closely with the load velocity relationship usually obtained during the squat. Such task-specific calibration enhanced the validity and practical utility of the instrument in applied training contexts. Another central finding from Romagnoli's investigations concerned the role of familiarization. Initial results suggested that a prolonged familiarization period (five weeks) led to significant improvements in PV accuracy and reduced the differences initially observed between the back squat and the bench press[82]. Subsequent studies, however, demonstrated that a much shorter familiarization process (four sessions across two weeks) was sufficient to achieve accuracy levels comparable to those reached after five weeks, thus making PV monitoring more accessible and feasible in practice[83,84]. Lastly, Romagnoli investigated whether physical or mental fatigue, conditions in which athletes might commonly find themselves when training at the end of the day, could negatively affect PV[83,84]. Controlled experiments showed that PV accuracy remained stable under conditions of both physical and mental fatigue, suggesting that it might be employed in more ecological settings, including real-world training scenarios.

3.2 Is it feasible to prescribe a VBT program in the temporary absence of specific and reliable instrumentation: Velocity Loss perception

In parallel, the volume-related line of research was initiated by Sindiani and colleagues[87], who introduced the concept of PVC. Their studies investigated whether athletes could detect changes in barbell velocity between successive repetitions, expressed as a percentage relative to the first repetition (e.g., if the first repetition was defined as 100%, subsequent faster or slower repetitions were expressed relative to this baseline). Their findings revealed that estimation errors increased as the number of repetitions progressed within a set, suggesting that PVC might only be reliable in short sets (approximately 4–5 repetitions)[87]. Additionally, athletes demonstrated greater perceptual accuracy in the bench press compared to the squat, possibly due to biomechanical or proprioceptive differences between the two exercises[87]. Lazarus and colleagues subsequently expanded this work, focusing on the role of familiarization in improving PVC accuracy[89]. By comparing pre- and post-familiarization trials, they demonstrated significant reductions in estimation error, with participants not only becoming more precise but also maintaining consistent accuracy even as the number of repetitions within a set increased. This suggested that familiarization plays a crucial role in enhancing perceptual sensitivity to intra-set velocity changes. More recently, Dello Iacono and colleagues[88] reframed the concept from PVC to PVL, evaluating whether athletes could identify the exact repetition at which a predefined percentage of velocity loss (%VL) occurred[88]. Results showed an average error of approximately one repetition across conditions, with intermediate loads (50–60% 1RM) producing more accurate estimates than either lighter or heavier loads. Lastly, De Silvia and colleagues[90] proposed a range-based approach to PVL (e.g., 15–30% VL), whereby any termination within this velocity-loss window was considered acceptable. Athletes correctly identified being within the target range in 50–75% of attempts, depending on load and exercise. However, test–retest analyses revealed limited reliability, indicating that while PVL shows promise, it requires further methodological refinement before it can be considered a robust tool for training prescription[90].

3.3 Is it feasible to prescribe a VBT program in the temporary absence of specific and reliable instrumentation: Current limitation in the framework of Perception of Velocity and Perception of Velocity Loss

As discussed in the previous two chapters, the research conducted so far on PV and PVL is undoubtedly promising and has clarified several key aspects of these constructs. However, certain elements remain insufficiently explored or not yet clearly understood in the current literature. These gaps represent the core for the aims and central outline of the present doctoral thesis. First, no study to date has precisely examined the true margin of error in PV estimation. Reporting only the mean Ds can be misleading, as it is influenced by both positive and negative values, thereby underestimating the actual magnitude of the error. Second, it is still unknown how long after the familiarization period the levels of PV and PVL remain stable. Third, the reason behind the relatively large standard deviation and high inter-individual variability commonly reported across PV studies has not yet been clearly identified. Finally, it remains unclear how physical and mental fatigue may influence PV and PVL under more ecologically valid conditions, compared to the controlled laboratory settings used in most prior investigations in PV.

3.4 Aim and outline

Based on the considerations discussed so far, the present thesis will be divided into two distinct sections. The first section aims to investigate the objective aspects related to Velocity-Based Training (aims 1 to 3), while the second section focuses on examining the subjective parameters associated with velocity perception (aims 4 to 7). Furthermore, a key objective of the present doctoral thesis is to investigate whether and how sex may represent a relevant variable for the prescription and monitoring of training when prescribed through a VBT approach.

1. To investigate whether and how the accuracy in predicting 1RM through load–velocity profiling can be improved by using the minimum velocity threshold in the back squat.
2. To examine whether and how mental fatigue negatively affects training sessions performed using the VBT approach.
3. To assess the validity of a new low-cost linear encoder for monitoring barbell velocity.
4. To examine whether the levels of accuracy in PV and PVL remain stable four weeks after the familiarization period.
5. To investigate the effects of physical and mental fatigue on PV and PVL.
6. To validate a new velocity perception scale specifically designed for the bench press exercise.
7. To investigate whether and how visual input can influence PV.

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Chapter 4: Common methodologies employed

Before examining the specific research activities that constitute the core of this doctoral dissertation, this chapter outlines several methodological aspects that are common to many of the studies presented herein. More precisely, these shared elements can be grouped into two main categories: (i) the familiarization with VBT to which participants were exposed across the various studies (Studies 2, 4, 5, 6, and 7), and (ii) the procedures used to assess the accuracy of PV and PVL (Studies 4, 5, 6, and 7).

Chapter 4.1: Common methodologies employed: The familiarization

The familiarization process consistently comprised four distinct sessions conducted over a two-week period. This procedure served a dual purpose: first, to familiarize participants with performing the lifting phase at the highest possible concentric velocity (Studies 2, 4, 5, 6, and 7); and second, to familiarize them to PV (Studies 4–7), as well as both PV and PVL (Studies 4 and 5).

In Studies 2, 4, and 5, the familiarization protocol was performed using the back squat exercise, which was subsequently employed in the testing sessions. The structure of this familiarization protocol is presented in the following tables

Day 1: Familiarization with heavy loads

Mean Propulsive Velocity (m/s)	Reps
>0.8	4
0.6-0.7	4
0.4-0.5	20%VL

0.4-0.5	40%VL
<0.4	20%VL
<0.4	40%VL

Day 2: Familiarization with medium loads

Mean Propulsive Velocity (m/s)	**Reps**
>1.0	4
0.8-0.9	20%VL
0.8-0.9	40%VL
0.6-0.7	20%VL
0.6-0.7	20%VL

Day 3: Familiarization with intermediate and heavy loads

Mean Propulsive Velocity (m/s)	**Reps**
>1.0	4
0.8-1.0	4
0.6-0.7	20%VL
0.6-0.7	40%VL
0.4-0.5	20%VL
0.4-0.5	40%VL

Day 4: 1RM test assessment protocol

Mean Propulsive Velocity (m/s)	**Load (Kg)**	**Reps**	**Rest (min)**
	20	5	3
>0.8	+20	3	3
0.6-0.7	+10	2	3
0.6-0.7	+5	1	5
0.4-0.5	2.5	1	5

In Studies 6 and 7, the familiarization procedures followed a similar structure to those previously described but employed different velocity ranges due to the use of the bench press exercise. Accordingly, exercise-specific velocity thresholds were applied. Moreover, percentage velocity loss (%VL) was not used to determine the number of repetitions, as the objectives of these studies did not include examining the PVL.

Day 1: Familiarization with heavy loads

Mean Propulsive Velocity (m/s)	**Reps**
Repetitions were performed at the highest possible concentric velocity using only the barbell load	6
0.9-1.0	3
0.6-0.7	3
0.4-0.5	2
<0.3	2

Day 2: Familiarization with medium loads

Mean Propulsive Velocity (m/s)	**Reps**
Repetitions were performed at the highest possible concentric velocity using only the barbell load	6
1.0-1.05	4
0.85-0.95	4
0.65-0.75	4

Day 3: Familiarization with light loads

Mean Propulsive Velocity (m/s)	**Reps**
Repetitions were performed at the highest possible concentric velocity using only the barbell load	6
>1.2	4
1.1-1.2	4
1.0-1.1	4

Day 4: 1RM test assessment protocol

Mean Propulsive Velocity (m/s)	**Load (Kg)**	**Reps**	**Rest (min)**

	20	5	3
>0.8	+20	3	3
0.5-0.8	+10	2	3
0.3-0.5	+5	1	5
<0.3	2.5	1	5

Chapter 4.2: Common methodologies employed: The PV and PVL assessment

As previously described (Chapters 3.1 and 3.2), the assessment of PV and PVL in the literature has typically relied on the Ds for PV and on a metric subsequently termed Vscore for PVL. In the present research, absolute values of these parameters are also considered for the first time. This approach allows not only an examination of their dispersion and central tendency but also an evaluation of the actual magnitude of error. The following sections provide a detailed description of how these metrics were calculated.

Ds is calculated as the difference between perceived velocity and real velocity (Ds = Vp - Vr), thereby preserving the sign of the error and indicating whether PV is overestimated (positive value) or underestimated (negative value). In contrast, |Ds| is derived from the absolute difference between Vp and Vr (|Ds| = |Vp - Vr|) and quantifies the magnitude of the error discarding its direction. This dual approach provides a comprehensive evaluation, with Ds revealing the error's direction and |Ds| offering a precise measure of its absolute magnitude. To evaluate the accuracy of PVL, a metric called the Vscore was used. The Vscore was defined as the difference between the number of repetitions performed by the participant (Np) and the number of repetitions required to reach the prescribed VL threshold (Nr) (Vscore = Np – Nr). Finally, consistent with the approach used and explained for Ds, the absolute Vscore (|Vscore|) was calculated to provide a more precise quantification of the error magnitude (|Vscore| = |Np - Nr|).

Table 1: How to assess Ds and |Ds|

Real Velocity (Vr-m/s)	Perceived Velocity (Vp-m/s)	DeltaScore (Ds)	Absolute DeltaScore (|Ds|)
0.78	0.70	-0.08	0.08
0.86	0.94	+0.08	0.08

Table 2: How to assess Vscore and |Vscore|

Repetition at which the prescribed %VL was reached (Nr)	Repetitions performed by the participant (Np)	Vscore	|Vscore|
8	9	+1	1
11	9	-2	2

When a participant terminated the set before reaching the prescribed %VL, a regression model was constructed between the number of repetitions performed and velocity measured at each repetition. Using the resulting equation, the first repetition at which the prescribed %VL would have been reached was subsequently estimated.

An example of the procedure described is presented in the following table and figure, in which the participant was instructed to reach a 20% VL

Table 3: Example of a set in which the participant did not reach the prescribed %VL.

Mean Propulsive Velocity (m/s)	**Percentage of velocity loss from the fastest repetition**	**Number of Repetition**
0.75	-	1
0.73	-2.6	2
0.71	-5.3	3
0.67	-10.6	4
0.63	-16	5
0.61	-18.8	6

In the presented set, the participant did not reach the target velocity loss (20%VL), stopping instead at 18.8%. To determine the repetition number that would have been required to attain the prescribed threshold, a linear regression was generated using the velocity of each individual repetition (x-axis) and the corresponding repetition number (y-axis). Using the resulting equation, we calculated the repetition at which the 20%VL would have occurred.

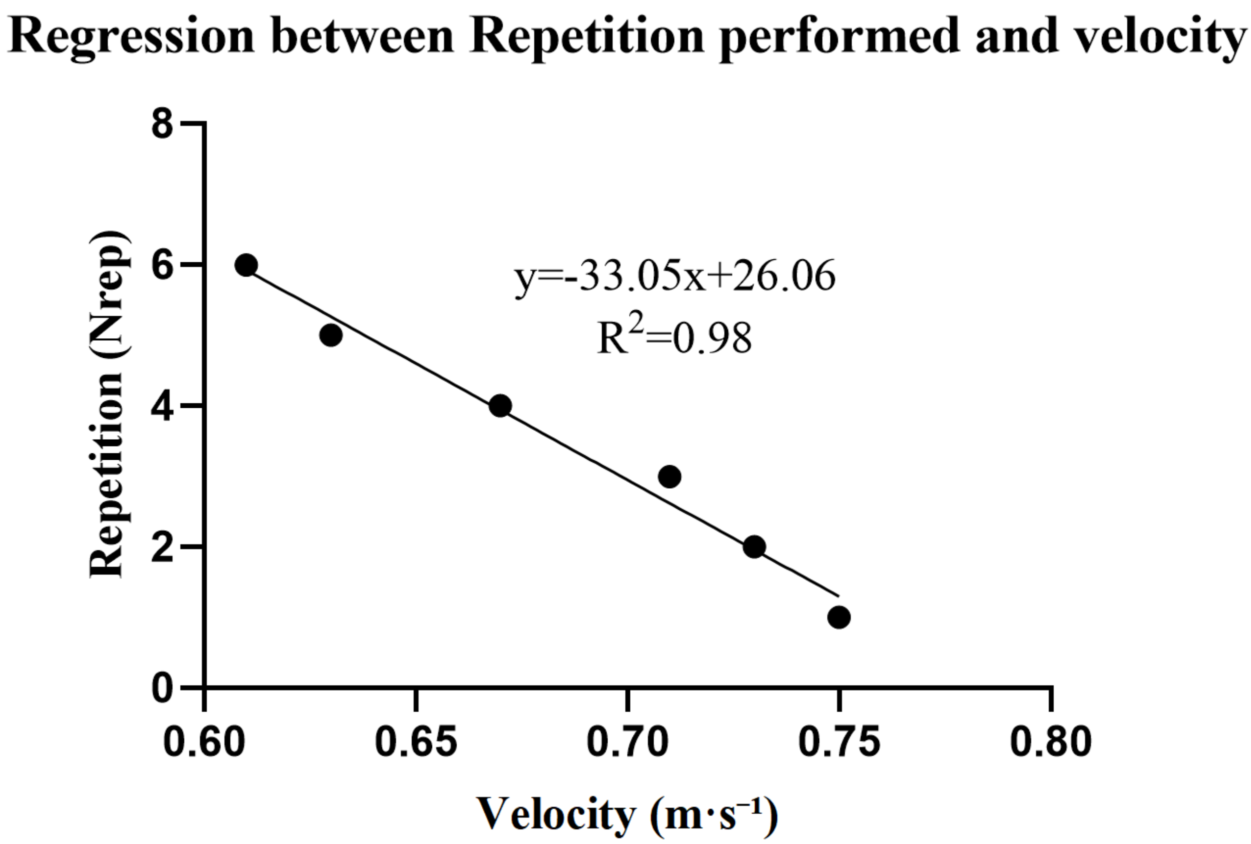

*Figure 1: Regression between number of repetitions performed and velocity (*m·s⁻¹)

Solving the equation shown in the figure, using the velocity corresponding to the 20%VL (0.60 m·s⁻¹) derived from the fastest repetition in the set (0.75 m·s⁻¹) used as an example, yielded a value of 6.2. Because fractional repetition cannot exist, any value exceeding a whole number was rounded up to the next integer; thus, in this case, the correct estimated repetition was 7. In conclusion, based on our data, the participant performed 6 repetitions (Np = 6), yet would have reached the prescribed %VL only at the seventh repetition (Nr = 7). Therefore, the Vscore (Np − Nr) equals −1, and the corresponding absolute Vscore (|Vscore|) equals 1.

Chapter 5: How does Load Selection and Sex Influence 1RM Prediction Using the Minimal Velocity Threshold During Free-Weight Back Squat?

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Title: How Does Load Selection and Sex Influence 1RM Prediction Using the Minimal Velocity Threshold During Free-Weight Back Squat?

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Abstract: The aim of the present study is to predict a 1RM through the load–velocity relationship using the minimum velocity threshold (MVT) in a free-weight back squat. Twenty-five males and twenty-five females performed a 1RM test during a free-weight back squat, based on which individual load–velocity relationships were created. Ten regression models to predict the 1RM were developed. The models included a two-point (mean propulsive velocity (MPV) ≈ 1 $m \cdot s^{-1}$; MPV ≈ 0.50 $m \cdot s^{-1}$) and a three-point linear equation (MPV ≈ 1 $m \cdot s^{-1}$; MPV ≈ 0.75 $m \cdot s^{-1}$; and MPV ≈ 0.50 $m \cdot s^{-1}$) with an MVT of 0.3 $m \cdot s^{-1}$and 0.4 $m \cdot s^{-1}$ and, additionally, an MVT of 0.25 $m \cdot s^{-1}$ for females. The repeated measures ANOVA revealed no significant differences between the predicted and measured 1RM in males using an MVT of 0.30 $m \cdot s^{-1}$ and in females with an MVT of 0.25 $m \cdot s^{-1}$. In contrast, models using an MVT of 0.30 $m \cdot s^{-1}$ in females underestimated the measured 1RM, as did those using an MVT of 0.40 $m \cdot s^{-1}$ in both sexes. It appears possible to accurately predict the 1RM during a free-weight back squat using the load–velocity relationship. However, it is important to avoid using loads with velocities higher than 1 $m \cdot s^{-1}$ for the regression models and to use different MVTs for males and females.

Keywords: sex difference; load–velocity relationship; velocity-based training; regression model; resistance training; injury prevention

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1. Introduction

Resistance Training (RT) has gained significant importance over the past decades due to its substantial benefits for performance [1]. It has been demonstrated that performing RT improves both strength and endurance parameters, leading to increased power, speed, balance, and coordination in athletes [2,3]. Today, RT is recommended by major global health organizations for most populations, including adolescents, healthy adults, and the elderly [4,5,6]. The most utilized method for prescribing RT sessions is known as the “traditional method” [7,8] that utilizes the percentage of the one-repetition maximum (% 1RM) to determine training intensity. For this reason, an incremental maximal test is necessary to establish 1RM [9], a test that is time consuming and presents several challenges, such as the physical and mental fatigue experienced by athletes [10], and the increased risk of injury during subsequent training days [11,12]. In order to minimize these risks and negative aspects of the 1RM test, recent studies have explored the possibility of predicting the 1RM through sub-maximal tests [10,13,14,15,16]. These investigations have focused on using velocity as a parameter to estimate intensity, based on the inverse relationship between load and velocity, first mentioned by Hill [17].

Recent findings have generated predictive equations for the 1RM for different populations, based on the relationship found between % 1RM and barbell velocity, both with the Smith Machine and free-weights [9,10,13,14,18,19]. One of the most studied and precise methods for predicting the 1RM utilizes the Minimum Velocity Threshold (MVT), which corresponds to the barbell's velocity at the 1RM for each specific exercise [10]. This method, commonly known as $1RM_{MVT}$, uses the exercise-specific MVT as the final data point in the regression model used to create the load–velocity relationship from which the 1RM is then estimated [10]. The accuracy of a 1RM prediction from the load–velocity relationship depends on the precision of these relationships [16], and it is crucial to use equations generated from individualized load–velocity relationships rather than generalized ones [20]. Additionally, it is important to consider the execution technique, which tends to vary with extremely light loads (<20%) and extremely heavy loads (>90%) [21]. Therefore, it is recommended to use loads between 20 and 90% 1RM to create the load–velocity relationship. Recent evidence suggests that using loads closer to 40% 1RM as the lightest load may lead to benefits in the accuracy of a 1RM prediction [21]. Various studies have also examined the impact of the number of loads on prediction accuracy. Using more than three loads offers no significant benefit in terms of accuracy compared to using two or three but considerably increases the test duration and fatigue [12,15].

Hence, in real training contexts, it is advised to use two or three reference loads, with these loads positioned at the two extremes of the load–velocity curve and, if used, a third point intermediate between the two extremes [22]. The study conducted by Hughes et al. [21] compared various methodologies for predicting a 1RM during a free-weight back squat, based on the load–velocity relationship: $1RM_{MVT}$, load at zero velocity, and the method based on the force–velocity curve [23]. The results confirmed that the most precise methodology is the $1RM_{MVT}$, demonstrating higher intersession reliability compared to the other tested methodologies and very strong correlations with the measured 1RM. However, despite the $1RM_{MVT}$ method being recognized as the most precise methodology for predicting a 1RM in a free-weight back squat, a recent review of the literature [10] concluded that it consistently overestimates the predicted 1RM compared to the actual measured value, questioning its reliability for accurate 1RM prediction. Additionally, since this method depends on MVT, and MVT has been primarily investigated in males [24], it is still questionable if and how potential differences between males and females in MVT might affect the accuracy of 1RM prediction. The few studies that have included female participants have reported inconsistent results, suggesting potential differences in MVT between males and females [24,25,26]. These differences need to be addressed to refine the $1RM_{MVT}$ method for broader applicability in a female population. Lastly, very recent studies have proposed the use of an "optimal" MVT, defined as the velocity that minimizes the error between the predicted and the actual measured 1RM [15,16]. However, since this value must be determined a priori through an incremental test, Chen et al. [15] recently suggested using a fixed MVT value of 0.40 $m \cdot s^{-1}$, which represents the average of the optimal MVTs previously observed. Nevertheless, although this optimal MVT has shown promising results in male subjects, it has never been tested in female athletes [15].

Therefore, the main aim of this research is to investigate the possibility of predicting the 1RM in the free-weight back squat using the $1RM_{MVT}$ methodology in both males and females by

(1) Comparing the use of two or three loads.

(2) Comparing differences between males and females.

(3) Evaluating the use of "Optimal MVT" of 0.40 $m \cdot s^{-1}$ in females.

We hypothesized that both the 2-point and 3-point models would successfully predict the 1RM using the aforementioned methodology. Furthermore, we hypothesized that differences between males and females in MVT would be significant and crucial for the accurate prediction of the 1RM. Lastly, we hypothesized that an MVT of 0.40 $m \cdot s^{-1}$ will significant underestimate the 1RM in females due to the important differences in the load–velocity relationship between males and females.

2. Methods:

All subjects performed a maximal incremental test on the free-weight back squat. Based on the test results, the load–velocity relationship was calculated for each subject. To predict the 1RM, four models were developed for males. The four models involved a two-point linear equation (Mean Propulsive Velocity (MPV) ≈ 1 $m \cdot s^{-1}$; MPV ≈ 0.50 $m \cdot s^{-1}$) and a three-point linear equation (MPV ≈ 1 $m \cdot s^{-1}$; MPV ≈ 0.75 $m \cdot s^{-1}$; and MPV ≈ 0.50 $m \cdot s^{-1}$), both generated with the literature-recognized MVT for males of 0.30 $m \cdot s^{-1}$ and with the "optimal MVT" suggested of 0.40 $m \cdot s^{-1}$. The four generated equations were then used to predict the 1RM using the $1RM_{MVT}$ method. For the female population, the same MVTs were used. In addition, if statistically significant differences related to MVT between males and females are found, such differences will be considered in order to create two additional regression models specifically for females. Such regression models, if needed, will be constructed using the mean MVT of female participants experimentally measured during the 1RM tests.

2.1. Subjects

The present study included 25 males (age: 26.75 years ± 5.84; body weight: 79 kg ± 10.47; height: 179 cm ± 6.89; 6.6 ± 3.67 years of RT experience; 1RM/BW: 1.63 ± 0.32; and MVT: 0.29 ± 0.04 $m \cdot s^{-1}$) and 25 females (age: 24.68 years ± 3.54; body weight: 56 kg ± 4.7; height: 164 cm ± 4.66; 4.64 ± 2.89 years of RT experience; 1RM/BW: 1.57 ± 0.27; and MVT 0.25 ± 0.04 $m \cdot s^{-1}$). The prerequisites for participation in the study required at least two years of experience in RT with the ability to perform each repetition at the highest possible velocity during the concentric phase, an age between 18 and 35 years, and the absence of current or previous injuries. Given their prior experience with both the exercise and the execution modality, the subjects attended the laboratory on a single occasion only. After being adequately informed about the procedures, risks, and ethical aspects of the study and receiving a copy of the explanatory information sheet, subjects signed informed consent and data processing forms. The proposed study protocol was drafted in accordance with the current revision of the Helsinki Declaration, which aims to ensure the protection of the rights, integrity, and well-being of the subjects involved in experiments and was approved by CAR 75/2021/est. Participation in the study could be discontinued at any time at the request of the subject and/or staff, without the need to provide reasons and without suffering any consequences.

2.2. 1RM Test

Prior to the test, subjects performed a dynamic warm-up consisting of mobility, stretching, and body weight exercises. Subjects performed a maximal incremental test on the free-weight back squat. They were instructed to perform each repetition as fast as possible. The initial load of the test was set at 20 kg for 5 repetitions. The load increased from 2.5 kg to 20 kg depending on barbell velocity (Table 1). During each repetition, verbal encouragement was provided from the researcher. The test ended when the athlete could not complete a single repetition with a given load [27]. The incremental test was recorded using a GoPro Hero 8 Black camera (GoPro, Inc., San Mateo, CA, USA) to ensure proper execution of the movement. The squat was performed to a depth where the hip crease descended below the level of the knee when viewed laterally [27]. At the end of each lift considered questionable, the footage was reviewed in slow motion by a certified FIPE (Italian weightlifting federation) referee. If the lift was deemed invalid, the participant was required to repeat the attempt with the same load before progressing to the next increment. A linear position transducer “Vitruve” (SPEED4LIFTS S.L., Madrid, Spain) was utilized to measure MPV, maximum velocity, range of motion, and power output. Recent research has demonstrated that it is reliable for low (MPV < 0.50 m·s^{-1}) [28] and intermediate velocities (MPV ≤ 1 m·s^{-1}) [28] when compared to other linear position transducers, considered a gold standard, and has shown one of the highest levels of reliability among all devices analyzed [28,29].

Table 1. 1RM incremental test protocol [28].

Velocity (m·s^{-1})	Load Increment (Kg)	Repetition	Rest (min)
	20	5	3
>0.8	20	3	3
0.6–0.8	10	2	3
0.5–0.6	5	1	3
<0.5	2.5	1	3

2.3. Sample Size Estimation and Justification

A priori power analysis was conducted to determine the required sample size for the present study. The primary analysis was the repeated measures ANOVA, involving a minimum of four within-subject comparisons. The analysis was performed using G*Power 3.1.9.7software, selecting the F test—repeated measures ANOVA, within factors, and with an a priori approach. The following parameters were set: a large partial eta-squared effect size ($\eta^2 = 0.20$), an alpha level of 0.05, statistical power ($1 - \beta$) of 0.90, and an assumption of sphericity violation. Based on these criteria, the estimated sample size was 18 male and 18 female participants. However, considering a secondary aim of the study was to explore potential sex differences in MVT, we opted to recruit a larger sample than required for the repeated measures ANOVA. A total sample size of 25 participants per group was recruited. This decision was supported by a priori power analysis conducted using G*Power (t test—means: difference between two independent means, two-tailed, and $\alpha = 0.05$). Assuming a large but realistic effect size (Cohen's d = 0.80), the minimum sample size required to achieve a statistical power of 0.80 was estimated to be 25 participants per group.

2.4. Statistical Analysis

Data were normally distributed, according to the Kolmogorov–Smirnov test ($p > 0.05$). An unpaired samples t-test was conducted between the MVT of males and females. A repeated measures ANOVA was performed to compare the predicted values from various models with the actual 1RM for both males and females. Sphericity was tested using Mauchly's test, and if found significant, the Greenhouse–Geisser correction was applied. Moreover, the validity and agreement of the predicted values with the actual 1RM for each model were investigated using Standard Error of Estimate (SEE), Coefficient of Variation (CV), Bland–Altman plots, and the Pearson correlation. SEE is calculated by taking the square root of the sum of the squared differences between the observed values and the predicted values, divided by the degrees of freedom. The CV was calculated as the ratio of the standard deviation of the predicted values from each model to their mean, both expressed as a percentage of the 1RM.

3. Results

Load–velocity profiles were created using MPV ≈ 1 $m\cdot s^{-1}$ and MPV ≈ 0.50 $m\cdot s^{-1}$ for the 2-point model and MPV ≈ 1 $m\cdot s^{-1}$; MPV ≈ 0.75 $m\cdot s^{-1}$; and MPV ≈ 0.50 $m\cdot s^{-1}$ for the 3-point model, which, according to the analysis, corresponded to 43.99 ± 6.2% 1RM, 67.86 ± 5.1% 1RM, and 86.18 ± 2.6% 1RM for males, and to 36.59 ± 7.21% 1RM, 60.34 ± 6.69% 1RM, and 79.52 ± 4.8% 1RM for females. The MVT was significantly different between males and females, $T(48) = -2.652$; $p = 0.011$, with an effect size of 1.00, where males showed a mean MVT of 0.29 ± 0.04 $m\cdot s^{-1}$, while females showed a mean MVT of 0.25 ± 0.04 $m\cdot s^{-1}$. Given the significant difference, two additional regression models with an MVT of 0.25 $m\cdot s^{-1}$ were considered for females. The Mauchly's test of sphericity was significant ($p < 0.05$) in the repeated measures ANOVA for both the males' and females' regression models; therefore, the Greenhouse–Geisser correction was applied.

The repeated measures ANOVA was significant in males' regression models, $F(2.29) = 264.103$; $p < 0.001$; and $\eta^2 = 0.917$. Post hoc pairwise comparisons revealed that statistically significant differences were found between both prediction models (two and three points) constructed with the MVT of 0.4 $m \cdot s^{-1}$ (i.e., Optimal MVT) and the regression model with 0.3 $m \cdot s^{-1}$ and real 1RM; meanwhile, post hoc pairwise revealed no differences between the regression model (both two and three points) with real 1RM. Moreover, the repeated measures ANOVA was significant in females' regression models, $F(2.080) = 532.789$; $p < 0.01$; and $\eta^2 = 0.957$. Pairwise comparisons revealed that statistically significant differences were found between both the prediction models (two and three points), both constructed with the MVT of 0.3 $m \cdot s^{-1}$ and MVT of 0.40 $m \cdot s^{-1}$, and the models built with the MVT of 0.25 $m \cdot s^{-1}$ and the actual 1RM ($p < 0.05$). Conversely, no statistically significant differences were found between the models constructed with the MVT of 0.25 $m \cdot s^{-1}$ and the actual 1RM ($p > 0.05$).

The SEE showed similar values across all models, except for the models built with the MVT of 0.4 $m \cdot s^{-1}$ for both sexes and for the model built with the MVT of 0.30 $m \cdot s^{-1}$ in females (Table 2). The Pearson correlation (r) revealed very high values for all models (Table 2). Finally, the CV reported very low values for all models (Table 2). Lastly, the Bland–Altman plots indicated a high degree of accuracy in all models used, except for the models where an MVT of 0.40 $m \cdot s^{-1}$ was applied (Figure 1 and Figure 2) and for the models in females where an MVT of 0.30 was used. In these cases, the models consistently tended to underestimate the actual maximal values (Figure 2).

Table 2. Accuracy of the different regression models.

Model	**SEE (Kg) − (95%CI)**	**Pearson r**	**CV (%)**
Males 2 points 0.4 $m \cdot s^{-1}$ MVT	10.09 − (−30.5; +11.49)	0.99	2.06
Males 3 points 0.4 $m \cdot s^{-1}$ MVT	9.86 − (−29.09; +10.87)	0.99	1.39
Males 2 points 0.3 $m \cdot s^{-1}$ MVT	2.86 − (−5.73; +5.85)	0.99	2.23
Males 3 points 0.3 $m \cdot s^{-1}$ MVT	1.98 − (−4.20; +3.96)	0.99	1.60

Females 2 points 0.4 $m \cdot s^{-1}$ MVT	12.61 − (−38.15; +13.93)	0.99	2.50
Females 3 points 0.4 $m \cdot s^{-1}$ MVT	12.62 − (−38.23; +13.89)	0.99	2.21
Females 2 points 0.3 $m \cdot s^{-1}$ MVT	4.20 − (−12.42; +4.88)	0.99	1.95
Females 3 points 0.3 $m \cdot s^{-1}$ MVT	4.26 − (−12.74; +4.80)	0.99	1.45
Females 2 points 0.25 $m \cdot s^{-1}$ MVT	1.76 − (−3.22; +4.04)	0.99	2.06
Females 3 points 0.25 $m \cdot s^{-1}$ MVT	1.21 − (−2.65; +2.63)	0.99	1.45

Table 2: SEE = standard error of estimate; CI = confidence intervals; CV = coefficient of variation; and MVT: minimum velocity threshold.

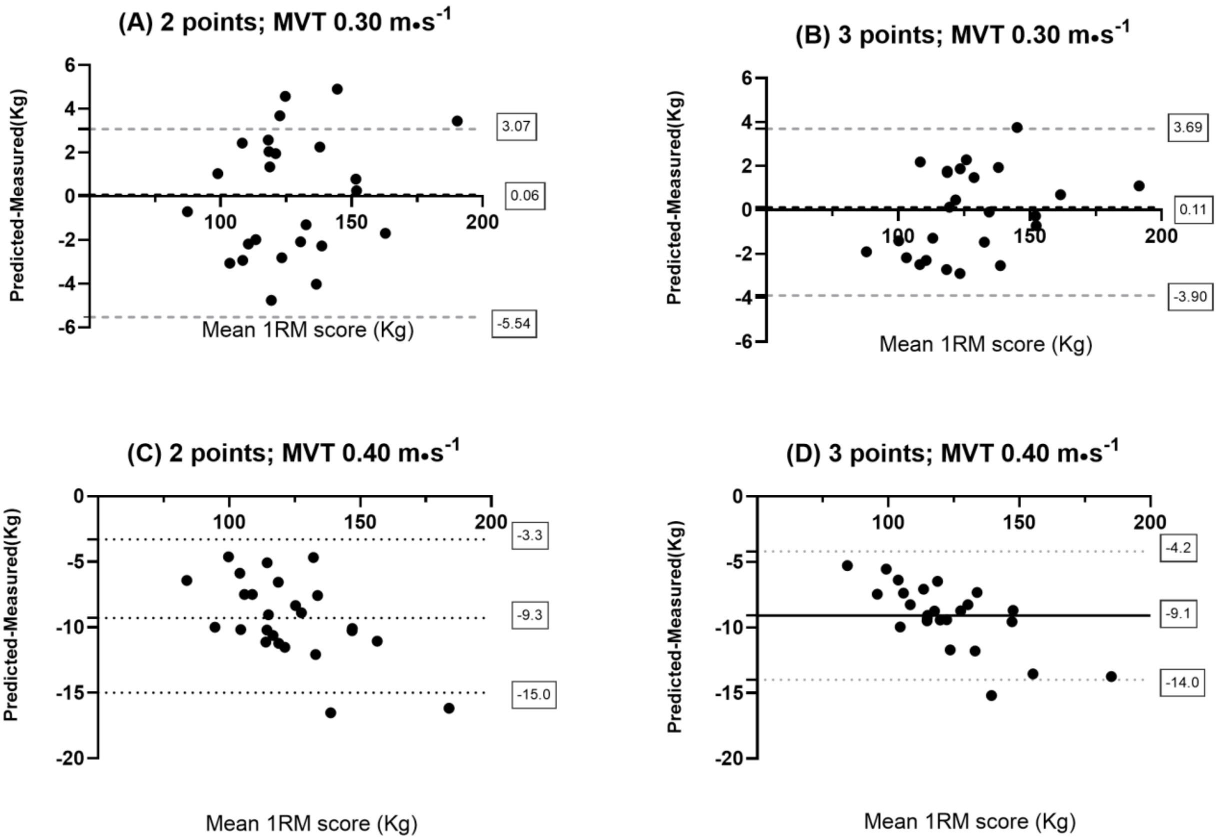

Figure 1. Bland–Altman plot results: (A) 2-point method in males with MVT of 0.3 m·s^{-1}; (B) 3-point method in males with MVT of 0.3 m·s^{-1}; (C) 2-point method in males with MVT of 0.4 m·s^{-1}; and (D) 3-point method in males with MVT of 0.4 m·s^{-1}.

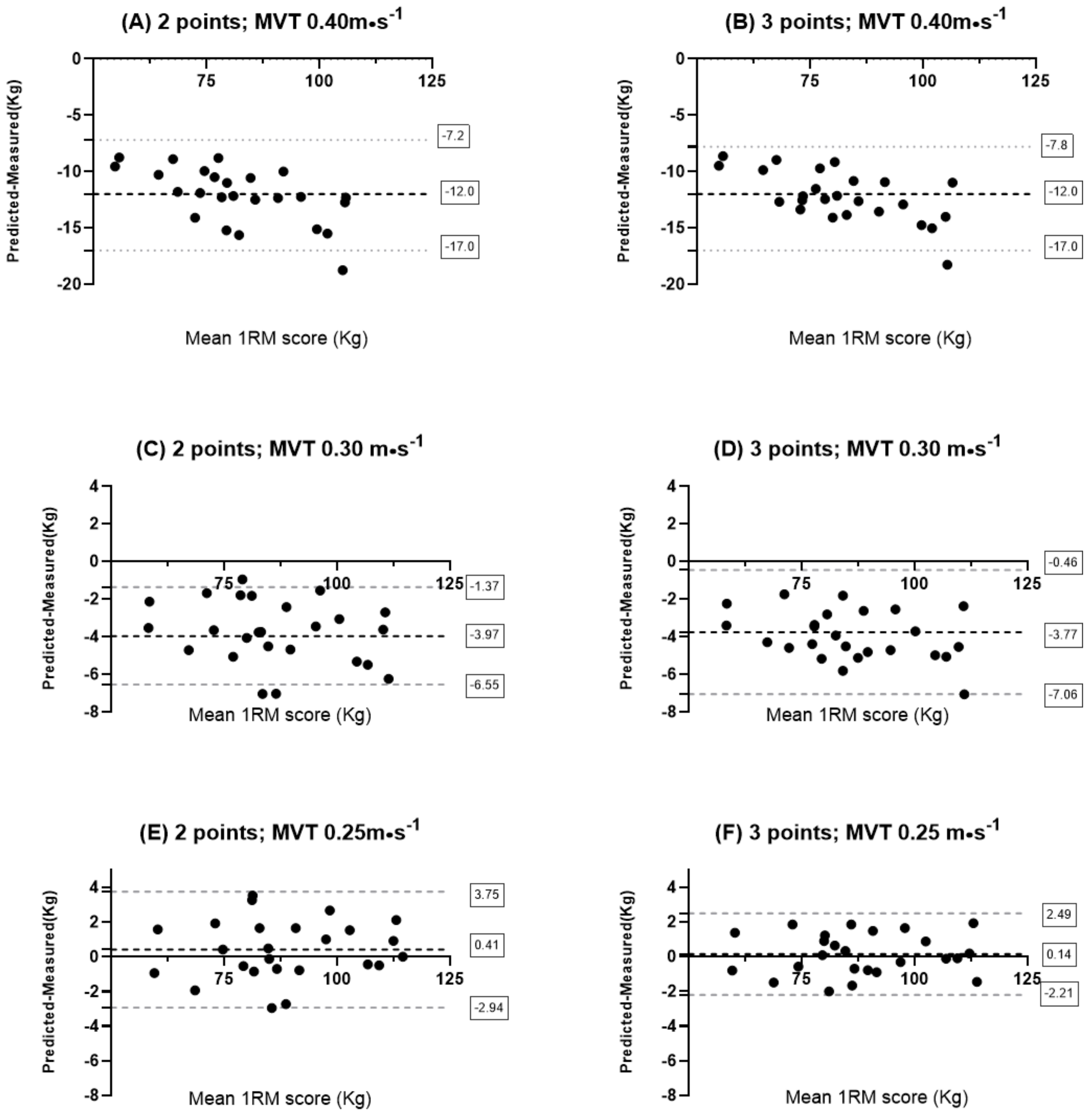

Figure 2. Bland–Altman plot results: (A) 2-point method in females with MVT of 0.4 m·s^{-1}; (B) 3-point method in females with MVT of 0.4 m·s^{-1}; (C) 2-point method in females with MVT of 0.3 m·s^{-1}; (D) 3-point method in females with MVT of 0.3 m·s^{-1}; (E) 2-point method in females with MVT of 0.25 m·s^{-1}; and (F) 3-point method in females with MVT of 0.25 m·s^{-1}.

4. Discussion

The present study had several goals: First of all, to predict the 1RM in the free-weight back squat using the $1RM_{MVT}$ method; secondly, to analyze any differences in using two or three loads to predict the 1RM; and third, to evaluate, if any, differences in MVT between males and females and to assess how these differences might impact the accurate prediction of the 1RM in a female population. The results of this study highlight that the 1RM was predicted with remarkable accuracy using both two and three loads, using a MVT of 0.30 $m \cdot s^{-1}$ in males and 0.25 $m \cdot s^{-1}$ in females, and without any significant difference between the two models in both males and females. Furthermore, the models built with the optimal MVT of 0.40 $m \cdot s^{-1}$ revealed the worst accuracy among all the models (Figure 1 and Figure 2) for both males and females. Moreover, females showed a lower MVT than males. More importantly, this difference was crucial in accurately predicting the 1RM in females. Notably, the most inaccurate models were the 2-point and 3-point regression models for females using an MVT of 0.30 $m \cdot s^{-1}$, which is typically the MVT measured in males during the back squat, and the models built with the optimal MVT of 0.40 $m \cdot s^{-1}$. These models consistently underestimated the 1RM, had significantly higher SEE (Table 2) than the other models, and showed statistically significant differences between predicted and measured values ($p < 0.05$). These findings are partially in contrast with the scientific literature.

4.1. Importance of Sex-Specific Minimum Velocity Threshold

Consistent with previous studies, this study observed that females exhibit a lower MPV compared to males for light and intermediate loads [25,30,31]. However, contrary to the literature, a significant difference at higher (>80% 1RM) and maximal loads (MVT) was found [24,25,26]. Regarding MVT, a recent meta-analysis concluded that current data indicate no significant difference between males and females [24]. However, it is essential to note the limited amount of scientific evidence currently available on this topic, indicating that it remains an area requiring further investigation. Furthermore, the few existing studies that have analyzed the differences between males and females included males with greater training experience compared to the females [24]. This could partly explain why no significant differences in MPV were found at high or maximal loads since greater experience is known to negatively correlate with velocities at very high and maximal loads (MVT), with more experienced athletes showing lower velocities than novices or amateurs at the same load when it exceeds 85% 1RM [32]. Our results, on the other hand, highlighted significant differences even at maximal loads (MVT) when training experience was similar between sexes.

4.2. Importance of Load Selection for 1RM Prediction

Regarding the prediction of the 1RM using MVT in the back squat, our results are in contrast with the current literature. A recent systematic review and meta-analysis by LeMense et al. [10] highlighted how the current results do not allow for a precise estimation of the 1RM in the free-weight back squat using the $1RM_{MVT}$ method. Specifically, they reported that this methodology systematically overestimates the 1RM, with an error ranging from 3.4 to 20.1 kg. A possible explanation for these results, as hypothesized by Hughes et al. [21], is that the velocity measured at very light loads, even those above 20% 1RM and up to 35% 1RM, is less reliable due to the high velocities achieved during the execution. The poor reliability of the measured velocity may be attributed to the fact that high velocities have been associated with lower coordination and a greater variety of muscle activation patterns [33,34]. A recent study [15] used loads corresponding to 40% 1RM and 90% 1RM for the two points employed to develop the regression models, as previously suggested by Hughes et al. [21], and suggested the use of an "optimal MVT" of 0.40 $m \cdot s^{-1}$ to reduce the margin of error between predicted and measured values. Despite the existing evidence in the literature, our study revealed contrasting results. This may be explained by the numerous precautions taken during testing. First, as suggested by Hughes [21] et al. and later adopted by Chen et al. [15], the lightest load used for the regression model was approximately 35% 1RM, while the heaviest load remained below 90% 1RM, lower even than that used by Chen et al. [15]. Moreover, it is worth highlighting that the most accurate models were those developed for the female participants (Figure 2), where in fact, the highest load used was even lower, around 80% 1RM.

5. Conclusion

This finding suggests that future studies might benefit from investigating the use of maximal loads around 80% 1RM in male populations as well. Secondly, an MVT of 0.25 $m\cdot s^{-1}$, which represents the mean value for the tested females, was used to generate the regression models for females. Finally, throughout the entire incremental test, the researchers ensured that a correct and standardized execution technique was maintained at each load through the recording and evaluation of the lift by a certified FIPE referee. In conclusion, different MVT values should be used for males and females to achieve an accurate prediction of the 1RM. Furthermore, the use of an "optimal MVT" may be beneficial in contexts where accurately and precisely assessing lifting technique throughout the entire incremental test proves challenging. Conversely, when such assessment is feasible, our findings indicate that using average MVT values of 0.30 $m\cdot s^{-1}$ for males and 0.25 $m\cdot s^{-1}$ for females yield significantly more accurate results. However, to ensure accuracy, it is essential to use velocities that do not exceed 1 $m\cdot s^{-1}$ for the first point of the regression model and to maintain proper technical execution during each repetition.

6. Practical Application

Based on the results presented, it appears feasible to effectively predict the 1RM during the free-weight back squat using MVT, with loads ranging between 40% and 90% 1RM and using an MVT of 0.25 $m\cdot s^{-1}$ for females. It is important to emphasize that these results were obtained from highly trained subjects (1RM/BW $\geq$ 1.5). Furthermore, based on our results, the recommended number of loads to be used for creating regression models to predict the 1RM is two or three loads. Additionally, sex should be considered, as there are differences in MVT between males and females. Finally, the level of the athlete is crucial, as it has been demonstrated that athletes with a 1RM/BW > 1.5 ratio exhibit more accurate 1RM predictions using the load–velocity profile. Nevertheless, based on the strong validity, reliability, and accuracy demonstrated by our regression models, it is reasonable to suggest that using minimum loads close to 35% 1RM may allow these results to be replicated in less trained subjects with a 1RM/BW < 1.5. Based on these findings, further studies using the same protocol with less trained subjects, both males and females, are necessary to confirm the presented results.

7. Limitation

The main limitation of this study may lie in the values selected as MVTs for the female sample. While a threshold of 0.30 $m \cdot s^{-1}$ was used for the male participants, consistent with the previous literature and supported by several studies [20], the 0.25 $m \cdot s^{-1}$ MVT adopted for the female participants was determined based on the characteristics of our specific sample, as previously described. Therefore, future research should investigate how generalizable this value is to a similarly trained and experienced female population.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: Data available on request due to restriction (privacy).

Conflicts of Interest: The authors declare no conflicts of interest.

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Chapter 6: Mental Fatigue Impairs Training Performance in Resistance-Trained Males and Females: A Velocity-Based Approach

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Title: Mental Fatigue Impairs Training Performance in Resistance-Trained Males and Females: A Velocity-Based Approach

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Abstract

The aim was to investigate the effect of mental fatigue (MF) on training volume and velocity of the first repetition (V1Rep) during back squat in males and females, using velocity loss (VL) to determine training volume. Nineteen resistance-trained athletes (10 males, 9 females) completed six training sessions. Four sessions served as familiarization with maximal intent velocity during the concentric phase and with different VL thresholds. In the final two sessions, conducted in a randomized order, participants performed eight squat sets. The first four sets were completed under rested conditions, while the subsequent four sets were performed following either a 45-minute AX-CPT test (MF

condition) or a 45-minute documentary (control condition; CC). The squat protocol involved two VL conditions (20% VL and 40% VL) and two loading intensities (60% and 80% 1RM). Training volume was defined as the sum of repetitions across the four squat sets. For training volume, a time*condition interaction emerged, indicating that the MF led to significant reductions in training volume in both sexes, whereas no significant changes were observed in the CC. Regarding V1Rep, a significant time*condition and time*sex*condition interaction was found, showing that the only MF condition induced a significant reduction in V1Rep in both males and females, with males exhibiting a greater decrease in velocity compared to females. These findings suggest that MF negatively affects resistance training sessions, with this effect potentially differing between sexes. Therefore, it is essential to avoid cognitively demanding tasks before resistance training or adopt strategies to counteract MF.

Introduction

Mental fatigue (MF) is a psychobiological state caused by prolonged periods of intensive cognitive demands[1,2] that is characterized by subjective feelings of tiredness and a lack of energy[1,2]. MF may arise in daily activities such as studying[3], working[4], and driving[5–7].

The psychophysiological factors behind MF and its effects on sports performance have been extensively studied[1,8,15–18]. It has been suggested that the mechanism underlying MF is the adenosine accumulation in the anterior cingulate cortex with a consequent inhibition of dopamine release[19]. This accumulation appears to be responsible for the increased Rate of Perceived Exertion (RPE) at the same external load observed in MF condition[8,14,17], with a consequent decrease in endurance performance despite no changes in physiological parameters[8,9,15,17]. In order to induce an adequate level of MF in a laboratory setting, an active cognitive task lasting at least 30 minutes is currently used[8,9]. Three of the most common tasks used to induce MF are the AX-Continuous Performance Test

(AX-CPT), Psychomotor Vigilance Task and the Stroop Task and all have been validated [6]. To assess the presence of MF both objective and subjective methods can be used[1,10,11]. The objective method, considered as the gold standard, is the electroencephalogram (EEG)[10,11]. On the other hand, subjective methods, while validated for detecting the presence of MF[6,10], cannot characterize it[10]; nevertless, they remain more practical in real training environments and are therefore often utilized[6,12,13]. Among these, the Visual Analogic Scale (VAS) has been shown to be the most practical and sensitive method for detecting small variations in MF[6,10]. However, monitoring MF alone is not sufficient, as it is also necessary to assess whether, and to what extent, the task performed may have influenced the participants' mood profile due to its monotony[9,14]. For this reason, in addition to the VAS, specific mood assessment tools such as the Brunel Mood Scale (BRUMS) or the Profile of Mood States (POMS) are commonly used, as well as a VAS specific for motivation[7]. Monitoring these specific scales allows for a more accurate determination of whether any observed effects following a MF-inducing task can be attributed directly to MF itself, rather than to changes in one or more dimensions of the mood profile, which may be altered as a result of the monotonous nature of the task[9,14].

Alongside the psychophysiological aspects, the specific effects of MF on physical performance have been studied[1,2,8,9,14]. MF reduces endurance[1,14], strength endurance[1,2], and sport-specific motor skill performance[8,9,16]. Instead, no alterations have been observed in explosive and maximal strength[14,20], or in high-intensity and maximal anaerobic performance [1,14,21]. Concerning endurance performance, it has been shown that MF leads to a reduced time to exhaustion[15,22], an increased completion time[14,23], a decreased self-paced velocity[14,24], and a decreased self-selected power output[14,25]. Meanwhile, regarding the effect of MF during resistance training sessions, several studies have examined its impact on training volume[1,2,12,13,17,26–29], reporting how in MF condition participants were able to perform less repetitions per set compared to a control condition in both upper and lower body exercise[2]. Notably, almost all the cited studies required participants to perform repetitions to muscular failure[2], a widely used method for prescribing training volume in RT sessions but requiring a long recovery period[30,31], often unsuitable for athletes[32]. For this reason, it is of considerable interest to investigate the relationship between MF and training volume using alternative prescription methods, such as the percentage of velocity loss (%VL) typically used during Velocity-Based Training (VBT) sessions[33]. VBT is an alternative approach for prescribing resistance training sessions, where each repetition is executed as fast as possible in the concentric phase of the movement[33]. VBT uses barbell velocity to adjust training intensity and %VL (i.e., the reduction in movement velocity within a set) to modulate training volume[33]. To the best of our knowledge, the only study that investigated the effects of MF on training volume prescribed using %VL showed no alteration in this parameter in either the bench press or the back squat with MF induced through smartphone use[29]. However, a recent study found no alteration in EEG signals when the MF was induced throughout smartphone use[34], supporting the interpretation that this method may induce a MF level not sufficient to alter training volume during a RT session.

Regarding the effect of MF on training intensity, three studies have investigated its influence on barbell's velocity during the first repetition (V1Rep)[12,27,35] highlighting conflicting results. Moreover, recent studies have reported a differential impact of MF between males and females on landing biomechanics[36], cycling time to exhaustion[37], and Motor Unit (MU) Firing Rate[38], hypothesizing sex-specific neuromuscular adaptation to MF as a possible explanation for these disparities[36,38]. However, to the best of authors' knowledge, no study has investigated the possible differential impact of MF on RT performance

Considering these gaps in the literature, the present study aims to investigate whether MF induced by AX-CPT test (a) reduces training volume in training sets executed until specific %VL thresholds are reached, (b) reduces the barbell velocity of the first repetition of each set (V1Rep), and (c) whether these possible alterations differ between sexes, as differences in under MF condition have been previously found in other studies[36,38]. In light of previous findings[2,27], our hypothesis is that training volume will be reduced, whereas V1Rep will remain unaltered.

Methods

Participants

The present study included a total of 19 well resistance trained subjects, ten males (age: 28.8 ± 2.9 years; body weight: 81.8 ± 7.6 kg; height: 1.80 ± 0.61 m; 6.8 ± 3.2 years of experience) and nine females (age: 25.2 ± 4.6 years; body weight: 62.4 ± 4.6 kg; height: 1.61 ± 0.6 m; 5.2 ± 2.6 years of experience). The inclusion criteria for participation in the study required at least two years of experience in resistance training, age between 18 and 35 years, and absence of current or previous injuries for at least two years. After being adequately informed about the procedures, risks, and ethical aspects of the study and receiving a copy of the explanatory information sheet, subjects signed an informed consent and data processing forms. The proposed study protocol was drafted in accordance with the current revision of the Helsinki Declaration, which aims to ensure the protection of the rights, integrity, and well-being of the subjects involved in experiments, and was approved by the Institutional Review Board (CAR 165/2023). Participation in the study could be discontinued at any time at the request of the subject and/or staff, without the need to provide reasons and without suffering any consequences.

Experimental Design

A randomized cross-over study design was employed to investigate the effects of MF on training volume and V1Rep. Participants visited the laboratory for a total of six sessions. During the first three sessions, subjects were familiarized with performing each repetition at maximal velocity to ensure more accurate and realistic measures of training volume in subsequent testing sessions. In the fourth session, an incremental 1RM test was performed. Lastly, in the final two sessions, conducted in a randomized order, participants completed four sets of squats at 60% and 80% of their 1RM, with both loads executed at 20% and 40%VL. Subsequently, they underwent a protocol designed to induce MF or a control condition (CC). Lastly, participants performed the same four sets of squats again.

Familiarization session

During the first testing session, participants signed informed consent and data processing consent forms before any data collection began. Subsequently, information on participants' height, weight, age, and resistance training experience was collected. In the first three sessions, after a standardized warm-up (i.e., 5 minutes of cycling at a self-selected pace and 10 minutes of self-selected mobility exercises) participants performed six sets of squats per session. During each session, the first two sets were used as a warm-up, with the load self-selected by the subject. Subjects were instructed to progressively increase the load after each set of warm-ups. Following the warm-up, four sets of squats were performed for each familiarization session. On day one, participants completed four sets of back squat with heavy loads (MPV < 0.5 $m \cdot s^{-1}$) at both 20% and 40% VL. On day two, four sets of back squat were performed with moderate loads (MPV between 0.6 $m \cdot s^{-1}$and 0.8 $m \cdot s^{-1}$), also at 20% and 40% VL. On day three, a combination of moderate loads (MPV ~0.7 $m \cdot s^{-1}$) and heavy loads (MPV < 0.5 $m \cdot s^{-1}$) was used for the four sets. On day four, participants performed a maximal incremental test on the back squat to calculate their 1RM[39]. The purpose of these familiarization sessions was to accustom participants to executing repetitions at maximal velocity and to ensure reliable measurements of training volume.

Mental fatigue and control condition session

In the final two sessions, performed in a randomized order, participants completed the previously mentioned standardized warm-up in both sessions, followed by three sets of back squats with a self-selected load. At the end of the warm-up protocol, subjects performed a total of four squat sets at

60%1RM and 80%1RM, each with 20%VL and 40%VL. The number of repetitions for each set were recorded. Subsequently, VAS scores related to MF and motivation, along with a POMS, were provided. Depending on the protocol scheduled for the day, participants then either performed 45 minutes of the AX-CPT test (MF protocol) or watched a 45-minute neutral documentary (CC)[7]. At the end of the AX-CPT test or the documentary, the VAS and POMS were provided again. Lastly, due to the 45 minutes of inactivity, subjects repeated the same standardized warm-up as previously prescribed, followed by four squat sets at 60%1RM and 80%1RM, each performed with 20%VL and 40%VL. Training volume was defined as the total number of repetitions across the four sets of back squat.

Mental fatigue assessment

To assess the presence of MF, two VAS scales were used, as previously described, one specifically targeting motivation and another assessing MF. Each VAS consisted of a 20 cm horizontal line, with the left end labeled either "no mental fatigue" or "no motivation," and the right end labeled "maximum mental fatigue" or "maximum motivation"[7]. Participants were instructed to place a vertical mark on the line to indicate their perceived level of MF or motivation[7]. The use of VAS is a validated and widely used method for verifying the presence of MF[6,10]. In addition to the VAS assessments, participants also completed a 32-item POMS questionnaire[40]. For each item, participants rated their response on a scale from 0 ("not at all") to 4 ("very very much so")[40]. The scores of each subscale were combined to obtain the total mood score (i.e. sum of negative subscales minus positive subscale). Instructions for completing the POMS were: "Please respond according to how you feel at this very moment."

Statistical Analysis

Data normality was tested using the Shapiro–Wilk test. Data are reported as mean ± standard deviation according to the distribution presented. Paired t-tests were employed to analyze the differences in between the Pre- and Post-intervention (MF or CC), for both the VAS and between POMS total mood score. A two-way mixed ANOVA (time*condition) performed with sex as a between-group factor analyzed the impact of the performed protocol on training volume. A two-way repeated mixed ANOVA (time*load*condition) with sex as a between-group factor analyzed the effect of the protocol on V1Rep. A significance level of $p < 0.05$ was adopted. Statistical analyses were performed in Microsoft Office Excel® (Microsoft Inc., Redmond, WA, USA) and SPSS v25 (SPSS Inc., Chicago, IL, USA).

Sample size estimation and justification

An a priori power analysis was conducted using G*Power (version 3.1.9.7; Universität Düsseldorf, Germany) to determine the required sample size for the mixed-model designs employed in the present study. Two main analyses were planned: the effect of the MF condition on training volume and on V1Rep, considering sex as a between-subject factor and, for V1Rep, load as an additional within-subject factor. For the analysis on training volume, the test family was set to F tests, and the statistical test specified as ANOVA: repeated measures (within–between interaction), with an alpha level of 0.05, two groups (sex), and four repeated measurements (2 conditions [MF, CC] × 2 time points [Pre, Post]). Based on an expected medium effect size ($f = 0.30$), $\alpha = 0.05$, and desired statistical power $(1 - \beta) = 0.80$, the required sample size was 18 participants (9 per sex). For the analysis on V1Rep, the test family was also set to F tests with the statistical test ANOVA: repeated measures (within–between interaction), using an alpha level of 0.05, two groups (sex), and eight repeated measurements (2 conditions [MF, CC] × 2 time points [Pre, Post] × 2 loads). Assuming an effect size of $f = 0.25$, $\alpha = 0.05$, and power $(1 - \beta) = 0.80$, the required sample size was 16 participants (8 per sex). Considering the physically demanding nature of the experimental protocol and anticipating potential dropouts (estimated n = 2), a total of 20 participants (10 males and 10 females) were recruited. The final analysis included 19 participants (10 males and 9 females), due to one dropout unrelated to the study procedures.

Results

The paired-samples t-test revealed a significant difference in VAS scores for perceived MF between Pre- and Post-AX-CPT ($p<0.05$), but not in the CC ($p > 0.05$; Figure 1). In contrast, motivation did not show any significant change either after the AX-CPT test or after the documentary (Figure 1). The paired-samples t-test conducted on the POMS total mood revealed no significant changes following either the AX-CPT test or the viewing of the documentary ($p > 0.05$; Figure 1)

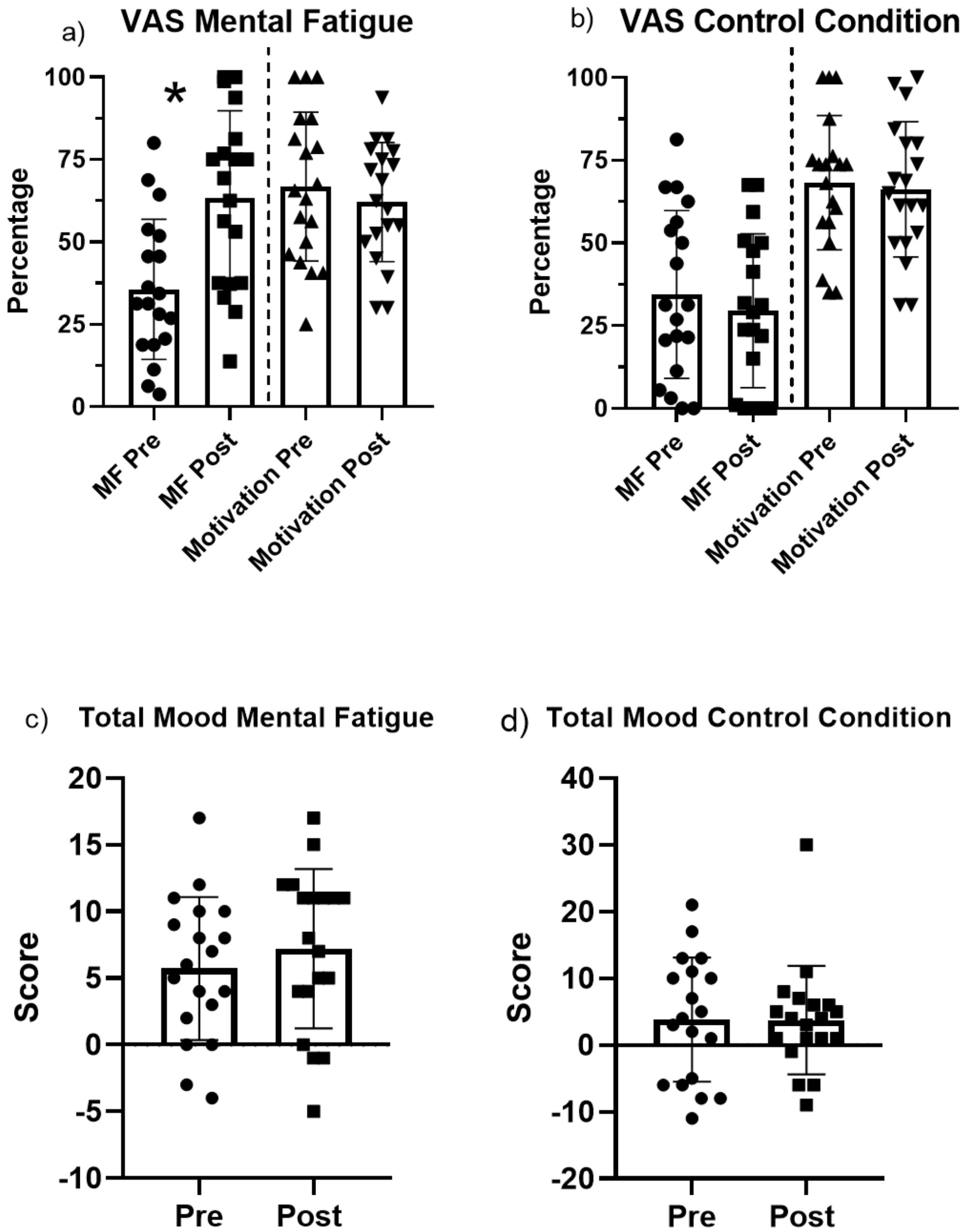

*Figure 1: Differences in VAS and POMS total mood scores Pre-Post MF and CC; a) Perceived MF and Motivation Pre-Post MF; b) Perceived MF and Motivation Pre-Post CC; c) POMS total mood scores Pre-Post MF; d) POMS total mood scores Pre-Post MF; * significant difference between Pre and Post condition*

The two-way mixed ANOVA for training volume revealed significant differences over time ($F(1) = 28.08$; $p<0.01$; $\eta^2=0.62$) and time*condition ($F(1) = 11.03$; $p<0.01$; $\eta^2=0.39$), but not for the time*sex interaction ($p=0.15$) or time*condition*sex ($p=0.18$). Pairwise post-hoc comparisons revealed that both males ($p = 0.03$) and females ($p < 0.01$) experienced a significant decrease in training volume in MF condition, with an average reduction of 4.5±4.6 repetitions in males (i.e. 15.0%) and 9.11±7.5 repetitions (i.e. 24.3%) in females (table 1), but not in the CC.

Sex	Condition	Total Volume Pre (N. rep)	Total Volume Post (N. rep)	Difference (N. rep)
Males	Mental Fatigue	29.6±8.3	25.1±7.4*	4.5±4.6
Females	Mental Fatigue	34.8±9.6	25.6±7.9*	9.1±7.5
Males	Control Condition	28.6±7.4	27.4±7.8	1.2±3.3
Females	Control Condition	33.8±10.1	32.8±9.5	1.0±3.3

*Table 1: Differences in training volume Pre-Post MF and CC; Total Volume Pre: total number of repetitions performed across the four set of squats Pre condition; Total Volume Post: total number of repetitions performed across the four set of squats Post condition; * significant difference between Pre and Post condition*

Regarding the two-way mixed ANOVA used to analyze the effect of MF on V1Rrep, a significant effect of time ($F(1)=36.11$; $p<0.01$; $\eta^2=0.50$), time*sex ($F(1)=6.49$; $p=0.01$; $\eta^2=0.15$), time*condition ($F1)=24.67$;$p<0.01$; $\eta^2=0.41$), time*condition*sex ($F(1)=4.22$; $p=0.047$; $\eta^2=0.11$ (Figure 2) were found, whereas other interactions were not significant ($p>0.05$) (Figure 2). The pairwise post-hoc comparisons for time*condition revealed that both males and females showed a significant decrease in V1Rep in MF condition but not in CC ($p<0.01$). The post-hoc regarding time*condition*sex revealed that females showed lower V1Rep in all conditions besides after MF protocol (Figure 2). Since no significance was found for time*load*condition or time*load*condition*sex, the presented figure will not take in consideration the load as parameter for simplicity.

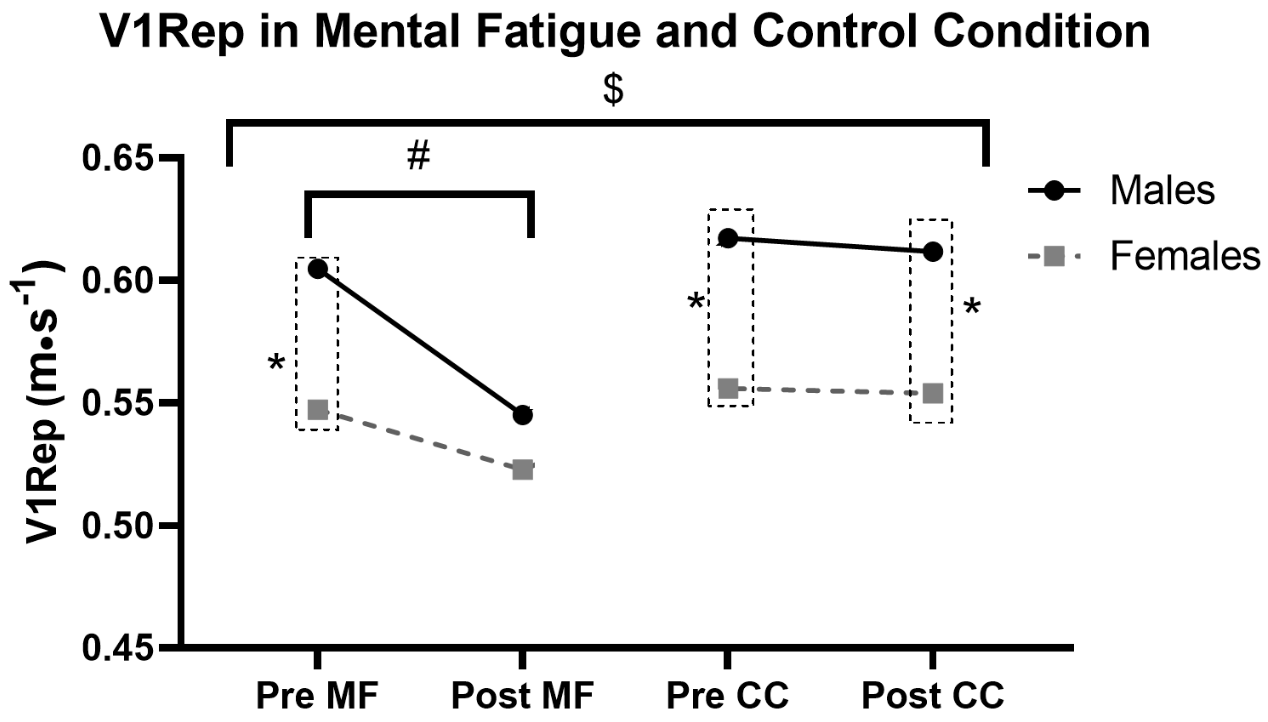

*Figure 2: Figure 2: Differences in V1Rep Pre-Post MF and Control condition; *= significant differences between males and females; #= significant interaction time*condition; $= significant interaction time*condition*sex*

Discussion

The present study aimed to investigate the effects of MF induced by AX-CPT test on training volume, prescribed using %VL, and training intensity monitored by V1Rep. A second aim was to evaluate the potential differences in MF response between sexes. The results showed that the AX-CPT test effectively induced MF as reported by the significant increase in VAS without changes in motivation or mood. As expected, a decrease in training volume was observed in the MF condition, in both females (24.3%) and males (15.0%) with no significant differences between sexes. Contrary to our hypothesis V1Rep was also influenced by the MF condition, showing sex-specific differences, with males exhibiting a significantly greater decrease in V1Rep (-10.2%) compared with females (-5.7%) (figure 2). These findings should be taken into account, considering that the performance alteration induced by MF could lead to suboptimal training adaptation in power-related parameters, such as Rate of Force development, according to recent findings[41].

Regarding training volume, our results are in line with a recent literature review finding that MF caused a reduction in training volume[2]. However, this was the second study to investigate the effect of mental fatigue on training volume prescribed using %VL. The main difference between the two studies is that the previous one induced mental fatigue through smartphone use[29], whereas the present study employed a 45-minute AX-CPT task. In contrast to Fortes et al. [29], who reported no changes in training volume in either the CC or MF, the present study found a significant reduction in training volume following MF condition. A possible explanation for these results is that, although smartphone use effectively increased the subjective feeling of MF[29], it may have been too low to reduce training volume. This hypothesis is supported by a recent investigation[34], which found that smartphone use induced lower levels of MF, without alteration of EEG activity, compared to the Incongruent stroop task designed to induce MF[34,42]. Regarding the other studies conducted on this topic, all investigations employed repetitions to muscular failure[13,17,26] and showed a consistent reduction in training volume with two exceptions[27,28]. In one, MF was induced by smartphone use[27] which, consistent with our hypothesis and, supported by recent findings[34], may not always elicit sufficient levels of MF to reduce training volume. Meanwhile, in the second one, the version of the Stroop task used may have been too short to induce MF (10 minutes)[28] according to previous findings which indicate that a task must last at least 30 minutes in order to induce mental fatigue[9]. Additionally, only one set until repetition to muscular failure was performed[28], which may have minimized the outcome.

Considering that MF does not influence maximal anaerobic performance[1,2], we expected to observe no alteration in V1Rep as previously reported[12,35]. Contrary to our hypothesis, a reduction in V1Rep was found after a MF task. These findings are in line with those of Alix-Fages et al[27], who reported a reduction in the fastest repetition in some of the sets performed only in the MF condition and not in the CC. In particular, in our results, males showed a greater decrease in V1Rep compared to females. A possible explanation for these sex-based differences could be attributed to different neuromuscular adaptation strategies to MF between sex, as previously suggested[36,38]. In particular, Kowalski et al.[38] found a reduction in MU firing rate in both sexes at 20% of maximal voluntary contraction (MVC), but only in males at 50% of MVC[38]. These results could suggest different alterations of MU firing rate in MF conditions between sexes during submaximal isometric contractions[38]. Possible differences in MU firing rate during non-maximal and maximal dynamic efforts, such as executing the concentric phase as fast as possible or landing, in MF condition have not yet been investigated. Thus, further studies are needed to confirm the hypothesis of sex-specific neural drive strategies under MF conditions during dynamic efforts, which could explain the sex-based differences observed in this study and the previous one[36].

Based on these results, we hypothesize that MF tends to reduce the sex-related differences generally observed under resting conditions, where females typically perform a higher number of squat repetition to reach the same %VL[43], while males usually achieve higher movement velocity at the same relative load[44], particularly at light to moderate intensities (<80%1RM)[43]. Further research is warranted to confirm or refute the proposed hypothesis.

Practical application:

MF negatively influences both training volume and training intensity when prescribed through %VL and V1Rep, respectively. Furthermore, MF appears to affect males and females differently. Males showed a greater reduction in V1Rep regardless of load. Meanwhile, both males and females showed reduction in training volume (Male = -15.0%; Female = -24.3%). Based on these results, coaches and athletes should avoid cognitively demanding tasks prior to training or adopting strategies[45] such as music[46], caffeine intake[47] or an aerobic warm up lasting around 15 minutes [46] to counteract MF and its negative effects. Future studies should further examine the sex-specific effects of mental fatigue, particularly how it appears to reduce the differences typically seen between males and females at rest.

Conclusion:

Mental fatigue induced by 45 minutes of the AX-CPT test negatively affected sports performance during resistance training sessions prescribed using a velocity-based approach, in both males and females, with sex-specific differences. Both males and females showed a reduction in training volume of 15.0% and 24.3%, respectively; however, males experienced a greater loss in V1Rep (Males: - 10.2%; Females: - 5.7%), regardless of the load used.

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Chapter 7: Exploring validity of the "Velocity Matters" Linear Position Transducer in the Back Squat and Bench Press

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Title: Exploring validity of the "Velocity Matters" Linear Position Transducer in the Back Squat and Bench Press

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Abstract

The purpose of the present study was to validate a new linear encoder by comparing mean velocity (MV) and peak velocity of two linear position transducers during free-weight back squat (SQ) and bench press (BP) exercises. Barbell velocity was simultaneously recorded using GymAware (reference standard) and Velocity Matters. Fifteen male participants completed two testing sessions, each involving six repetitions (two sets of three) across five velocity ranges: >1.00 to 0.51 $m \cdot s^{-1}$ in SQ and >1.02 to 0.40 $m \cdot s^{-1}$ in BP. In total, 180 repetitions per velocity range were analyzed for each exercise. Validity was assessed using Pearson's correlation (r), mean absolute error (MAE), Bland–Altman plots, intraclass correlation coefficient (ICC), and concordance correlation coefficient (CCC). Pearson's r indicated good to excellent correlations across all ranges and exercises. However, acceptable MAE values were found only for MV in SQ (except at >1.00 $m \cdot s^{-1}$) and for both MV and peak velocity in BP at velocities <0.70 $m \cdot s^{-1}$. Despite acceptable MAE in some cases, Bland–Altman analyses revealed systematic underestimation by Velocity Matters, with wide limits of agreement, up to −0.08 $m \cdot s^{-1}$ in SQ and −0.09 $m \cdot s^{-1}$ in BP, even where MAE was acceptable. ICC values were generally >0.70 but showed wide confidence intervals, indicating high uncertainty. CCC values were consistently poor (<0.90) across all velocity ranges and both exercises, except for peak velocity in the lowest velocity range during BP. In conclusion, Velocity Matters may be cautiously used to monitor MV during SQ at velocities <1.00 $m \cdot s^{-1}$, but it does not provide sufficient accuracy for use in BP across any load.

Introduction

Velocity-based training (VBT) is a method for prescribing and monitoring resistance training sessions that has grown in popularity in recent years[1,2]. Effective implementation requires that the concentric phase of each repetition be executed with maximal intent. Typically, the velocity of the first repetition is used to modulate training intensity[1], while the decrement in velocity within a set serves to regulate training volume[1]. Three velocity metrics are commonly used within the VBT framework[1]: mean velocity (MV), mean propulsive velocity (MPV), and peak velocity. MV represents the average velocity of the barbell throughout the entire concentric phase, measured from the start of the concentric phase until the barbell reaches its maximum height[1]. MPV is defined as the average velocity during the portion of the concentric phase in which the acceleration of the bar remains greater than gravitational acceleration[1]. Peak velocity, on the other hand, refers to the maximal instantaneous velocity reached by the barbell during the concentric phase[1]. While peak velocity is commonly used for monitoring velocity during ballistic movements[1], MV and MPV are typically preferred for non-ballistic ones[1]. Thus, devices to measure barbell velocity are essential for an accurate prescription during VBT[3,4]. In this regard, three-dimensional motion capture, such as "Vicon", is considered the gold standard for assessing barbell velocity[3]. However, the camera setup for this method is very expensive, as well as impractical for real training settings[4]. Therefore, other devices such as Linear Position Transducers (LPTs), Linear Velocity Transducers (LVTs), Inertial Measurement Units (IMUs), and Smartphone APPs have been widely used as alternatives for prescribing VBT sessions[4,5]. For this reason, the validity and reliability of all these devices have been investigated in order to give important feedback to strength training coaches[5,6]. Among the available technologies suitable for field-based practice, IMUs and most smartphone applications fail to meet acceptable validity thresholds across the full load–velocity spectrum[4,5]. Furthermore, while some applications are capable of providing accurate data, they do not offer real-time feedback, which significantly limits their applicability in practical settings[5,7]. For this reason, current research supports the use of LVTs and LPTs as the preferred tools for accurate training prescription [3,4]. Although both LPT and LVT use a cable attached to the barbell, they rely on two different methods to determine movement velocity[8,9].Concerning LVT, it provides velocity measurements by recording the electrical signals generated proportionally to the cable's extension velocity[8,9]. Instead, LPTs calculate movement velocity based on the recorded displacement of the cable[8,9]. Due to their high accuracy and the possibility to provide real-time velocity feedback, GymAware (LPT) and T-Force (LVT) have been used as gold standards to assess the validity and reliability of other devices when 3D motion capture is not available[10–12]. In particular, T-force provides more accurate velocity data during exercises performed on the Smith machine[6,9] . However, GymAware appears to be more accurate for free barbell exercises, as it can distinguish between the cable's horizontal and vertical displacement[6]. Unfortunately, the costs of these two devices remain too expensive (>2000$)[4,13,14] for the majority of the strength and conditioning coaches, especially if more than one is needed such as in team settings. For this reason, recently, a new low cost LPT named 'Velocity Matters', is available on the market at an approximate cost of 300 USD. Despite its growing popularity, no studies have yet assessed its validity. Therefore, the present study aims to verify the validity of Velocity Matters in providing MV and peak velocity metrics during two free barbell exercises: Bench Press (BP) and Back Squat (SQ).

Material and Methods

Participants

The present study included a total of 15 well resistance trained males classified as tier 2 according to Mckay et al.[15] (age: 25.4 ± 3.1 years; body mass: 80.7 ± 9.3 kg; height: 1.80 ± 0.05 m; 5.8 ± 2.8 years of experience). Inclusion criteria were: a minimum of two years of resistance training experience, age between 18 and 35 years, and absence of musculoskeletal injuries in the year preceding the study. Prior to participation, all subjects were fully informed about the procedures, potential risks and ethical considerations of the study and received a detailed information sheet. Written informed consent and authorization for data processing were obtained from each participant. The study was conducted in accordance with the latest revision of the Declaration of Helsinki, which is designed to safeguard the rights, well-being, and dignity of individuals participating in research, and received approval from the appropriate Institutional Review Board (CAR 165/2023).

Procedures

Participants visited the laboratory on two separate occasions. During the first session, they provided informed consent and received a detailed information sheet outlining the study procedures and testing protocols. Anthropometric measurements were then collected. In both sessions, participants performed free-weight back squats and bench press. For each exercise, they completed two sets of three repetitions, separated by three-minute rest, across five distinct velocity ranges (squat: velocity range 1: >1.00 $m \cdot s^{-1}$; velocity range 2: 1.00–0.87 $m \cdot s^{-1}$; velocity range 3: 0.87–0.75 $m \cdot s^{-1}$; velocity range 4: 0.75–0.63 $m \cdot s^{-1}$; velocity range 5: 0.63–0.51 $m \cdot s^{-1}$; bench press: velocity range 1: >1.02 $m \cdot s^{-1}$; velocity range 2: 1.02–0.86 $m \cdot s^{-1}$; velocity range 3: 0.86–0.70 $m \cdot s^{-1}$; velocity range 4: 0.70–0.56 $m \cdot s^{-1}$; velocity range 5: 0.56–0.40 $m \cdot s^{-1}$). The selected velocity range corresponds to relative load zones ranging from 30% to 85% of one-repetition maximum (1RM), based on exercise-specific load–velocity relationships defined in the literature[16,17]. Lighter loads were excluded as they are rarely used during typical training sessions[5], while heavier loads were avoided to prevent excessive fatigue that could impair the following set[5]. The loads were determined on the first testing day based on the participants' self-reported 1RM. If the selected load resulted in a movement velocity outside the target velocity range, it was subsequently adjusted and the set was repeated. On the second testing day, the same loads identified in the initial session were used. The GymAware device, considered the gold standard in this study, was used as the reference to verify whether the selected loads fell within the intended velocity range. In total, across the two testing sessions, 900 repetitions per exercise were analyzed, with 180 repetitions recorded for each velocity range. Two different devices were used in the study: GymAware (gold standard; (GymAware PowerTool, Kinetic Performance Technologies, Canberra, Australia) and Velocity Matters (, Green Wellness, Novara, Italy). The two devices were placed on metal plates on the same side of the barbell, positioned side-by-side to prevent potential misalignment between devices during the data collection.

Statistical Analysis

The validity of MV and peak velocity values provided by Velocity Matters was analyzed. Data distribution was tested for normality using the Shapiro–Wilk test, which confirmed normal distribution ($p > 0.05$). Validity was assessed separately for exercise and for velocity range. For the validity analysis, all 180 data points collected per velocity range across the two testing days were analyzed together. Validity was assessed using Bland–Altman plots, mean absolute error (MAE), mean absolute percentage error (MAPE), Pearson's correlation coefficient (r), coefficient of determination (R^2), intraclass correlation coefficient (ICC; model 2, form 1), and Lin's concordance correlation coefficient (CCC). The ICC was interpreted as poor when <0.50, moderate between 0.50 and 0.75, good between 0.75 and 0.90, and excellent when >0.90[18]. The CCC was considered poor when <0.90, moderate between 0.90 and 0.95, substantial between 0.95 and 0.99, and almost perfect when >0.99[19]. Pearson's r was interpreted as trivial when <0.10, small between 0.10 and 0.30, moderate between 0.30 and 0.50, high between 0.50 and 0.70, very high between 0.70 and 0.90, and nearly perfect when >0.90. Validity was considered acceptable when MAE was below 0.05 $m \cdot s^{-1}$ (~5%1RM), ICC was greater than 0.75, r> 0.70 and CCC was greater than 0.90. Lastly, it was required that the Velocity Matters device did not miss the measurement of any repetition for each velocity range tested in both exercises.

Results:

Free Weight Back Squat:

During the back squat validity assessments, no repetitions were missed at any velocity range. The mean values of MV and peak velocity for each velocity range and device are presented in Table 1. Velocity Matters reported similar MAE and MAPE across the 5 different velocity ranges used and showed greater precision in MV compared to peak velocity (table 1). Pearson's correlation coefficient

(r) showed values ranging from very high (0.823) to nearly perfect (0.926) in MV (Table 1), while all values in peak velocity fell within the nearly perfect correlation range (>0.90).

Mean Velocity						
	GymAware ($m \cdot s^{-1}$)	**Velocity Matters ($m \cdot s^{-1}$)**	**MAE (Mean±SD)**	**MAPE(Mean±SD)**	**Pearson r**	**Coefficient of determination (R^2)**
VR1	1.09±0.06	1.04±0.05	0.06±0.03	5.0±2.3%	0.871	0.76
VR2	0.95±0.03	0.91±0.04	0.04±0.02	4.3±1.9%	0.823	0.68
VR3	0.82±0.03	0.78±0.04	0.04±0.02	4.6 ±1.9%	0.901	0.81
VR4	0.69±0.04	0.66±0.04	0.04±0.01	5.4±2.1%	0.926	0.86
VR5	0.57±0.04	0.54±0.05	0.04±0.02	6.5±2.8%	0.924	0.85
Peak Velocity						
	GymAware ($m \cdot s^{-1}$)	**Velocity Matters ($m \cdot s^{-1}$)**	**MAE (Mean±SD)**	**MAPE(Mean±SD)**	**Pearson r**	**Coefficient of determination (R^2)**
VR1	1.86±0.13	1.76±0.12	0.11±0.05	5.8±2.3%	0.925	0.85
VR2	1.69±0.10	1.59±0.10	0.10±0.03	5.8±1.7%	0.926	0.86
VR3	1.53±0.11	1.45±0.09	0.09±0.04	6.0±2.4%	0.907	0.82
VR4	1.43±0.10	1.33±0.09	0.09±0.03	6.5±2.0%	0.957	0.91
VR5	1.33±0.10	1.24±0.10	0.09±0.03	6.9±2.5%	0.932	0.87

Table 1. Differences between GymAware and Velocity Matters in free weight back squat. VR1: Velocity range >1.00 m·s-1; VR2: Velocity range 1.00–0.87 m·s-1; VR3: Velocity range 0.87–0.75 m·s-1; VR4: Velocity range 0.75–0.63 m·s-1; VR5: Velocity range 0.63–0.51 m·s-1; MAE: mean absolute error; MAPE: mean absolute percentage error.

The Bland–Altman plots indicate that Velocity Matters systematically underestimates MV (Figure 1). A similar underestimation is observed for peak velocity, although with a larger margin of error. Notably, unlike the MV results, the peak velocity analysis shows several data points falling well outside the 95% limits of agreement, indicating the presence of potential random errors.

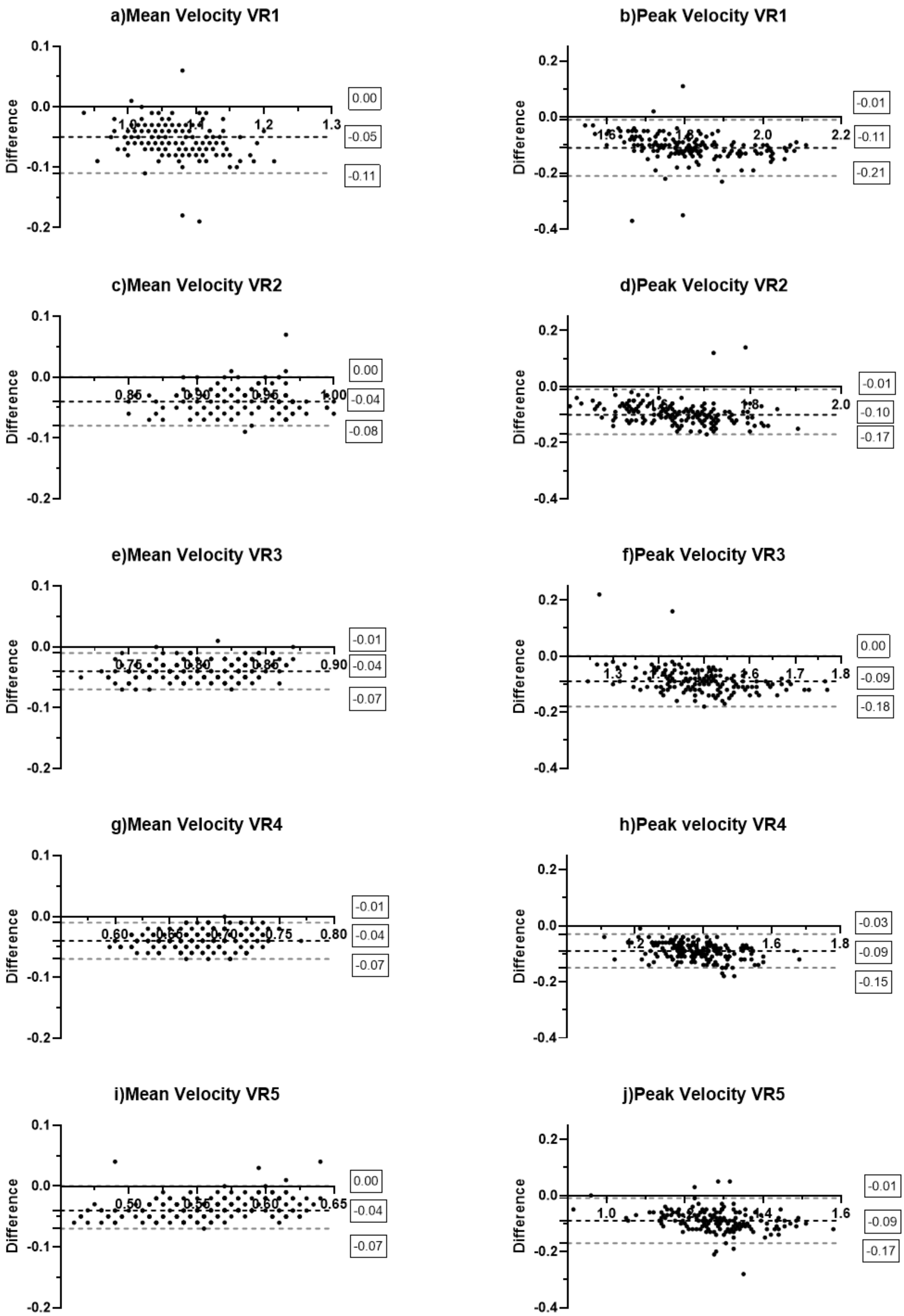

a)Mean Velocity VR1
Difference
0.00
-0.05
-0.11
b)Peak Velocity VR1
-0.01
-0.11
-0.21
c)Mean Velocity VR2
0.00
-0.04
-0.08
d)Peak Velocity VR2
-0.01
-0.10
-0.17
e)Mean Velocity VR3
-0.01
-0.04
-0.07
f)Peak Velocity VR3
0.00
-0.09
-0.18
g)Mean Velocity VR4
-0.01
-0.04
-0.07
h)Peak velocity VR4
-0.03
-0.09
-0.15
i)Mean Velocity VR5
0.00
-0.04
-0.07
j)Peak Velocity VR5
-0.01
-0.09
-0.17

Figure 1. Bland Altman Plot Velocity Matter-GymAware in free weight back squat. VR1: Velocity range >1.00 m·s-1; VR2: Velocity range 1.00–0.87 m·s-1; VR3: Velocity range 0.87–0.75 m·s-1; VR4: Velocity range 0.75–0.63 m·s-1; VR5: Velocity range 0.63–0.51 m·s-1.

The ICC for MV ranged from moderate (0.656) to good (0.818) (table 2), whereas all ICC values for peak velocity fell within good (>0.70) (table 2). However, notably wide 95% confidence intervals were observed (table 2). Finally, for the CCC, poor values were reported across all analyzed velocity range, with values of 0.691 or lower for both MV and peak velocity at all velocity ranges (table 2).

Mean Velocity				
	Back Squat		**Bench Press**	
	ICC (95%CI)	**CCC (95%CI)**	**ICC (95%CI)**	**CCC (95%CI)**
VR1	0.727(−0.183 - 0.916)	0.570 (0.501-0.632)	0.314 (−0.131 - 0.665)	0.185 (0.138 – 0.230)
VR2	0.656 (−0.187 – 0.887)	0.486 (0.414-0.552)	0.507 (−0.139 - 0.819)	0.338 (0.276 – 0.396)
VR3	0.731 (−0.144 – 0.922)	0.575 (0.509-0.634)	0.641 (−0.173 - 0.883)	0.470 (0.399 – 0.535)
VR4	0.760 (−0.120 – 0.934)	0.611 (0.549-0.667)	0.750 (−0.165 - 0.916)	0.599 (0.525 – 0.663)
VR5	0.818 (−0.155 – 0.949)	0.691 (0.632-0.742)	0.800 (−0.083 - 0.933)	0.665 (0.595 – 0.726)
Peak Velocity				
	Back Squat		**Bench Press**	
	ICC (95%CI)	**CCC (95%CI)**	**ICC (95%CI)**	**CCC (95%CI)**
VR1	0.802 (−0.149 - 0.945)	0.668 (0.606- 0.721)	0.701 (−0.115 - 0.914)	0.538 (0.475 – 0.596)
VR2	0.780 (−0.133 – 0.940)	0.638 (0.577- 0.692)	0.850 (− 0.100 - 0.955)	0.738 (0.682 – 0.785)

VR3	0.786 (−0.169 – 0.938)	0.640 (0.576-0.695)	0.917 (0.046 - 0.976)	0.846 (0.809 – 0.876)
VR4	0.793 (−0.092 – 0.947)	0.656 (0.599-0.706)	0.944 (0.704 - 0.978)	0.893 (0.862 – 0.917)
VR5	0.803 (−0.137 – 0.947)	0.669 (0.610-0.721)	0.967 (0.823 - 0.987)	0.935 (0.915 – 0.950)

Table 2: Intra Class Correlation and Concordance correlation coefficient results. ICC: Intra Class Correlation; CCC: Concordance correlation coefficient; CI: confidence interval

Bench Press results:

During the bench press validity assessments, the Velocity Matters device failed to record 49 out of 900 repetitions, corresponding to 5.4% of the total. Of these 49 unrecorded repetitions, 6 occurred at velocity range 1, 6 at velocity range 2, 13 at velocity range 3, 9 at the velocity range 4, and 15 at velocity range 5. The mean values of MV and peak velocity for each velocity range and device are presented in Table 3. Velocity Matters reported lower MAE in velocity range 3 to velocity range 5. Moreover, greater precision in MV compared to peak velocity was found only at velocity range 1 and velocity range 2 (table 3). Pearson's correlation coefficient (r) showed values ranging from high (0.628) to very high (0.851) in MV (Table 3), while all values in peak velocity fell within the nearly perfect correlation range (>0.90).

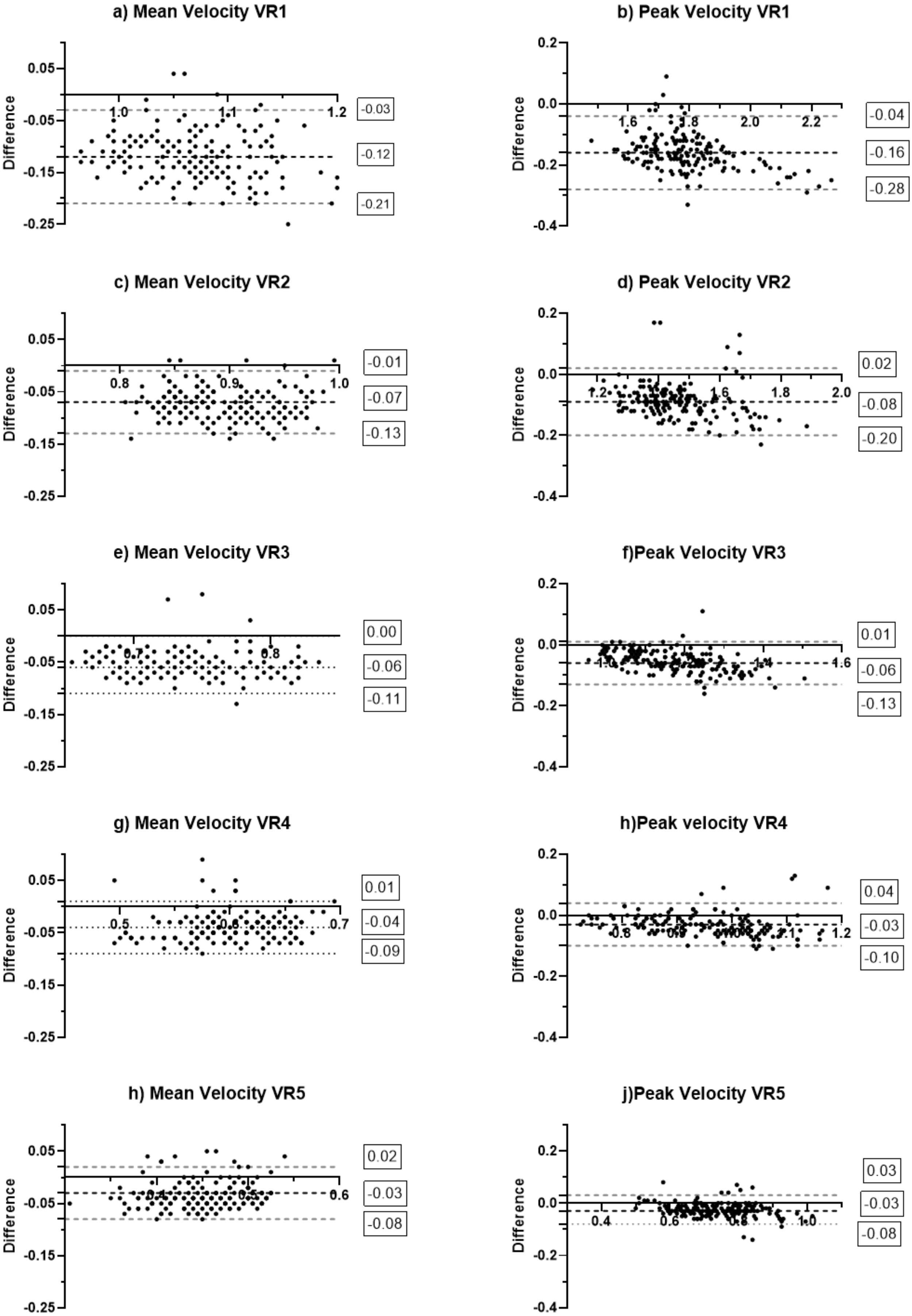
Mean Velocity						
	GymAware ($m \cdot s^{-1}$)	**Velocity Matters ($m \cdot s^{-1}$)**	**MAE (Mean±SD)**	**MAPE(Mean±SD)**	**Pearson r**	**Coefficient of determination (R^2)**
VR1	1.12±0.05	1.01±0.05	0.12±0.04	10.5±3.7%	0.628	0.39
VR2	0.93±0.05	0.86±0.05	0.08±0.03	8.0±3.0%	0.785	0.62

VR3	0.77 ±0.05	0.71±0.04	0.06±0.02	7.4 ±2.6%	0.831	0.69
VR4	0.61±0.04	0.57±0.05	0.04±0.02	7.1±3.2%	0.826	0.68
VR5	0.47±0.04	0.43±0.05	0.04±0.02	8.3±3.9%	0.851	0.72
Peak Velocity						
	GymAware ($m \cdot s^{-1}$)	**Velocity Matters ($m \cdot s^{-1}$)**	**MAE (Mean±SD)**	**MAPE(Mean±SD)**	**Pearson r**	**Coefficient of determination (R^2)**
VR1	1.87±0.15	1.71±0.13	0.16±0.05	8.6±2.7%	0.920	0.85
VR2	1.50±0.13	1.41±0.12	0.10±0.04	6.3±2.6%	0.911	0.83
VR3	1.20±0.12	1.14±0.10	0.06±0.03	4.6±2.4%	0.961	0.93
VR4	0.97±0.10	0.93±0.10	0.04±0.03	4.2±2.5%	0.941	0.89
VR5	0.75±0.10	0.72±0.10	0.03±0.02	4.0±2.8%	0.966	0.93

Table 3. Differences between GymAware and Velocity Matters in free weight bench press. VR1: Velocity range >1.02 m·s-1; VR2: Velocity range 1.02–0.86 m·s-1; VR3: Velocity range 0.85–0.70 m·s-1; VR4: Velocity range 0.70–0.56 m·s-1; VR5: Velocity range 0.56–0.40 m·s-1; MAE: mean absolute error; MAPE: mean absolute percentage error.

The ICC for MV ranged from poor (0.314) to good (0.800) (Table 2), whereas for peak velocity, values ranged from good (0.701) to nearly perfect (0.967) (Table 2). However, notably wide 95% confidence intervals were observed (Table 2). Lastly, CCC indicated poor agreement across all tested loads for both MV and peak velocity (<0.90), except for peak velocity at velocity range 5, which showed a higher value (0.935) (Table 2)

The Bland–Altman plots (Figure 2) show that Velocity Matters systematically underestimates MV. A comparable trend is observed for peak velocity, though with a larger margin of error. In contrast to the MV data, the peak velocity analysis displays several points beyond the 95% limits of agreement, suggesting the presence of potential random errors.



a) Mean Velocity VR1
Difference
-0.03
-0.12
-0.21
b) Peak Velocity VR1
Difference
-0.04
-0.16
-0.28
c) Mean Velocity VR2
Difference
-0.01
-0.07
-0.13
d) Peak Velocity VR2
Difference
0.02
-0.08
-0.20
e) Mean Velocity VR3
Difference
0.00
-0.06
-0.11
f)Peak Velocity VR3
Difference
0.01
-0.06
-0.13
g) Mean Velocity VR4
Difference
0.01
-0.04
-0.09
h)Peak velocity VR4
Difference
0.04
-0.03
-0.10
h) Mean Velocity VR5
Difference
0.02
-0.03
-0.08
j)Peak Velocity VR5
Difference
0.03
-0.03
-0.08

Figure 2. Bland Altman Plot Velocity Matter-GymAware in free weight bench press. VR1: Velocity range >1.02 m·s-1; VR2: Velocity range 1.02–0.86 m·s-1; VR3: Velocity range 0.86–0.70 m·s-1; VR4: Velocity range 0.70–0.56 m·s-1; VR5: Velocity range 0.56–0.40 m·s-1.

Discussion

The aim of the present study was to assess the validity of Velocity Matters, a new affordable LPT, during two free weight exercises: SQ and BP. For each exercise, the accuracy of both MV and peak velocity was tested across five velocity ranges spanning from >1.00 m·s-1 to 0.51 m·s-1 for the SQ, and from >1.02 m·s-1 to 0.40 m·s-1 for the BP.

Validity of Velocity Matters for monitoring Back Squat:

In the case of SQ, Velocity Matters satisfied the first validity criterion, as it consistently recorded all repetitions without omissions. This could represent an advantage over IMUs, where missed repetitions have previously been reported[4].

Regarding the MV, the analysis revealed, for all velocity ranges, a Pearson's r ranging from high to nearly perfect (Table 1), which, together with good R^2 values (Table 1), suggests that the measurements of two devices are highly correlated. Moreover, an acceptable MAE was found for all velocity ranges, except for the lightest one, which exceeded the acceptable error threshold of 0.05 $m \cdot s^{-1}$ (Table 1). However, although the ICC for MV ranged from moderate to good, wide 95%CI were observed for all velocity ranges (Table 2), which may reflect a high degree of measurement variability, also evident in the broad limits of agreement (LoA) (lower LoA ranging from -0.07 $m \cdot s^{-1}$ to -0.11 $m \cdot s^{-1}$) in the Bland–Altman analysis (Figure 1). Lastly, poor values of CCC were found for all velocity ranges, indicating systematic bias between the measurements of Velocity Matters and GymAware (Table 2). These findings may indicate uncertainty in the agreement between the two LPT measurements and suggesting possible limited validity of the Velocity Matters.

For peak velocity, Pearson's r and R^2 demonstrated nearly perfect correlations between devices (Table 1). However, unacceptable MAE values were found for all velocity ranges (Table 1), suggesting that Velocity Matters is not a valid device for prescribing VBT sessions based on peak velocity. Moreover, the wide 95%CI observed in the ICC, despite good values (Table 2), may indicate high error variability, which is also evidenced by the broad limits of agreement in the Bland-Altman plots (Figure 1). Moreover, the Bland-Altman analysis showed that Velocity Matters systematically underestimates the peak velocity. Finally, as with MV, poor CCC values for peak velocity were found for all velocity ranges (Table 2). However, it has to be highlighted that peak velocity is a valid metric for ballistic exercises [1], making this a more negligible limitation in the context analyzed in the present study.

In summary, for the SQ, Velocity Matters appears to be a suitable device only for monitoring MV when target velocities are <1.0 $m \cdot s^{-1}$, as indicated by the MAE (0.04 $m \cdot s^{-1}$) (Table 1). However, due to the wide 95% limits of agreement (lower limits ranging from -0.07 to -0.11) (Figure 1), and to the wide 95%CI of the ICC (Table 2), caution should be taken when using Velocity Matters to monitor MV, regardless of the target velocity.

Validity of Velocity Matters for monitoring Bench Press:

For BP, the first validity criterion was not met by the Velocity Matters device, as it failed to record 49 out of 900 repetitions, corresponding to 5.4% of the total.

Concerning the MV, a high to very high correlation between the two devices was observed, as indicated by Pearson's r and R^2 (Table 3). This result, together with the high to nearly perfect correlation found for the SQ, shows that the MV measurements of the Velocity Matters are correlated with those of the GymAware regardless of the exercise performed. Moreover, an acceptable MAE was found for velocity range 4 and velocity range 5(Table 3). The ICC was also investigated for the MV of this exercise, showing values ranging from poor (velocity ranges1-3) to good (velocity ranges4-5) (Table 2). However, the wide ICC 95% CI observed across all velocity ranges (Table 2), together with the wide 95% limit of agreement observed in the Bland-Altman plots for all velocity ranges (Figure 2), may reflect a high degree of measurement variability, suggesting overall low accuracy. Moreover, the Bland-Altman analysis revealed that, as in the SQ, Velocity Matters systematically underestimate MV (lower limits ranging from -0.08 to -0.21) (Figure 2); in addition, in the BP, the presence of random errors was also observed (Figure 2). Lastly, as with the SQ, the CCC observed for MV during the BP was poor across all velocity ranges (Table 2).

Regarding the peak velocity, Pearson's r together with R^2 showed nearly perfect correlation across all velocity ranges between the two LPT (Table 3), highlighting the consistent pattern of error. Moreover, for velocity ranges 4 and 5, nearly perfect ICC values (Table 2), acceptable 95% CI (Table 2) and acceptable MAE values (Table 3) were observed. Moreover, for velocity ranges 4 and 5, also the CCC values met the validity criteria (Table 2), as they were considered moderate. For the other velocity ranges (1-2-3) a wide 95% CI and poor CCC were found (Table 2). However, the large dispersion of errors, mainly underestimation, and the presence of random error shown in the Bland-Altman plot (Figure 2), suggests that Velocity Matters is not a fully adequate device for monitoring peak velocity, even at slower velocities. However, as previously stated, the validity of peak velocity in the context of non-ballistic exercises remains limited [1].

In summary, for BP although some velocity ranges showed acceptable MAE for both MV and peak velocity (Table 3), Bland-Altman analysis (Figure 2) revealed too wide 95% limits of agreement across all velocity ranges, demonstrating an unacceptable systematic underestimation of both metrics.

However, for velocity ranges 4 and 5, the criteria of validity of both ICC and CCC (Table 2) were met for peak velocity suggesting good consistency between the measurements of the two devices. Nevertheless, peak velocity measured by Velocity matters should be used with caution for monitoring VBT sessions, even at slow velocities, as a large dispersion and random error (Figure 2) were found. Moreover, in the BP, the first validity criterion was not met by Velocity Matters, as 5.4% of the repetitions were missed, which can be considered a limitation of the device. It has to be highlighted that all missed repetitions involved very well-trained athletes, who typically perform a slow eccentric phase regardless of the load. We hypothesize that an excessively slow eccentric velocity may have compromised the detection of repetitions by Velocity Matters, as in all missed repetitions the eccentric velocity, measured by GymAware, was below 0.20 $m \cdot s^{-1}$. This could represent a practical limitation of the device, since eccentric velocities below 0.20 $m \cdot s^{-1}$ can often be reached at submaximal loads by experienced athletes, which may reduce the suitability of Velocity Matters for monitoring under these specific conditions. However, the present study fails to systematically investigate this limitation; therefore, further studies are necessary to clarify our hypothesis.

Conclusions

Velocity Matters failed to meet all validity criteria across the full velocity range spectrum, both in the BP and in the SQ. Nonetheless, concerning the SQ, measurements for MV appeared to be acceptable for velocities below 1.00 $m \cdot s^{-1}$. However, a constant and substantial underestimation and variability of MV error must be taken into account. For the peak velocity, the accuracy in SQ was found to be unacceptable. With regard to the BP, Velocity Matters showed good consistency of measurements and acceptable MAE only for peak velocity at velocity ranges 4 and 5. However, the occurrence of missed repetitions, probably due to the excessively slow eccentric velocity, along with the wide dispersion of error and the presence of random error, suggest that Velocity Matters may not be considered a valid tool for prescribing VBT sessions in BP exercise during resistance training sessions.

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Chapter 8: Temporal Stability and Practical Relevance of Velocity and Velocity loss perception

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Title: Temporal Stability and Practical Relevance of Velocity and Velocity loss perception

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Abstract:

The aim of this study was to investigate the accuracy and stability of both Perception of Velocity (PV) and Perception of Velocity Loss (PVL) over four weeks, without any feedback regarding velocity during training sessions. Fifteen subjects performed six training sessions: four session familiarized the athletes with PV and PVL and the final two sessions to assess the accuracy and stability of PV and PVL, one conducted 48 hours after the familiarization and the other after 4 weeks. To assess PV and PVL, two loads (60%1RM and 80%1RM) and two velocity losses (20%VL and

40%VL) were employed. PV accuracy was measured by the DeltaScore, the difference between perceived velocity (Vp) and actual encoder velocity (Vr): DetlaScore = Vp – Vr. PVL was measured by the Vscore, the difference between repetitions where the subject perceived the target %VL (Np) and repetitions that actually met it (Nr): Vscore = Np – Nr. The analysis performed revealed no differences in DeltaScore nor in Vscore between the two test sessions ($p>0.05$). On the other hand, the effect of load on both DeltaScore and Vscore was significant ($p<0.05$). PVL and PV accuracy are stable throughout time. PVL may be used to prescribe and monitor velocity-based training. Conversely, when prescribing training sessions based on PV, it is essential to pair PV with a perception scale and incorporate an encoder when possible.

Keywords: Velocity based training, resistance training, velocity perception, velocity loss perception

1. Introduction

Proper resistance training (RT) prescription is fundamental for optimizing performance improvements and enhancing health outcomes [1,2,3]. RT programs are developed by manipulating several variables, with intensity and volume being two of the most crucial [2]. Historically, the most common method for prescribing RT has been percent-based training (PBT) [4]. PBT determines the intensity as a percentage of the one-repetition maximum (%1RM) and prescribes the training volume based on that intensity [5]. The main limitation of PBT is that it does not consider daily fluctuations in 1RM, which could lead to a less precise training prescription [5]. Velocity-based training (VBT) [5] instead, uses the velocity of the barbell during the concentric phase of the movement to modulate the intensity, and the percentage of velocity loss (VL) within the sets to prescribe training volume [5]. VBT shifts the focus from the absolute load lifted to the measurement of movement velocity [5]. This approach is based on the close inverse relationship between the lifted load and the average propulsive velocity, which makes it possible to create a general or individual load-velocity profile [6,7]. Through the load-velocity profile, which is exercise- [6] and sex-specific [7], 1RM can be accurately estimated [6,7,8,9]. Therefore, barbell velocity can be used to account for daily readiness and fatigue, which allows day-by-day adjustments to optimize the training session [10,11]. However, despite these advantages, the main issue in VBT is the cost of the devices used for monitoring velocity. Indeed, the most reliable devices, linear position transducers (LPTs) [12,13], are quite expensive, with prices ranging from ~400$ for the cheaper ones to ~2000$ for those considered as the gold standard [13]. For this reason, in recent years, many studies have investigated the accuracy of perceiving barbell velocity, with the goal of using the perception of velocity (PV) for training whenever LPTs are unavailable [14,15,16,17,18,19,20,21,22].

PV is the ability to estimate the velocity of a single repetition during exercise [16,19]. Previous studies have demonstrated that, after a period of familiarization with the combined use of LPT and a PV scale, the subjects' perceived velocity becomes substantially closer to the real barbell velocity, measured by devices [18,19]. The accuracy of PV is assessed using a Delta Score (Ds), calculated as the difference between perceived velocity (Vp) and real velocity (Vr) (Ds = Vp − Vr). Therefore, a Ds closer to 0 indicates a more accurate PV [18,19]. Previous studies reported that a Ds for medium (40–70% 1RM) intensities is more accurate than that for low (<40% 1RM) and high (>70% 1RM) intensities, where Vp tends to be overestimated and underestimated, respectively [14,15]. However, increasing the familiarization period has been shown to increase PV accuracy at all intensities [16,19]. Furthermore, a familiarization period consisting of four sessions over two weeks (i.e., two sessions per week) [17,18] appears sufficient to yield results comparable to those observed following a five-week familiarization period with the same weekly session frequency [16]. Lastly, it has been proven that PV is a stable parameter even under both physical and mental fatigue conditions [17,18].

Another aspect that has been investigated is the ability to perceive changes in barbell velocity [20,21,22,23,24], which has been examined in three different ways [20,21,22]. Firstly, perception of velocity loss (PVL) accuracy has been assessed by asking participants to verbally report, starting from the second repetition, the perceived change in barbell velocity, expressed as a percentage of the first repetition [20,22]. In these studies, the difference between the perceived and the actual change in velocity reflects PVL accuracy [20,22]. Meanwhile, Dello Iacono et al. asked participants to verbally report when they thought their velocity, compared to the first repetition, had dropped by 20% and 40% [21]. PVL accuracy was calculated as the difference between the number of repetitions at which the participant reported 20% and 40% PVL and the actual repetitions corresponding to those velocity losses [21]. Lastly, da Silva et al. asked participants to stop the sets when they thought their %VL was between 15% and 30% and thereafter calculated the percentage of sets stopped correctly [24]. As with PV, it has been proven that PVL accuracy also increases after familiarization, although the familiarization protocols used were shorter than those used for PV [22]. Finally, PVL accuracy seems to be related to the number of repetitions performed, where an increase in repetitions corresponds to an increase in the PVL error [20,21,22]. Despite these issues, some studies conclude that PVL can be implemented as a VBT monitoring tool whenever LPTs are limited or not available [21,24].

Although the research conducted so far is encouraging, no study has explored the possibility of combining PV and PVL simultaneously. Thus, it is important to highlight that using both velocity and %VL in combination is essential for accurately prescribing VBT. Therefore, the first aim of this study was to investigate the possibility of using both PV and PVL simultaneously, and whether the combined use of these two parameters influences the accuracy of one (PV), the other (PVL), or both. Furthermore, as mentioned previously, it is well established that familiarizing subjects with PV and PVL enhances accuracy levels; however, it remains unclear whether these improvements are maintained over time and, if so, for how long. Therefore, the second aim of the present study was to assess whether the accuracy of PV and PVL remains stable after four weeks, during which participants trained using classical PBT rather than velocity-based training, and without receiving any form of velocity feedback during their sessions.

2. Material and Methods

2.1 Participants

The present study included 15 well-trained subjects (8 males, 7 females, age: 22.6 ± 1.8 years, height: 1.78 ± 0.10 m, body weight: 77.05 ± 12.04 kg, 4.7 ± 2.4 years of experience; 1RM/BW 1.5 ± 0.2). The study's inclusion criteria required participants to have at least two years of experience in RT, regularly perform the back squat in their training routine, be aged between 18 and 35 years, and have no current or prior injuries for a minimum of two years. After being thoroughly informed about the study's procedures, risks, ethical considerations, and provided with a copy of the explanatory information sheet, participants signed informed consent and data processing forms. The study protocol was developed in accordance with the latest revision of the Helsinki Declaration, which ensures the protection of the rights, integrity, and well-being of individuals participating in experiments, and received approval under CAR 165/2023. Participants were free to withdraw from the study at any time, either at their own request or that of the staff, without needing to provide a reason and without facing any consequences.

2.2 Experimental Design

A test–retest reliability design was used to analyze the effect of time on PV and PVL accuracy. Each participant completed a total of six training sessions, performing two or three sessions per week, with at least 48 h between sessions. During the first four sessions, participants were accustomed to VBT, focusing on the velocity performed during each repetition and the VL across each set. In the final two sessions, conducted 48–72 h after the last familiarization session and four weeks apart, participants performed four sets of squats at 60% and 80% of their 1RM, with both loads executed at 20% and 40% VL. The sets were performed in a randomized order, and the weights were concealed during all sets to ensure that participants were unaware of the loads on the barbell. For each set, participants reported the velocity of the first repetition. They were then instructed to stop the set when they believed they had reached either 20% or 40% VL, depending on the condition (Figure 1). Participants were not informed about the number of loads or the aforementioned randomization. Finally, at the beginning of each set, participants were reminded to perform each repetition with maximal intent during the concentric phase of the movement. However, no verbal encouragement was provided to avoid influencing their perceived exertion.

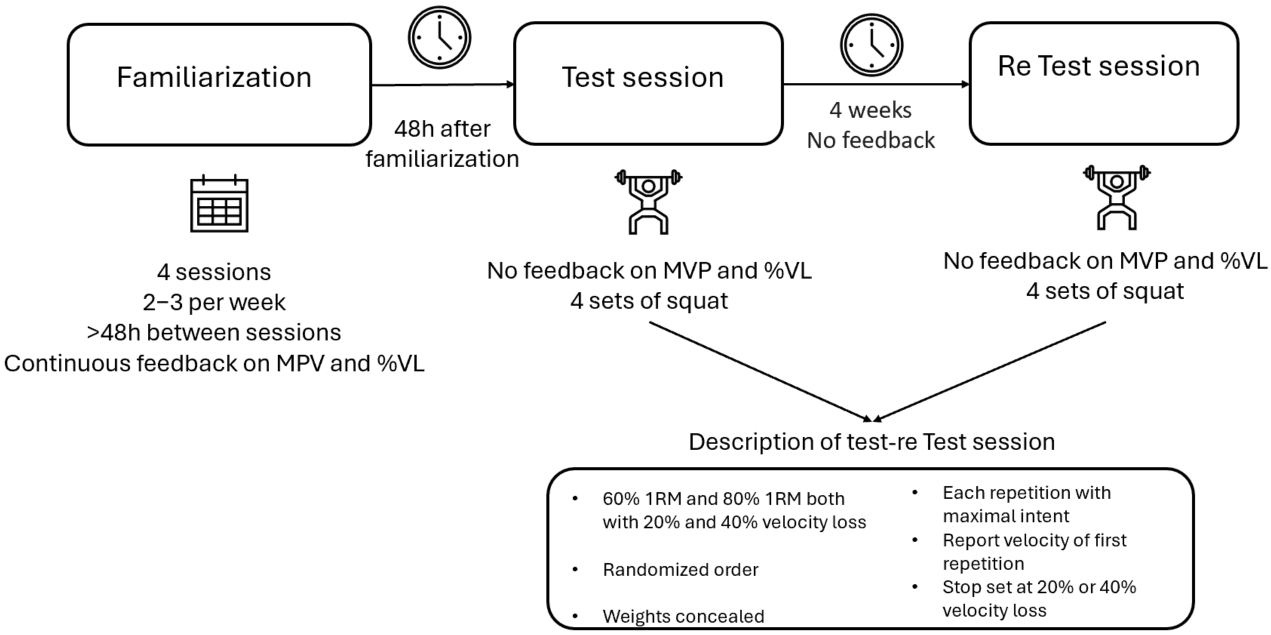

Figure 1. Experimental design of the study. MPV: mean propulsive velocity; %VL: percentage of velocity loss.

2.3 Familiarization session and one-repetition maximum test

During the whole session a linear position transducer "Vitruve" (SPEED4LIFTS S.L., Madrid, Spain) was utilized to measure mean propulsive velocity (MPV). The first three familiarization sessions were designed to help participants become acquainted with PV and PVL. During the initial testing session, participants provided informed consent and allowed for data processing prior to the beginning of data collection. Information regarding their height, body weight, age, and experience in RT was subsequently gathered. During the first three sessions, after a standardized warm-up (i.e., 5 minutes of self-selected intensity cycling followed by 5 minutes of joint mobility exercises), participants performed six or seven sets of squats per session, with a rest period of 3 to 5 minutes between sets. On each occasion, the first two sets (three on the first day) were designated as warm-up sets, with participants selecting their own loads. They were instructed to progressively increase the load with each successive warm-up set. After the warm-up, four sets of squats were completed during every familiarization session. On the first day, participants performed four sets of back squats using heavy loads, characterized by a MPV < 0.5 $m \cdot s^{-1}$. On the second day, the four sets of back squat were executed with moderate loads (MPV from 0.80 $m \cdot s^{-1}$ to 0.60 $m \cdot s^{-1}$). The third day included two sets with moderate loads (MPV ~ 0.70 $m \cdot s^{-1}$) and two more with heavy loads (MPV < 0.5 $m \cdot s^{-1}$). Each of the loads with a specific target velocity was performed at both 20% and 40% VL. Finally, on the fourth day, participants performed a maximal incremental back squat test to determine their 1RM [16]. During every familiarization session, participants received auditory feedback regarding the velocity achieved during each repetition and another auditory signal was given when the velocity loss threshold required was reached, both signals were given from the encoder. After each set, participants were presented with the validated PV squat scale [20], along with the velocity attained during that set. Participants were instructed to focus on the perceived effort associated with 20%VL or 40%VL rather than the number of repetitions performed.

2.4 PV and PVL assessment

The final two sessions were performed 4 weeks apart and we assessed PV and PVL. During the four weeks between the test and re-test, subjects continued their regular training using the %1RM to calculate the daily load. During this period, they did not receive any feedback regarding PV or PVL, and did not use the PV scale [19] or LPT.

PV was evaluated using two distinct metrics: the Delta Score (Ds) and the absolute Delta Score (|Ds|). Specifically, Ds is calculated as the difference between perceived velocity and real velocity (Ds = Vp − Vr), thereby preserving the sign of the error and indicating whether PV is overestimated (positive value) or underestimated (negative value). In contrast, |Ds| is derived from the absolute difference between Vp and Vr (|Ds| = |Vp − Vr|) and quantifies the magnitude of the error discarding its direction. This dual approach provides a comprehensive evaluation, with Ds revealing the error's direction and |Ds| offering a precise measure of its absolute magnitude. To evaluate the accuracy of PVL, a metric called the Vscore was used. In line with the methodology employed by Dello Iacono et al., the Vscore was defined as the difference between the number of repetitions performed by the participant (Np) and the number of repetitions required to reach the prescribed VL threshold (Nr) (Vscore = Np − Nr) [21]. Finally, consistent with the approach used and explained for Ds, the absolute Vscore (|Vscore|) was calculated to provide a more precise quantification of the error magnitude (|Vscore| = |Np − Nr|). During these sessions, participants performed a total of four sets of squats with two different loads (60% and 80% 1RM), each with two VL thresholds (20% VL and 40% VL). The order of the loads and VL thresholds was randomized. During the sets, the weights on the barbell were concealed to ensure they were unidentifiable to the participants. Prior to performing the prescribed four sets, participants were instructed to complete at least three warm-up sets of back squats. They were informed that after the third warm-up set, any load could be used, ranging from very light to very heavy, and were therefore advised to be prepared to lift loads potentially close to their 1RM. Additionally, for safety reasons, participants were instructed to always approach the barbell assuming it was loaded with an extremely heavy weight, emphasizing the importance of being both mentally focused and physically prepared to execute the set. Lastly, participants were instructed to end the set when they believed they had reached the required %VL. If a set was terminated prematurely, the VL slope during the set was used to estimate the number of repetitions needed to reach the prescribed %VL (Nr)

2.5 Statistical Analysis

The data were normally distributed, as confirmed by the Shapiro–Wilk test ($p > 0.05$). PV accuracy was assessed using the Delta Score (Ds), which represents the difference between Vp and Vr. Ds was analyzed using a two-way repeated-measure ANOVA to examine the effects of load (60% and 80% of 1RM) and time (test–retest session). The agreement between Vp and Vr and their correlation was assessed using Bland–Altman plots and Intra-Class Correlation (ICC), respectively, for both test and re-test sessions. Additionally, simple linear regression between Vp and Vr was performed for each session to determine the coefficient of determination (R^2). PVL accuracy was calculated using the Vscore (Np − Nr). A three-way repeated-measure ANOVA was used to analyze the effect of Load (60% and 80% of 1RM), Velocity Loss (20%VL and 40%VL) and Time (test–retest session) and their interaction on Vscore. The relationship between Np and Nr was evaluated through Bland–Altman plots to assess agreement and ICC to determine their correlation, for both the test and re-test sessions. Lastly, for each session, a simple linear regression was performed between Np and Nr to determine the coefficient of determination (R^2). The magnitudes of ICC were classified as follows: poor (<0.5), moderate (0.5–0.75), high (0.5–0.75), good (0.75–0.90), and excellent (>0.9) [25]. A priori power analysis was conducted using G*Power 3.1.9.7. An F-test with the "ANOVA: Repeated measures, within–factor" option was selected. An effect size ($f = 0.3$), an alpha level of 0.05, and a statistical power of 0.8 were used, with two groups and four measurements (2 time × 2 loads), assuming a correlation of 0.7 among repeated measures. The estimated required sample size was 15 participants. Moreover, a posteriori power analysis was conducted for the results identified as significant in order to estimate the power of our findings.

3. Results

3.1 Delta Score and Velocity perception

The two-way repeated-measure ANOVA showed significant effects for load ($F(1) = 11.9$, $p = 0.02$, $\eta^2 = 0.31$), but not for time or load*time interaction ($p > 0.05$). The results of the Bland–Altman plot are presented in Figure 2. ICC showed good results between Vr and Vp in both the test and re-test sessions (Table 1). Linear regressions revealed similar R^2 values between the pre- and post-test conditions (Table 1). Lastly, the |Ds| between pre- and post-test are reported in Figure 3. We conducted a posteriori power analysis using G*Power 3.1 to evaluate the statistical power of the significant impact of load on PV. In this analysis, we set the test family to F-test and used repeated-measures ANOVA (within factors) with an alpha level of 0.05. Based on our data, the observed effect size ($\eta^2 = 0.31$) from the two-way ANOVA resulted in a power of 0.73 for the load effect on PV. Although the statistical power we observed is relatively low, we strongly believe that increasing the sample size would enhance both the power and robustness of our findings. This is supported by existing literature, which shows that PV accuracy improves with higher loads [20].

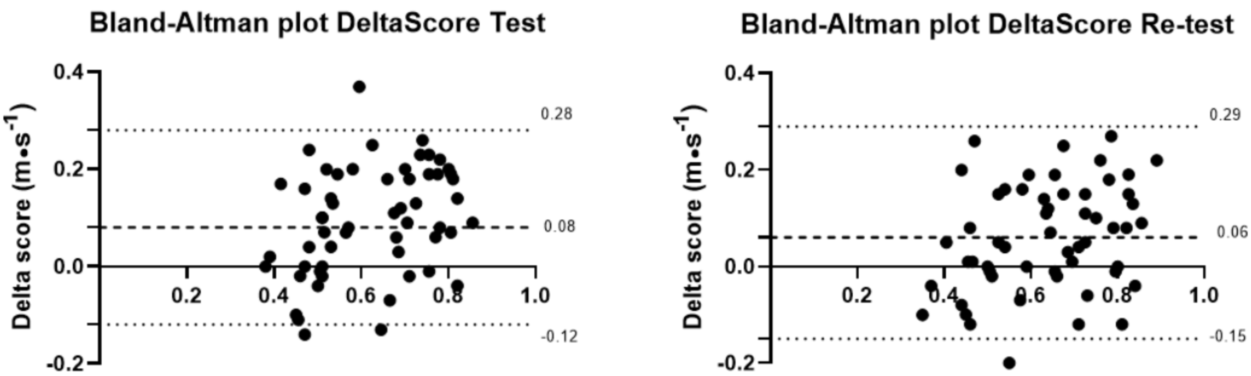

Figure 2. DeltaScore: Differences between perceived velocity and real velocity (Vp − Vr); Vr: real velocity; Vp: perceived velocity. Test: Test session 48–72 h after the familiarization protocol; Re-Test: Test session 4 weeks after the test session.

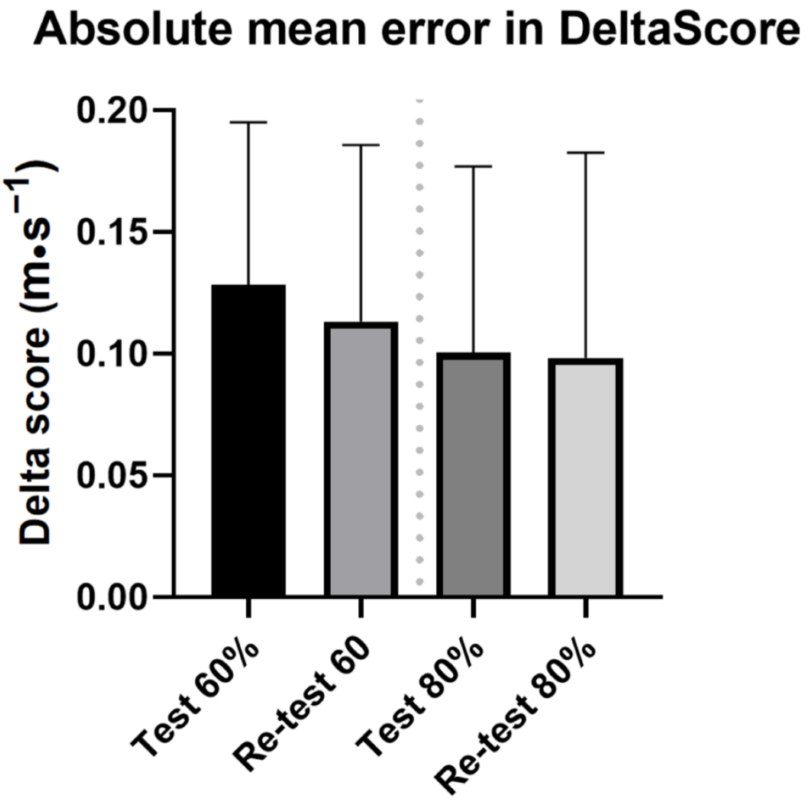

Figure 3. Absolute DeltaScore: Absolute differences between perceived velocity and real velocity (|Vp − Vr|); Vr: real velocity; Vp: perceived velocity; Test 60%: Error in |Ds| with 60%1RM during the test session; Test 80%: Error in |Ds| with 80%1RM during the test session; Re-test 60%: Error in |Ds| with 60%1RM during the re-test session; Re-test 80%: Error in |Ds| with 80%1RM during the re-test session; Test session 48–72 h after the familiarization protocol; Re-Test: Test session 4 weeks after the test session.

Table 1. Intra class correlation coefficient (ICC) and coefficient of determination (R^2) between Vp-Vr and Np-Nr.

	Test		Re-test	
	ICC	**R^2**	**ICC**	**R^2**
Vp-Vr	0.828	0.600	0.837	0.607
Np-Nr	0.980	0.947	0.986	0.923

3.2 Vscore and Velocity-Loss perception

The three-way repeated-measure ANOVA revealed significant effects only for velocity loss ($F(1) = 33.54$, $p < 0.001$, $\eta^2 = 0.72$), meanwhile a trend for load ($p = 0.06$, $\eta^2 = 0.25$), and load*velocity loss interaction ($p = 0.08$, $\eta^2 = 0.06$) was found, indicating that Vscore is influenced mainly by velocity loss. Conversely, time, load*time, velocity loss*time, and load*velocity loss*time interactions were not significant ($p > 0.05$). The results of the Bland–Altman plot for Np and Nr are presented in Figure 4. ICC showed an excellent correlation between Nr and Np in both the test and re-test sessions (Table 1). Linear regressions revealed similar R^2 values between the pre- and post-test conditions (Table 1). Lastly, the |Vscore|, categorized by load and velocity loss, are reported in Figure 5. A posteriori power analysis to assess the statistical power of significant results for %VL in PVL was performed. Based on our dataset, we set the test family to F-test and used a repeated-measure ANOVA (within factors) with an alpha level of 0.05. In the three-way ANOVA for %VL, we observed an effect size of $\eta^2 = 0.72$, which corresponded to a statistical power of 0.99. These findings indicate that, despite a small sample size, the statistical power for %VL in PVL was extremely high, suggesting that the limited sample size was not a constraint

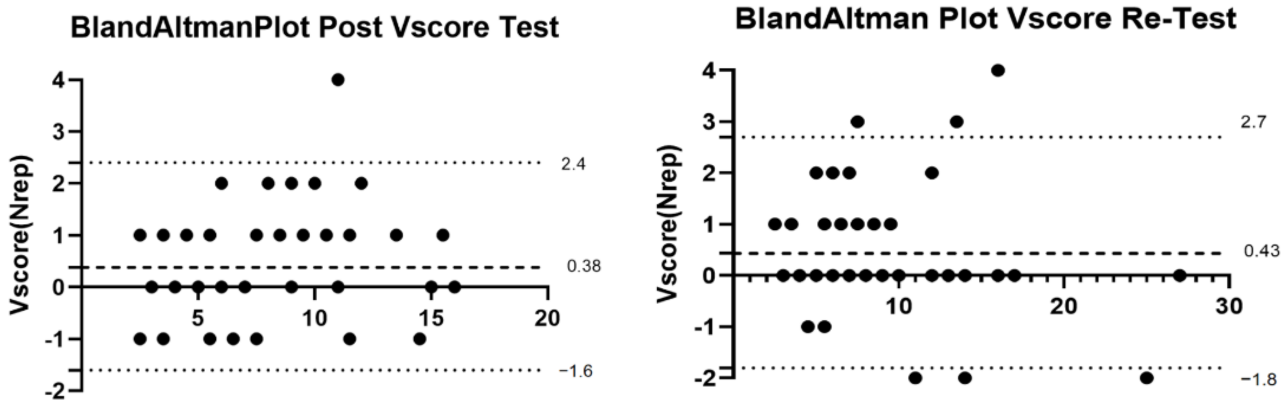

Figure 4. Vscore: Differences between Nr and Np (Nr − Np); Np: number of repetitions completed at the perceived threshold; Nr: number of repetition where the subject actually reached the required threshold; Test: test session 48–72 h after the familiarization protocol; Re-Test: test session 4 weeks after the test session.

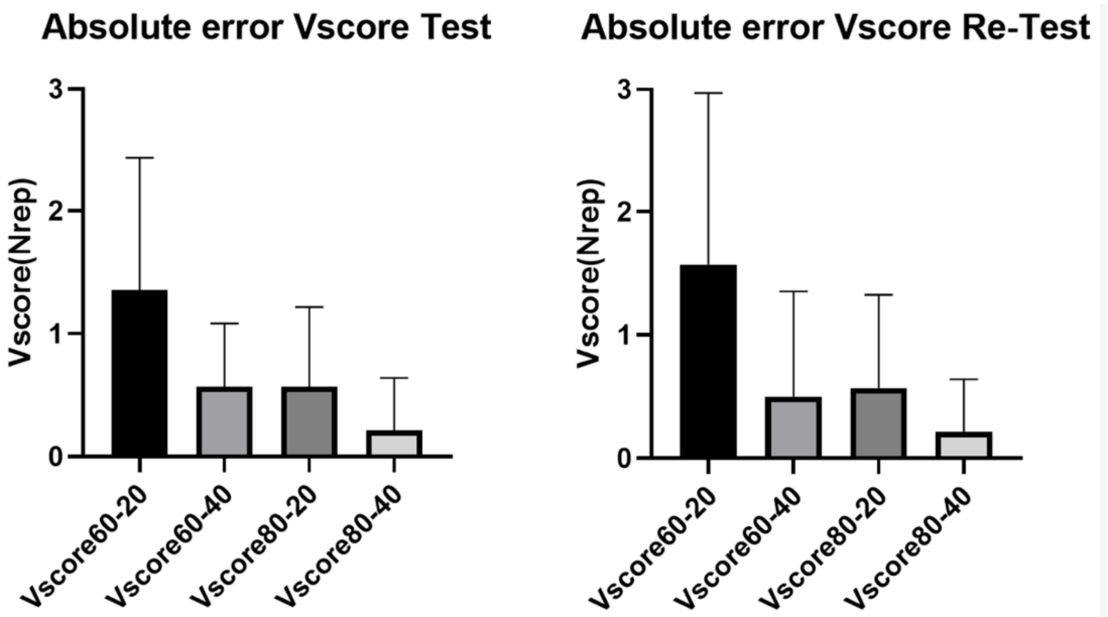

Figure 5. |Vscore|: Absolute differences between number of repetitions perceived and real number of repetitions (|Np − Nr|); Vscore 60–20: Error in number of repetitions performed with 60% 1RM and 20% VL; Vscore 60–40: error in number of repetitions performed with 60% 1RM and 40% VL. Vscore 80–20: Error in number of repetitions performed with 80% 1RM and 20% VL; Vscore 80–40: error

in number of repetitions performed with 80% 1RM and 40% VL; Test: test session 48–72 h after the familiarization protocol; Re-Test: test session 4 weeks after the test session.

4. Discussion

The aim of this study was to assess the stability of the accuracy of PV and PVL after four weeks during which participants did not receive any feedback on the velocity of the barbell's movement during their training sessions. Different findings have been observed**.**

4.1. Delta Score and Velocity Perception

In agreement with previous studies [16,17,19], we found significantly greater PV accuracy for higher loads compared to lower ones, both in the test and re-test session after 4 weeks. Moreover, a very high correlation between Vr and Vp in both test and re-test sessions was found, suggesting that PV is a stable parameter over time. To the authors' knowledge this is the first study to examine the stability of PV after four weeks without feedback with an encoder or PV scale. Indeed, PV is not only stable over time but, as found by Romagnoli et al., it is also unaffected by mental and physical fatigue [17,18]. Furthermore, the Ds reported in Figure 2 is comparable to what previously reported [16], indicating that the combined familiarization of PV and PVL does not appear to have altered the velocity perception accuracy. However, the Ds, which is the only parameter currently used to evaluate PV accuracy, is influenced by the presence of both positive and negative values (i.e., under or over estimation of the velocity); therefore, to accurately assess the magnitude of the error associated with PV we considered more appropriate to use the absolute difference between Vp and Vr. For the aforementioned reason, it is important to use both Ds and |Ds| to obtain information about the direction of the error as well as an accurate estimate of its magnitude. Since it is not influenced by the presence of both positive and negative values, |Ds| exhibited a slightly higher error than Ds.

Therefore, PV accuracy, with an absolute error of approximately 0.11 $m \cdot s^{-1}$ when using light loads, does not appear sufficiently precise for prescribing VBT intensity, potentially leading to incorrect load selection. Further research is needed to enhance the accuracy of PV across the entire load-velocity spectrum used in VBT sessions. Lastly, the |Ds| exhibited a large standard deviation (i.e., ~0.07 $m \cdot s^{-1}$), indicating that some subjects achieved high accuracy while others were markedly imprecise. Future studies should explore the underlying mechanisms behind these differences. One possible explanation is that differences in proprioception among subjects may account for variations in PV ability. Proprioception informs force generation and, in tandem with exteroceptive senses such as visual, vestibular, and tactile feedback, may help detect changes in velocity [26]. Moreover, some studies have suggested that proprioception varies based on individual factors such as experience [26], age [27], and sex [28]. Therefore, considering that this study did not account for these differences, future research should investigate this possibility. This could involve proprioceptive training interventions or comparative analyses across groups with known differences in proprioceptive ability, such as athletes versus non-athletes or younger versus older individuals [28,29,30]. Lastly, within the field of neuroscience, the perception of an object's velocity is considered to be determined by a combination of proprioceptive and exteroceptive afferents, such as vision [26,29,30]. Future studies could also investigate the impact of visual input on PV accuracy.

4.2. Vscore and Velocity-Loss Perception

This was the first study to investigate the consistency of PVL over four weeks. No significant differences in the Vscore were found pre and post the four-week period indicating PVL as stable for at least this time frame. Regarding the level and characteristics of PVL accuracy, some incongruences with previous studies have been found. It is important to note that this study is the first to use such an extended familiarization period before assessing PVL accuracy. In previous research, two studies provided no familiarization at all [15,18], and others performed only a single session [21,24]. Based on our results PVL appears to be primarily influenced by the %VL threshold, with higher thresholds corresponding to increased accuracy. The highest PVL accuracy was observed at the 40% VL threshold with the heaviest load (80% 1RM), where no participant exceeded a one-repetition error even after 4 weeks. Additionally, the |Vscore| for 40% VL at 60% 1RM had an error comparable to that for 20% VL at 80% 1RM. However, these results appear to be in contrast with findings from other studies that reported an increase in repetitions performed, therefore in %VL is associated with a higher PVL error [20,21,22]. Dello Iacono et al. hypothesized two pathways responsible for this [21]: (1) the time delay after the initial repetition may cause the sensation of velocity perceived during that first attempt to fade, potentially altering PVL, and (2) neuromuscular fatigue, which could lead to discomfort and hinder participants' ability to perceive velocity. However, our results do not support these hypotheses, as sets with higher %VL turned out to be more precise. We hypothesize that multiple factors may underlie these results. Firstly, two of the previously reviewed studies assessed a parameter that differs slightly from PVL, as those studies focused on the perception of changes in velocity, specifically, verbally reporting the velocity of each repetition [20,22]. Consequently, they did not evaluate the accuracy in identifying the attainment of a specific VL threshold, but rather the ability to perceive variations in repetition velocity within a set. In our view, perceiving the velocity of the final repetition is fundamentally different from recognizing the sensation associated with reaching a given percentage of velocity loss. This distinction may explain the discrepancies between our findings and those of earlier investigations. Furthermore, we suggest that during the familiarization sessions, participants may have begun associating specific %VL thresholds with distinct sensations of fatigue and proximity to momentary failure. Therefore, while Dello Iacono et al. hypothesized that PVL accuracy deteriorates over time due to the increasing temporal and mechanical separation between the first and last repetitions, our findings indicate the opposite trend: as the number of repetitions increases (i.e., higher %VL), accuracy improves, possibly because participants are progressively approaching failure. This interpretation is supported by evidence from previous research on repetitions in reserve (RIR), which shows that the closer individuals are to failure, the more accurate their RIR estimations tend to be [31]. Consequently, the 40% VL threshold at 80% 1RM yielded the highest precision and proximity to failure compared to other load and %VL combinations. Regarding the importance of load in PVL, results in the literature are conflicting [21,24]. da Silva et al. [24] found higher accuracy with heavy loads compared to lower ones. On the other hand, Dello Iacono et al. [21], found that PVL was more accurate with loads between 50 and 60% of 1RM compared to heavier ones [21]. The present investigation shows only a trend ($p = 0.06$) in line with the result of da Silva et al. [24]. Therefore, based on these results, it seems that PVL is a reliable parameter, also stable over time. Considering an error of 1 repetition negligible [21], in our opinion PVL could be used to prescribe VBT volume with loads of 80% 1RM at both 20% and 40% VL or even with loads of 60% 1RM if a 40% VL threshold is used.

5. Conclusions

This is the first study that evaluated the stability of PV and PVL accuracy over a four-week period. The main finding is that both parameters remained stable. PVL appears to be an acceptable metric for prescribing VBT volume in high-intensity and/or high-volume training, even four weeks after familiarization. Finally, PVL was found to be highly reliable at high loads with both 40% VL and 20% VL, but less reliable at medium loads with 20% VL. Future studies should investigate PVL accuracy at lower velocity-loss thresholds and with closer threshold ranges, particularly at medium intensities, to better understand its feasibility under various conditions. Conversely, PV accuracy, with an absolute error of approximately 0.11 $m \cdot s^{-1}$ when using light load, does not appear sufficiently precise for prescribing VBT intensity. An error of 10% 1RM could shift the focus of training away from the specific purpose [2], and a variation in velocity of ~0.10 $m \cdot s^{-1}$ corresponds to a difference of about 10% 1RM [32]; therefore, we consider acceptable error to be below 0.09 $m \cdot s^{-1}$. In light of these results, it is important, when prescribing training based on PV, to consistently use PV in conjunction with a PV scale and, whenever possible, to integrate the use of an encoder.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: Data are available on request due to restrictions (privacy).

Conflicts of Interest: The authors declare no conflicts of interest.

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Chapter 9: The impact of Mental and Physical Fatigue on Perceptual Load Monitoring

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Title: The Impact of Mental and Physical Fatigue on Perceptual Load Monitoring in Resistance Training

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Abstract

The study aimed to examine the effects of mental fatigue (MF) and physical fatigue (PF) on perception of velocity (PV) and perception of velocity loss (PVL) during resistance training. Nineteen participants (9 females) completed seven training sessions: The first four as familiarization with PV and PVL, while the remaining three inducing PF, MF and Control Condition (CC), in a randomized order. PF was induced by performing 5 sets of back squats at 75%1RM until failure, MF through a 45-minute AX-Continuous Performance Task and CC consisting of watching a 45-minute documentary. Participants' accuracy in PV and PVL were assessed pre- and post-condition (PF, MF, and CC), as well as their performance in countermovement jump (CMJ), maximal voluntary isometric strength (MVC) and rate of force development (RFD). PV and PVL assessments consisted of four sets of back squats at 60% and 80%1RM, with 20% and 40%VL, performed in a randomized order. Results showed a significant decline in CMJ, RFD, and MVC performance following both PF and MF protocols, but not in the CC. No impairments were observed in PV or PVL under any condition (PF, MF, or CC). In particular, PVL showed high accuracy across all conditions except at the lowest load and %VL (60%1RM–20%VL), while PV was accurate only under high-load conditions (80%1RM). These results indicate that both PV and PVL are reliable parameters under both PF and MF. Therefore, PVL appears suitable for training prescription across a range of loads and %VL, whereas PV should be used cautiously especially at low loads.

Keywords: velocity-based training; sex differences; autoregulation; performance assessment; barbell velocity

Introduction

Velocity-Based Training (VBT) is a resistance training methodology that has gained significant interest in the past decade in the athletic preparation of both professional and recreational athletes(13,37). VBT sessions are prescribed by monitoring barbell velocity, which represents the core parameter of this training method(9,23,32,37). Specifically, the velocity during the concentric phase is used to prescribe the training intensity, with higher velocities corresponding to lower relative loads, and vice versa(7,11,37). Meanwhile, training volume is regulated through the percentage of velocity loss (%VL) within a set, where greater %VL indicates higher training volume(12,38). VBT has shown several advantages compared to traditional percentage-based training(2,9,40). Among these benefits are the ability to monitor fatigue in real time during training sessions, thereby enabling optimal fatigue management, and the capacity to monitor training adaptations, such as increments in one repetition maximum (1RM), without the necessity for specific tests(37). Since movement velocity is the key factor for correctly planning VBT sessions, it is very important to have reliable tools to measure it(22,25). The gold standard, in a gym environment, is represented by linear position transducers, which offer higher accuracy compared to other devices (i.e. smartphone apps or accelerometers)(22,25). However, the necessity to utilize simultaneously more devices, especially in team sports trainings, could represent an important limitation in their effective utilization(28–31). For this reason, recent research has explored the possibility of assisting athletes and coaches in prescribing VBT sessions based on the perception of velocity (PV)(28–31) and perception of velocity loss (PVL)(17,19,33,34), in the temporary absence of such devices. The first step in this direction involved the development of perception velocity scales, aiming at helping athletes differentiate between various velocity ranges and, thereby, between intensity domains during training(3,28). The second step was to define a standard methodology to assess the accuracy of PV and PVL(35). Recent literature has adopted two distinct metrics for each parameter: the Delta Score (Ds) and the absolute Delta Score (|Ds|) for PV, and the Vscore and absolute Vscore (|Vscore|) for PVL(17,28,35). Specifically, Ds is defined as the difference between the velocity perceived by the athlete (Vp) and the actual velocity measured by the encoder (Vr), calculated as $Ds = Vp - Vr$(28). Similarly, the Vscore is calculated as the difference between the number of repetitions performed by the athlete (Np) and the number of repetitions required to reach the prescribed velocity loss (VL) threshold (Nr), expressed as $Vscore = Np - Nr$(17,35). Ds and Vscore provide information about the direction and variability of the error. While their absolute value ($|Ds| = |Vp - Vr|$, $|Vscore| = |Np - Nr|$), indicate the overall magnitude of the error, regardless of its direction(35). Findings indicate that PV accuracy generally improves with heavier loads compared to moderate or light ones(29–31,35). In contrast, results for PVL are inconsistent: some studies report greater accuracy at higher loads and %VL(35), while others suggest better accuracy at lower %VL(19,34). Furthermore, PV accuracy has been shown to improve after a familiarization period, with four sessions being sufficient to adequately accustom athletes with no prior experience in VBT to the use of PV scales(29,31,35). Moreover, Ds and |Ds|

accuracy appears to be consistent across different test days(28) and reliable over a period of at least four weeks(35). PV accuracy has also been assessed using relatively short testing protocols and solely through Ds, under both Physical (PF)(31) and Mental Fatigue (MF)(29) conditions. Interest in the potential impact of these states on PV arises from previous findings showing that both MF and PF not only impair performance(8,21) but also impact on the Rating of Perceived Exertion (RPE)(8). For these reasons, it could be hypothesized that PF and MF may reduce PV accuracy, which is a subjective autoregulatory training method as well, but previous results suggested no effect(29,31). However, the protocols included only two repetitions per set, conditions that differ significantly from those commonly used in standard training sessions. Moreover, no data on the effects of MF and PF on |Ds| are present at the moment. Therefore, it remains unclear whether these findings would hold in more ecologically valid training conditions, involving longer sets and more repetitions. Moreover, while there is some evidence, although limited, regarding the effects of PF and MF on PV, no study has yet investigated whether such forms of fatigue influence PVL. This represents a critical gap in the literature, as any potential impact of fatigue on PV or PVL accuracy would significantly compromise the validity of these measures as tools for training prescription. Moreover, previous studies have highlighted a considerable standard deviation within the accuracy ranges of PV(35), proposing, among other hypotheses, that sex may be a potential explanatory factor and recommending the investigation of possible differences between males and females.

The aim of the present study is therefore to assess the effects of both PF and MF on PV and PVL and the stability of these parameters across three consecutive testing days performed before inducing PF or MF. A second aim is to investigate potential sex-specific differences in PV accuracy. We hypothesize that neither PV nor PVL will be negatively influenced by fatigue (physical or mental) despite an impairment in performance(20,27) (reduced movement velocity and fewer repetitions to reach a given %VL). Moreover, as previously hypothesized(35), we expect that PV accuracy may differ between sexes.

Methods

Experimental approach to the problem

Participants

The present study included a total of 19 well trained subjects, ten males (age: 28.8 ± 2.9 years; body weight: 81.8 ± 7.6 kg; height: 1.80 ± 0.61 m; 6.8 ± 3.2 years of experience) and nine females (age: 25.2 ± 4.6 years; body weight: 62.4 ± 4.6 kg; height: 1.61 ± 0.6 m; 5.2 ± 2.6 years of experience). Inclusion criteria included: having at least two years of practicing resistance training, with no prior experience in VBT, being between 18 and 35 years old, and having no injuries (current or past) at least two years prior to the study. Before participation, all participants were fully informed about the procedures, potential risks and ethical considerations of the study and were given a detailed information sheet. Each participant then signed an informed consent and data processing authorization form. The study was prepared following the most recent amendment of the Declaration of Helsinki, which is designed to safeguard the rights, well-being, and dignity of individuals participating in research, and received approval from the appropriate Institutional Review Board (CAR 165/2023).

Familiarization session and one-repetition maximum test

Throughout all sessions, a linear position transducer (Vitruve, SPEED4LIFTS S.L., Madrid, Spain) was employed to measure mean propulsive velocity (MPV). The initial three sessions served as familiarization, aimed at getting participants used to VBT, specifically MPV and VL thresholds. At the beginning of the first session, participants provided informed consent and authorization for data processing. Anthropometric and demographic data, including height, body mass, age, and resistance training experience were then registered. Each familiarization session began with a standardized warm-up consisting of 5 minutes of cycling at a self-selected intensity followed by 5 minutes of joint mobility exercises. Following the warm-up, participants completed six sets of back squat per session, with inter-set rest intervals ranging from 3 to 5 minutes. The first two sets were considered warm-up sets, during which participants self-selected the loads and were instructed to progressively increase the intensity. Subsequently, four main sets of back squats were performed in each familiarization session. On Day 1, all four sets were executed using heavy loads (MPV < 0.50 $m \cdot s^{-1}$). On Day 2, moderate loads were utilized (MPV between 0.80$m \cdot s^{-1}$ - 0.60 $m \cdot s^{-1}$). Day 3 included two sets with moderate loads (MPV ~0.70 $m \cdot s^{-1}$) and two sets with heavy loads (MPV < 0.50 $m \cdot s^{-1}$). For all velocity conditions, sets were performed at both 20%VL and 40%VL. During each familiarization session, participants received real-time auditory feedback from the transducer regarding their velocity. An additional auditory cue indicated when the designated %VL had been reached. After each set, participants were shown the validated PV squat scale(28) alongside the real velocity of each repetition for that set. Instructions emphasized focusing on the perceived effort associated with the VL threshold (20% or 40%), rather than the number of repetitions completed. On Day 4, participants underwent a maximal incremental back squat test to determine their 1RM(36)

Test sessions

In the last three testing sessions, the effects of physical and mental fatigue on PV and PVL were evaluated. For this purpose, each participant underwent three sessions in a randomized and counterbalanced order. Each session consisted of five distinct phases (Figure 1), in addition to a standardized warm-up protocol previously described.

Performance Assessment (Figure 1a): this phase included three countermovement jumps (CMJ), measured using the Optojump (Opotojump Next; Microgate, Bolzano, 1.12.23.0), and three maximal voluntary isometric contractions on the leg press, using a load cell (Choro Jump Boscosystem 2.3.0-31). Maximal voluntary isometric contraction (MVC), early rate of force development (RFD 0–100 ms), late RFD (0–200 ms), and peak RFD (i.e., the steepest slope of the force-time curve) were collected.

PV and PVL Assessment (Figure 1b): subjects performed four sets of back squats, two sets at 60%1RM and two at 80%1RM, with each load tested under both 20%VL and 40%VL. Set order was randomized, and the loads were concealed from participants to minimize bias as previously described. During this phase PV and PVL were assessed.

Experimental Condition (Figure 1c): In this phase, participants performed, in a randomized order, the experimental protocol specific to each session. Depending on the condition, participants completed one of the following:

- PF protocol, consisting of five sets of back squats performed to failure, with 3 minutes rest, at 75% of 1RM. Participants were assisted in completing the final repetition of each set.
- MF protocol consisting of 45 minutes of the AX Continuous Performance Task (AX-CPT), a cognitive task widely validated for inducing MF(26);
- Control condition (CC), consisting of a 45-minute neutral documentary previously validated and used(26).

Post-Condition Performance Assessment (Figure 1d): Following the experimental condition, the initial performance assessments, as described in phase 1, were repeated. This post-assessment was used to: a) verify the effectiveness of the PF protocol in inducing measurable fatigue, as evidenced by performance decrements consistent with the literature; b) assess the impact of MF on neuromuscular performance; and c) determine whether performance declines occurred during the CC, potentially due to the prolonged duration of the testing session.

Post-Condition PV and PVL Assessment (Figure 1e): The four sets of squats described in Phase 2 were repeated in a new randomized order, with identical parameters to evaluate the effects of PF, MF, and CC on PV and PVL.

Figure 1: Experimental design of the test session

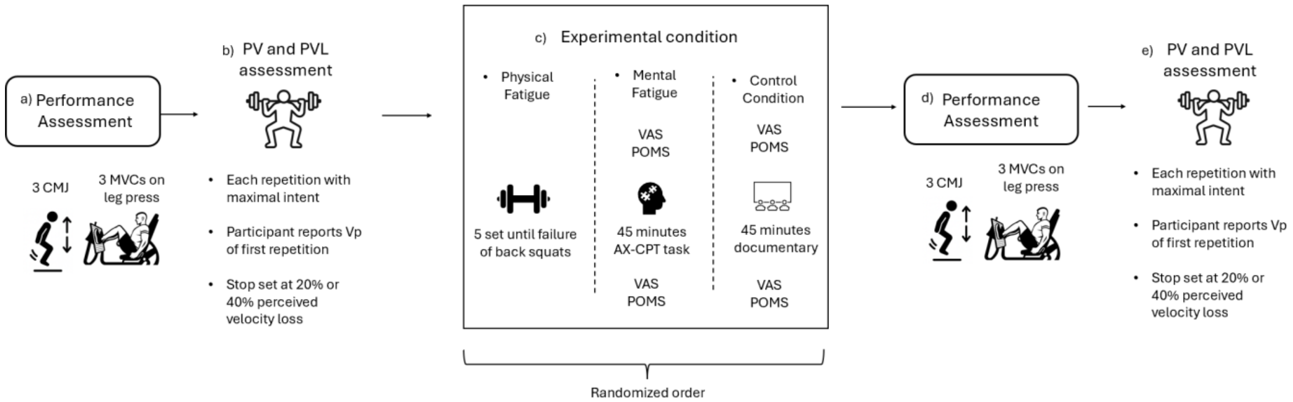


Figure 1. CMJ: Counter movement jump; MVC: Maximum voluntary contraction: PV: Perception of velocity; PVL: Perception of velocity loss; VAS: Visual Analogic Scale; POMS: Profile of Mood State

To evaluate the correct induction of MF and the potential impact of the experimental conditions (i.e., AX-CPT task or documentary) on participants' motivation, two Visual Analogic Scales (VAS), consisting of a 20 cm horizontal line, were utilized, one specifically assessing motivation and the other targeting MF(26). These VAS assessments were administered immediately before and immediately after the AX-CPT task or documentary intervention. For the MF scale, the left anchor was labeled "no mental fatigue" and the right anchor "maximum mental fatigue." For the motivation scale, anchors ranged from "no motivation" to "maximum motivation". Participants were instructed to draw a vertical mark along the line to represent their subjective perception of either MF or motivation at that moment(26). In addition, participants completed the Profile of Mood States (POMS) questionnaire to examine whether the experimental protocol influenced mood states. The version of the POMS used was a validated Italian adaptation, comprising 32 items grouped into five subscales: depression, anger, fatigue, vigor, and tension(6). Each item was rated on a 5-point Likert scale ranging from 0 ("not at all") to 4 ("very very much so"). Subscale scores were summed to calculate the total mood score, defined as the sum of negative subscales minus the positive ones(6). Changes in total mood from Pre- to Post-condition were then analyzed to identify any effects related to the experimental condition. Instructions provided for completing the POMS were: “Please respond according to how you feel in relation to the listed adjective, at this very moment”(6).

PV and PVL assessment

As previously mentioned, during the final three sessions, both PV and PVL were assessed before and after the respective experimental protocol (i.e. PF, MF or CC). In line with previous literature and established methodology, both PV and PVL were evaluated using the two distinct metrics introduced earlier: Ds and |Ds| for PV and Vscore and |Vscore| for PVL(35). Specifically, Ds is calculated as the difference between perceived velocity and real velocity (Ds = Vp - Vr), thereby preserving the sign of the error and indicating whether PV is overestimated (positive value) or underestimated (negative value). In contrast, |Ds| is derived from the absolute difference between Vp and Vr (|Ds| = |Vp - Vr|) and quantifies the magnitude of the error by discarding its direction. Similarly, to evaluate the accuracy of PVL, Vscore was used, defined as the difference between the number of repetitions performed by the participant (Np) and the number of repetitions required to reach the prescribed VL threshold (Nr) (Vscore = Np - Nr). Finally, consistent with the approach used and explained for Ds, the absolute Vscore (|Vscore|) was calculated to provide a more precise quantification of the error magnitude (|Vscore| = |Np - Nr|)(35). If a set was terminated prematurely, the VL slope during the set was used to estimate the number of repetitions needed to reach the prescribed %VL (Nr). This dual approach provides a comprehensive evaluation, with Ds and Vscore revealing the error’s direction and |Ds| and |Vscore| offering a precise measure of its absolute magnitude. Participants were instructed to a) verbally report the Vp of the first repetition; b) end the set when they believed they had reached the required %VL.

Statistical analysis

Normality of the data was assessed using the Shapiro-Wilk test, which was found to be non-significant ($p > 0.05$) for both Ds and |Ds| and also for VAS, CMJ and RFD, while it was significant for Vscore and |Vscore|($p<0.05$). Accordingly, parametric statistics were applied to Ds and |Ds|, while non-parametric statistics were used for Vscore and |Vscore|. The stability of Ds and |Ds| across the three testing sessions at rest (i.e., before each protocol), as well as the comparisons between Pre- and Post-condition values for each specific day (i.e., PF, MF, and CC) and influence of load (60%RM and 80%RM), were assessed using a three way mixed ANOVA (time × load × condition), with sex included as a between-subjects factor. Furthermore, the stability of Ds across the three testing days, with a total of six conditions, was explored through Bland-Altman Plot. The stability of both Vscore and |Vscore| across the three testing sessions under resting conditions (i.e., before each protocol), before and after each day-specific protocol (i.e., PF, MF and CC), was assessed using a Aligned Rank Test (ART; time × load× condition × %VL) and sex as between factors. Sphericity was tested using Mauchly's test, and if found significant, the Greenhouse-Geisser correction was applied. A repeated-measures ANOVA was conducted for each of the performance variables analyzed (CMJ, MVC, early RFD, late RFD, and peak RFD), with sex included as a between-subjects factor, in order to examine sex-based differences in response to PF and MF. A repeated measure ANOVA with sex as between factor was used to evaluate changes in VAS and POMS scores from Pre- to Post-protocol in both the MF and CC.

Sample Size estimation

The main analysis of the study consisted of a three-way mixed ANOVA (time × condition × load), with sex included as a between-subjects factor. Based on the study design, a priori power analysis was conducted using G*Power 3.1.9.7. An F-test with the "ANOVA: Repeated measures, within–between interaction" option was selected. A medium effect size ($f = 0.25$), an alpha level of 0.05, and a statistical power of 0.8 were used, with two groups and twelve measurements (2 time × three conditions × 2 loads), assuming a correlation of 0.5 among repeated measures and a conservative approach (0.7) on sphericity. The estimated required sample size was 16 participants (8 per group). However, considering the demanding testing protocol and the potential for participant dropout, a total of 20 participants (10 males and 10 females) were initially recruited to mitigate the impact of any potential withdrawal. By the end of data collection, one female participant withdrew from the study due to personal reasons unrelated to the research. As a result, the final sample size included in the analysis consisted of 19 participants.

Results

Stability of PV and PVL

The analysis of Ds revealed a significant main effect of load ($F (1) = 49.31$, $p = 0.00$, $\eta^2 = 0.59$). Conversely, no other significant main effect or interaction was found to be significant ($p > 0.05$). Likewise, the |Ds| showed comparable results, with the only significant effect observed for the load ($F (1) = 49.85$, $p = 0.00$, $\eta^2 = 0.60$). In both Ds and |Ds| higher load was associated with higher accuracy (i.e., $<0.08\ m{\cdot}s^{-1}$) compared to lighter ones (i.e., $> 0.10\ m{\cdot}s^{-1}$). Concerning the stability of Vscore and |Vscore| significant results was found for Load (Vscore: $F = 92.33$, $p < .001$, $\eta^2 = 0.20$; |Vscore|:($F = 96.48$, $p < .001$, $\eta^2 = 0.21$), Velocity Loss (Vscore: ($F = 92.05$, $p < .001$, $\eta^2 = 0.20$; |VScore|: ($F = 65.27$, $p < .001$, $\eta^2 = 0.15$), Load × Velocity Loss (Vscore ($F = 22.36$, $p < .001$, $\eta^2 = 0.06$; |Vscore|: ($F = 30.89$, $p < .001$, $\eta^2 = 0.08$) and Time × condition (Vscore ($F = 4.97$, $p=0.02$, $\eta^2 = 0.01$); |Vscore|: ($F = 5.82$, $p=0.01$, $\eta^2 = 0.02$) . Pairwise post hoc analyses for Time × Condition interaction revealed that both Vscore and |Vscore| were significantly lower in the post condition only after the PF protocol, where post-condition values were lower than in all other conditions. Lastly, the Bland-Altman Plot revealed great consistency across the six conditions analyzed (Pre and Post condition per three days) (Figure 2). Since no sex-specific differences were observed in any of the conditions analyzed for PV and PVL, the graphs will present the results combined across sexes for simplicity. However, tables reporting the data separated by sex and for each variable in each condition will be provided in the supplementary materials.

Figure 2: Bland-Altman Plot of Ds in different conditions and days

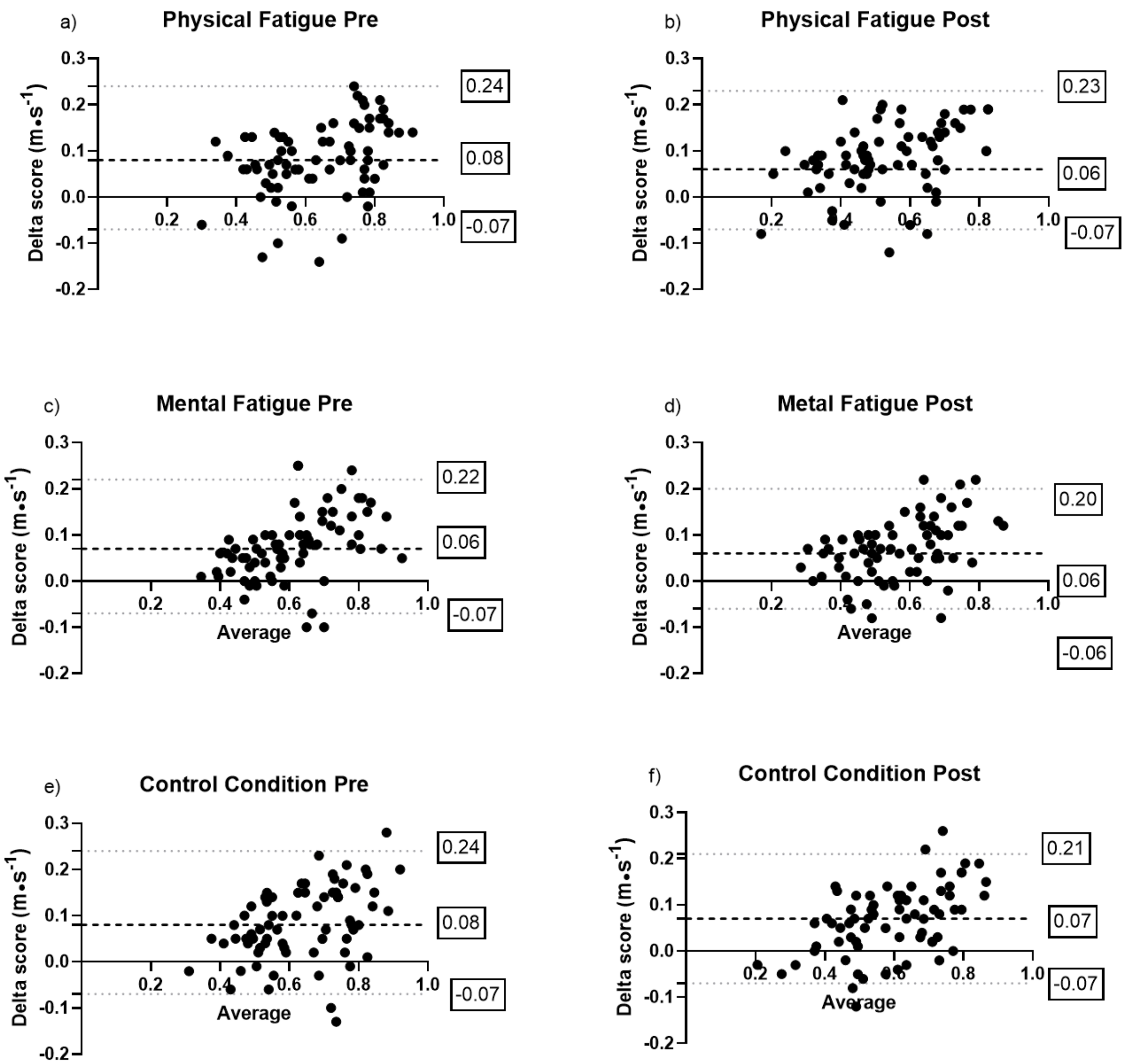


Figure 2. Delta Score: Differences between perceived velocity and real velocity (Vp-Vr); a) Bland-Altman Plot of Delta Score before physical fatigue; b) Bland-Altman Plot of Delta Score after physical fatigue; c) Bland-Altman Plot of Delta Score before mental fatigue; d) Bland-Altman Plot of Delta Score after mental fatigue; e) Bland-Altman Plot of Delta Score before control condition ;f) Bland-Altman Plot of Delta Score after control condition

Physical Fatigue

The physical fatiguing protocol led to significant performance decrements, as demonstrated by the results of the repeated-measures ANOVAs with sex as a between-subjects factor. A significant main effect of time was observed for CMJ performance ($F(1) = 47.96$, $p = 0.00$, $\eta^2 = 0.75$; Table 1). Additionally, the time × sex interaction was significant ($F(1) = 4.81$, $p = 0.04$, $\eta^2 = 0.23$). Pairwise post hoc analysis revealed that both males and females exhibited significant reductions in CMJ height ($p < 0.05$), although the magnitude of the decrease differed, with males showing a greater decline compared to females (Table 1). Furthermore, a significant main effect of time was found for peak RFD ($F(1) = 38.35$, $p = 0.00$, $\eta^2 = 0.71$), early RFD ($F(1) = 36.00$, $p = 0.00$, $\eta^2 = 0.69$), late RFD ($F(1) = 34.47$, $p = 0.00$, $\eta^2 = 0.67$), and MVC ($F(1) = 57.60$, $p = 0.00$, $\eta^2 = 0.78$) (Table 1). However, no significant time × sex interactions were observed for any of these variables, indicating that the reductions in performance were similar between males and females. Regarding Ds and |Ds|, as reported before, no significant main effects or interactions were found ($p > 0.05$) (Figure 3). As discussed before Vscore and |Vscore| yielded significant main effects for time (Figure 4). Pairwise post hoc revealed that both Vscore and |Vscore| was significantly lower after PF protocol (Figure 4a and 4b).

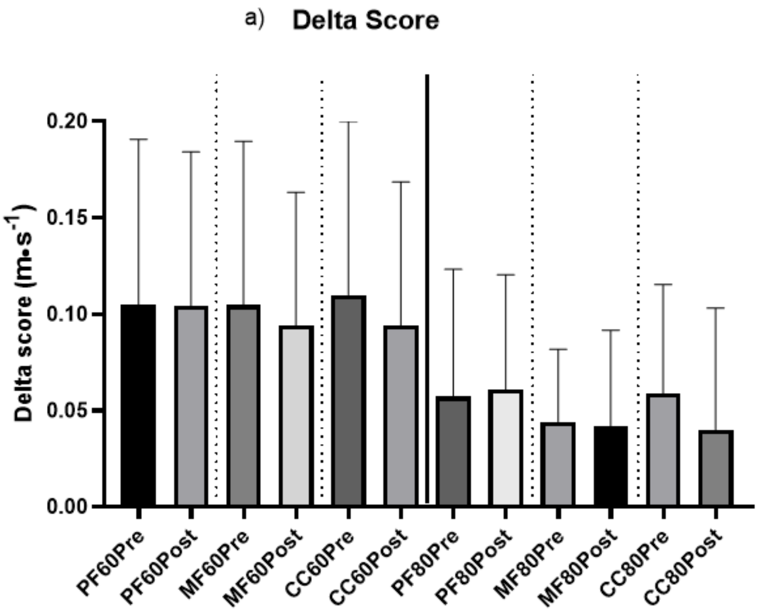
Table 1: Comparison between Pre- and Post-conditions of performance measurement

	Sex	Physical Fatigue		Mental Fatigue		Control Condition	
		Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*

CMJ (cm)	M	40.2±6.9	33.3±4.7*#	40.9±7.6	39.1±7.0*	40.3±7.9	39.6±7.4
	F	33.1±3.9	29.4±3.9*#	34.0±4.6	32.8±4.0*	33.4±5.0	32.9±4.5
Early RFD (N/s)	M	9062±1742	7057±982*	8812±1360	8130±1426*	8581±1434	8543±1364
	F	8268±1775	6539±1922 *	8196±1721	7822±2025*	7942±1742	7972±192
Late RFD (N/s)	M	6843±1621	5345±788*	6664±1081	6215±1103*	6605±1276	6582±1174
	F	6030±1425	4595±1415 *	5979±1309	5688±1475*	6094±1396	6021±1480
Peak RFD (N/s)	M	13007±2891	9994±2408 *	12695±2167	11752±2355*	12584±1759	12481±1918
	F	11741±2201	9513±2529 *	11772±2576	11094±3229*	10825±2810	11122±3336
MVC (N)	M	2430±636	2041±544*	2492±621	2387±610*	2323±588	2297±537
	F	1690±496	1276±428*	1528±425	1439±440*	1797±587	1754±56

*Table 1. CMJ: Counter movement jump; Early RFD: Rate of Force development 0-100ms; Late RFD: Rate of Force development 0-200ms; Peak RFD: Highest Rate of Force development registered; MVC: Maximum voluntary contraction; M: Males; F: Females; * significant differences between Pre and Post condition; # significant differences in time*sex interaction*

Figure 3: Comparison of Ds and |Ds| among the different conditions divided for Load



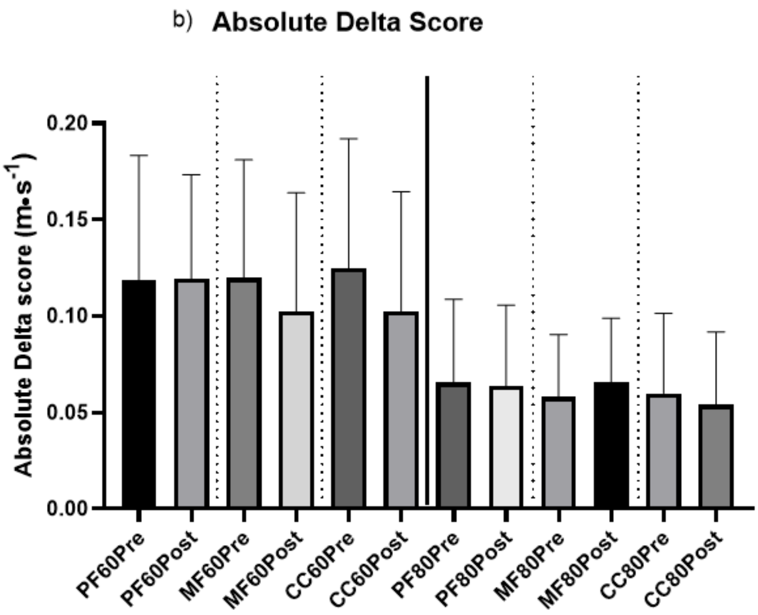


Figure 3. a)Delta Score: Differences between perceived velocity and real velocity (Ds= Vp-Vr); b) Absolute Delta Score: Absolute differences between Vp and Vr (|Ds|=|Vp-Vr|); PF60Pre: Ds and |Ds| before physical fatigue with 60%1RM; |); PF60Post: Ds and |Ds| after physical fatigue with 60%1RM; |); MF60Pre: Ds and |Ds| before mental fatigue with 60%1RM; |); MF60Post: Ds and |Ds| after mental fatigue with 60%1RM; |); CC60Pre: Ds and |Ds| before control condition with 60%1RM; |); CC60Post: Ds and |Ds| after control condition with 60%1RM; PF80Pre: Ds and |Ds| before physical fatigue with 80%1RM; |); PF80Post: Ds and |Ds| after physical fatigue with

80%1RM; |); MF80Pre: Ds and |Ds| before mental fatigue with 80%1RM; |); MF80Post: Ds and |Ds| after mental fatigue with 80%1RM; |); CC80Pre: Ds and |Ds| before control condition with 80%1RM; |); CC60Post: Ds and |Ds| after control condition with 80%1RM

Figure 4: Comparison of Vscore and |Vscore| among the different conditions divided for load and %Vloss

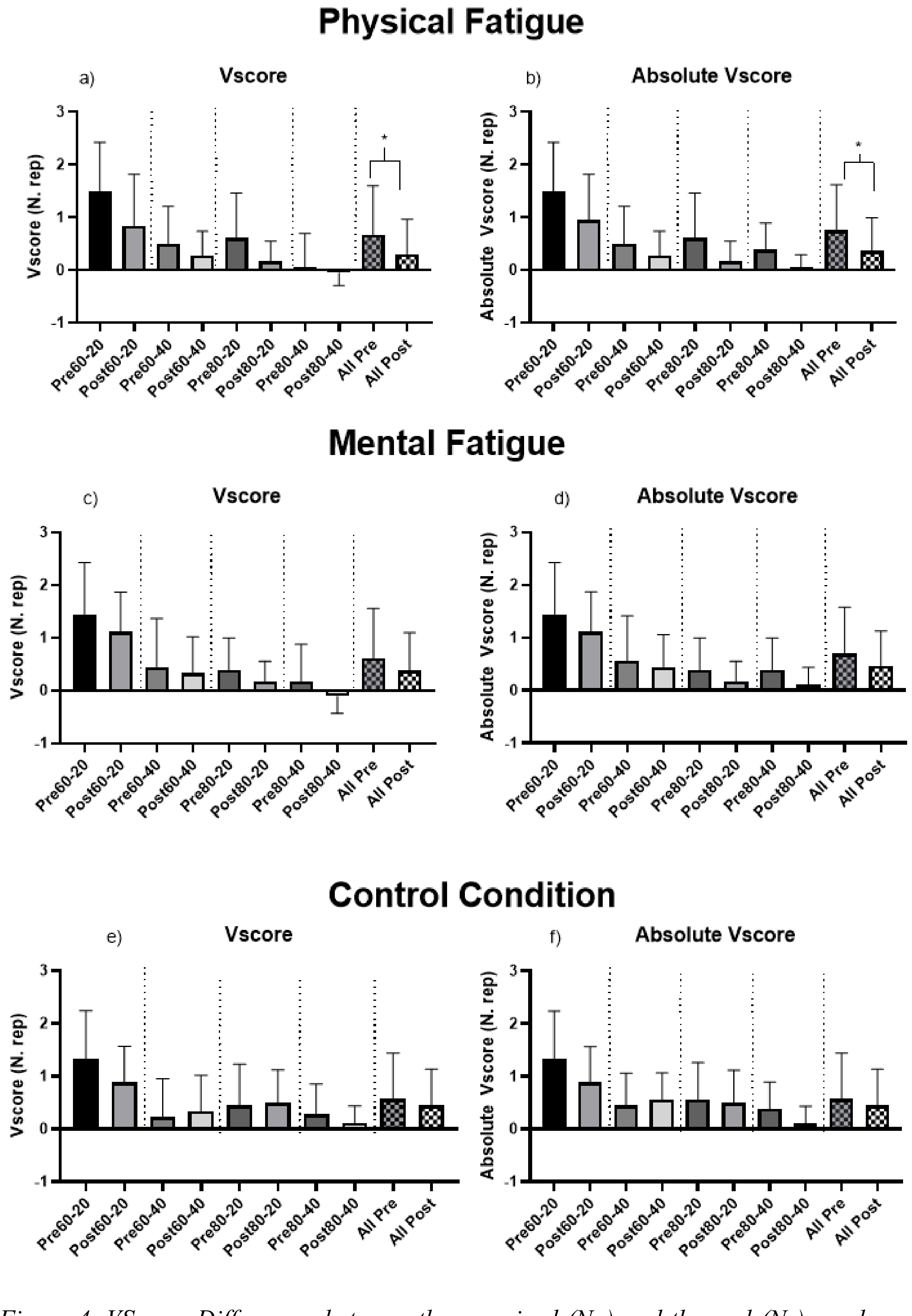


Figure 4. VScore: Differences between the perceived (Np) and the real (Nr) number of repetitions (Vscore= Np-Nr); b) Absolute V Score: Absolute differences between Np and Nr (|VScore|=|Np-Nr|); a) Vscore in physical fatigue condition; b) |Vscore| in physical fatigue condition; c) Vscore in Mental Fatigue condition; d)|Vscore| in mental fatigue condition; e) Vscore in control condition; f) |Vscore|

*in control condition; Pre60-20: Score before condition with 60%1RM and 20%VL; Post60-20: Score after condition with 60%1RM and 20%VL; Pre60-40: Score before condition with 60%1RM and 40%VL; Post60-40: Score after condition with 60%1RM and 40%VL; Pre80-20: Score before condition with 80%1RM and 20%VL; Post80-20: Score after condition with 80%1RM and 20%VL; Pre80-40: Score before condition with 80%1RM and 40%VL; Post80-40: Score after condition with 80%1RM and 40%VL; All Post: Score before condition, regardless of load and %VL; All Post: Score after condition, regardless of load and %VL * significant differences in Vscore or |Vscore| between Pre and Post condition*

Mental Fatigue

Perceived MF significantly increased ($p < 0.05$) following the AX-CPT task in both males and females with no significant differences between sexes. Motivation and total mood remained unchanged ($p > 0.05$). Further details on VAS and POMS are provided in the supplementary material (see supplementary materials). Repeated-measures ANOVAs with sex as a between-subjects factor revealed significant main effects of time for CMJ ($F(1) = 35.52$, $p = 0.00$, $\eta^2 = 0.68$) and MVC ($F(1) = 13.20$, $p = 0.02$, $\eta^2 = 0.45$) (Table 1). Pairwise post hoc analyses indicated that both males and females experienced significant performance declines in these measures ($p < 0.05$) (Table 1). Regarding RFD parameters, significant main effects of time were observed for peak RFD ($F(1) = 9.56$, $p = 0.07$, $\eta^2 = 0.37$), early RFD ($F(1) = 15.77$, $p = 0.01$, $\eta^2 = 0.50$), and late RFD ($F(1) = 15.52$, $p = 0.01$, $\eta^2 = 0.49$) (Table 1). However, pairwise post-hoc analyses showed that only males exhibited significant reductions across all RFD measures ($p < 0.05$), whereas females displayed a non-significant decreasing trend ($p = 0.07$–0.09). Despite these tendencies, no significant time × sex interactions emerged in any of the tests performed (all $p > 0.05$). As stated before for Ds and |Ds| no significant main effects or interactions were found ($p > 0.05$) (Figure 3). Likewise, Vscore and |Vscore| showed no significant main effects or interaction ($p>0.05$; Figure 4).

Control Condition

No significant differences in perceived MF, motivation, or POMS scores before and after the CC in both males and females ($p > 0.05$; supplementary materials) were found. Additional details on VAS and POMS are available in the supplementary material. Repeated-measures ANOVAs, with sex as a between-subjects factor, showed no significant effects for CMJ, peak RFD, early RFD, late RFD, or MVC ($p > 0.05$; Table 1). As previously discussed for Ds and |Ds| no significant main effects or interactions were found ($p > 0.05$) (Figure 3). Likewise, Vscore and |Vscore| showed no significant main effects or interaction ($p>0.05$; Figure 4).

Discussion

The present study investigated the consistency of PV and PVL across three consecutive days, and whether MF and PF alter their accuracy. The results showed that both PV and PVL are stable across three different training sessions, and, as hypothesized, were not affected by the two fatiguing conditions. Moreover, no differences between sexes were observed in PV and PVL.

Stability of PV and PVL

Similarly to previous studies, PV and PVL were consistent across the three testing days at rest(28,30,35). Regarding PV, in all testing sessions, the heavier load (80%1RM) showed a smaller error for Ds and |Ds| compared to the lighter one (60%1RM), finding consistent with the literature(28,30,31,35). Moreover, considering the potential influence of proprioception level on PV, we hypothesized sex-related differences in PV accuracy, as previous studies have suggested that proprioception may differ between sexes(24). However, our results did not support this hypothesis, as no differences in PV accuracy were observed between males and females. One possible explanation is that, although sex differences in proprioception have been reported(24), these results come from studies using single-joint tasks, which are very different from the free-weight back squat performed in this study. Indeed, it has been suggested that proprioceptive accuracy measured in relation to a specific body part (e.g., elbow) in one particular task (e.g., perception of muscle tension or joint position reproduction) cannot be generalized to other task(16). In fact, a previous review reported no correlation between different tests(16), and proprioceptive accuracy has been suggested to be both site-specific(16) (referring to muscular district) and test-specific(16).

In agreement with one study(35), greater precision in PVL was observed with heavier loads (80%1RM) and higher %VL (40%VL), while other studies showed controversial results(17,19,33,34). In fact, regarding load, some authors reported similar outcomes(33), while others found greater precision with medium loads(19) (~50-60%1RM). Concerning the %VL, some studies reported lower PVL accuracy as the number of repetitions increased(17,19,34). These differences could be partially explained by the different methodologies used(17,19,34). It is worth noting that the aforementioned studies provided limited familiarization, ranging from none(17,34) to a single session(19,33), and employed a different methodology to assess PVL. Specifically, Sindiani et al.(34) and Lazarus et al.(19) evaluated the accuracy of PV on a repetition-by-repetition basis within sets. However, from a practical point of view, it is more important to accurately determine the repetition where the %VL is exceeded instead of the identification of the velocity in each single repetition. This is particularly relevant because, regardless of the error in PV in each repetition, what ultimately matters is whether the subject can correctly identify the first repetition that exceeds the required %VL threshold, as the number of repetitions performed determines the training volume. Furthermore, asking the individual to monitor and report velocity changes on a repetition-by-repetition basis may demand a higher level of attentional focus compared to simply identifying the repetition at which they believe the prescribed threshold has been reached. Some recent studies have already investigated this direction with very interesting results, highlighting that the observed error is considered acceptable, or even negligible, for the purpose of prescribing training sessions(17,35). Moreover, in line with a previous study (35), we found that approaching failure enhances the detectability of the %VL threshold. In fact, sets performed at 80%1RM with 40%VL, those closest to failure, showed the best PVL accuracy(35). In addition, these findings align with those observed for another autoregulation resistance training method: Repetition-In-Reserve (RIR)(14). In fact, as observed for PVL, greater accuracy in RIR was also found when subjects performed sets closer to failure (14), suggesting the presence of a common underlying mechanism. The present findings suggest that extended familiarization enables individuals to associate the onset of failure both with a low RIR and by reaching the %VL threshold. Conversely, the lowest, but still acceptable, PVL accuracy was observed in sets performed at 60%1RM with 20%VL. Furthermore, sets at 60%1RM with 40%VL and 80%1RM with 20%VL, showed similar, and acceptable PVL precision. In conclusion, these findings suggest that load, %VL, and their interaction influence PVL accuracy.

Physical Fatigue condition

The reduced MVC and lower amplitude of all RFD components confirm that our protocol effectively induced PF (Table 1). Moreover, a reduction in CMJ height was observed, with a greater decrease in males compared to females.

In line with our hypothesis and as previously shown(31), the PF condition did not influence either Ds or |Ds|, suggesting that PV accuracy is not affected by PF. By adding also the |Ds|, we rule out the possibility that either an underestimation or overestimation of velocity might have masked a real change in PV accuracy. Concerning PVL, lower errors were found for both Vscore and |Vscore|

following PF protocols. These findings reinforce the results of earlier studies(35), which suggest that %VL thresholds can be identified more accurately as athletes approach momentary failure. Therefore, following the PF protocol, performing a set with the same absolute load and the same target %VL results in a more fatiguing effort, with its endpoint being closer to failure compared to a rested condition. This proximity to failure likely enhances the accurate identification of the intended %VL threshold, thereby reducing error in both Vscore and |Vscore|, for the same mechanism discussed above.

Mental Fatigue and Control Condition

This was the first study that investigated the effect of MF on PVL. In line with our hypothesis, characteristics and accuracy of PV and PVL were not affected by MF. Results of the VAS showed that the AX-CPT test effectively induced MF. Moreover, as expected, motivation and mood were not altered by the AX-CPT test. It was already been shown that MF does not affect PV, but with a shorter protocol (i.e sets with only two repetitions)(29). Longer test sessions were recommended for future research as it is a more ecological approach to the problem. We did not expect to observe any changes in CMJ, MVC, or RFD under the MF condition, based on the results of two reviews that reported no alterations in either maximal anaerobic performance(4) or strength endurance(1), including measures such as CMJ, MVC or maximum torque(1,4). Contrary to our hypothesis, yet consistent with a growing body of evidence(10,18,39), MF altered all performance parameters. Indeed, we reported a reduction in CMJ height, in line with Gonzalez et al., along with a reduction in MVC, as previously shown(10,18). Regarding the RFD, a significant decrease in all components was found in males, and a decreasing trend was observed in females. These results partially align with a previous investigation that found a decrease in RFD only during the later phase of force generation (between the 20% and 80% of maximum force interval)(39), but not in the 0-100 ms or 100-200 ms intervals, nor in peak RFD components(39) in MF condition. Further investigations are needed to understand the mechanism underlying the inconsistencies between these studies(5,10,39) and what previous reviews report(1,4), and to try to determine the actual effect of MF on anaerobic performance. As expected, in the Control Condition, results of VAS and POMS demonstrated that neither MF nor motivation were affected. Moreover, no significant differences were found in performance parameters between the Pre and Post CC, demonstrating that subjects were neither mentally nor physically fatigued. Regarding PV and PVL, no differences between the pre and post condition in Ds, |Ds|, Vscore, and |Vscore| were found.

Conclusion

The present study was the first to investigate the effects of MF and PF on PV and PVL assessed simultaneously in a training setting that closely replicated real world practice.

The results confirm our hypothesis, suggesting that no condition (neither PF nor MF) negatively affected PV and PVL in athletes after a short period of familiarization (i.e., 4 sessions). Both PV and PVL appear to be influenced by load, with higher precision at heavier loads. Moreover, PVL showed better accuracy with higher %VL. This is explained by the fact that Vscore and |Vscore| exhibited lower errors in all sets performed closer to muscular failure, supporting the previous hypothesis(35) that this condition enhances the detectability of the %VL threshold.

Regarding the accuracy of PV and PVL, a negligible error was found in sets with heavy loads and high velocity loss for |Vscore| (i.e., less than 1 repetition per set). For all other sets, the error was acceptable (i.e., less than 2 repetitions per set). Meanwhile, for |Ds|, an acceptable error (i.e., less than 0.08 $m\cdot s^{-1}$) was found only with high loads. Therefore, these results suggest that under these conditions, PV and PVL could be used to prescribe VBT in real training settings when linear position transducers are not available. However, at lighter loads (around 60%1RM), large errors in |Ds| (i.e., > 0.10 $m\cdot s^{-1}$) were observed. These outcomes suggest that the use of PV, in such sets could result, according to the American college of sports medicine(41), in a non-negligible error in load (10%1RM)(23), considering that the highest acceptable error has been reported to be 0.09 $m \cdot s^{-1}$ (35). Current results suggest that PVL can be effectively used to prescribe training volume, especially with high loads and high velocity loss. On the other hand, PV may be suitable for high loads but should be used with caution for lighter loads (less than 60%1RM), as it can produce a non-negligible margin of error.

Despite the present results, this study presents some limitations and consideration that should be taken into account for future research. a) This study employed only subjective methods (VAS and POMS) for MF assessment. Although these methods are validated(6,26), objective methods could be used to assess the temporal pattern and the actual inducement of MF; b) The participants exhibited similar ages and similarly high levels of resistance training experience. Therefore, further studies are needed to determine whether age and resistance training experience may influence PV and PVL accuracy; c) The present study did not investigate the level of subjects' proprioception. Considering the greater variability in PV accuracy, future research should implement methods to assess subjects' proprioceptive abilities, as previously suggested (15,16) , in order to determine whether these are correlated with PV accuracy. d) The lowest %VL employed in this study was 20%. However, other %VL values are also used in VBT sessions (i.e., 10%-30%VL). Therefore, future studies should investigate the accuracy of PVL at others %VL values, especially the ones below 20%, and the possibility of discriminating between such similar %VL

Practical application

Neither physical nor mental fatigue negatively affected PV or PVL in either males or females during a strength training session of back squat. Based on these findings, both PV and PVL can be considered valid alternatives for training prescription after a short period of familiarization (i.e., 4 sessions), regardless of the athlete's fatigue status. The error in PV and PVL was very low and acceptable under higher load and %VL conditions (>60%1RM and >20%VL), supporting the reliability of PV and PVL in these contexts. In contrast, when loads lower than 60%1RM are used, PV appears to show, at least in some individuals, error values that are not acceptable for accurate training prescription. The reasons underlying this inter-individual variability remain unclear to date

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Supplementary materials

Supplementary Materials. Table 1: Differences in Delta Score between males and females

	Sex	Physical Fatigue	Mental Fatigue	Control Condition

DeltaScore (m/s)		*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*
60%1RM	M	0.09±0.09	0.09±0.09	0.09±0.09	0.08±0.07	0.10±0.09	0.09±0.08
	F	0.11±0.07	0.11±0.06	0.12±0.05	0.10±0.06	0.11±0.09	0.09±0.05
80%1RM	M	0.06±0.05	0.06±0.05	0.04±0.04	0.04±0.04	0.06±0.06	0.05±0.05
	F	0.05±0.07	0.06±0.07	0.04±0.03	0.04±0.05	0.05±0.04	0.03±0.06

Supplementary Materials. Table 2: Differences in Vscore at 20%VL between males and females

Vscore 20%VL (Nrep)	**Sex**	**Physical Fatigue**		**Mental Fatigue**		**Control Condition**	
		Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*
60%1RM	M	1.5±0.7	1.1±0.9	1.4±1.2	1.0±0.9	1.6±0.8	0.8±0.8
	F	1.5±1.1	0.8±1.2	1.5±0.8	1.1±0.6	1±0.9	0.9±0.6
80%1RM	M	0.5±0.8	0.1±0.3	0.4±0.5	0.2±0.4	0.3±0.8	0.5±0.5
	F	0.7±0.8	0.3±0.4	0.3±0.7	0.2±0.4	0.6±0.7	0.5±0.7

Supplementary Materials. Table 3: Differences in Vscore at 40%VL between males and females

Vscore 40%VL (Nrep)	**Sex**	**Physical Fatigue**		**Mental Fatigue**		**Control Condition**	
		Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*
60%1RM	M	0.4±0.7	0.3±0.5	0.4±1.1	0.4±0.8	0.2±0.9	0.3±0.8
	F	0.6±0.7	0.3±0.5	0.5±0.8	0.3±0.5	0.3±0.5	0.4±0.5
80%1RM	M	0±0.7	-0.1±0.3	0.3±0.7	-0.1±0.3	0.2±0.6	0.1±0.3
	F	0.1±0.6	0.1±0.4	0.1±0.8	-0.1±0.4	0.4±0.5	0.1±0.4

Supplementary Materials. Table 4: Differences in total mood and VAS score between males and females

	Sex	**Mental Fatigue**		**Control Condition**	
		Pre	*Post*	*Pre*	*Post*
Total mood score	M	5.9±5.4	7.7±7.5	3.9±11.4	3.4±10.3
	F	5.56±5.6	6.67±4.1	3.8±7.0	4.1±5.2
VAS Mental Fatigue (%)	M	32.9±15.1	65.0±19.7	41.9±27.4	31.6±25.8
	F	38.6±27.1	61.7±33.6	36.1±21.3	27±21.5
VAS Motivation (%)	M	69.5±21.4	61.1±15.05	67.4±21.9	67.7±21.8
	F	63.7±24.7	63.3±21.9	69.1±19.7	64.5±19.9

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Chapter 10: Validation of a Velocity Perception Scale for the Bench Press: Accuracy in velocity perception and %1RM perception across multiple loads

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Title: Validation of a Velocity Perception Scale for the Bench Press: Accuracy in velocity perception and %1RM perception across multiple loads

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Abstract:

Dello Stritto, E, Sánchez-Valdepeñas, J, Romagnoli, R, and Piacentini, MF. Validation of a velocity perception scale for the bench press: Accuracy in velocity perception and %1RM perception across multiple loads. J Strength Cond Res XX(X): 000–000, 2025—The aim of this study was to validate a velocity perception scale specific for the bench press to help subjects accurately perceive the execution velocity of each repetition. In addition, we investigated whether subjects were also able to estimate the lifted %1RM and whether this estimation was more or less accurate than their perception of velocity (PV). Twenty healthy males completed 4 familiarization sessions with the velocity perception scale and 3 testing sessions, where they performed 7 different loads per session in a random order (velocity ranging from 1.10 $m \cdot s^{-1}$ to 0.20 $m \cdot s^{-1}$). For each repetition, the real velocity (Vr) measured, the perceived velocity (Vp) and the perceived %1RM (%1RMp) were registered. Pearson's correlation (r) and the coefficient of determination (R^2) demonstrated high values across all 3 days for both Vp-Vr ($r = 0.94$–0.95; $R^2 = 0.89$–0.90) and %1RMp-measured %1RM ($r = 0.89$–0.92; $R^2 = 0.80$–0.85). The reliability of Vp was assessed using intraclass correlation coefficient (ICC) model 2, form 1, and showed good values for each load used, ranging from ICC = 0.77–0.84 across the 7 loads. Perception of velocity accuracy was determined using the DeltaScore, defined as the difference between Vp and Vr (DeltaScore = Vp − Vr). Subsequently, %1RMp was converted into velocity using individual load-velocity relationships, leading to the creation of DeltaRM defined as the difference between %1RMp (converted to velocity) and Vr (DeltaRM = %1RMp − Vr). This conversion enabled a direct comparison between the accuracy of the DeltaScore (Vp − Vr) and DeltaRM (%1RMp − Vr) via Bland-Altman plots, which consistently revealed a lower error for the DeltaScore. In conclusion, Vp proved to be a very stable parameter across the 3 days, and subjects were able to accurately discriminate even small velocity variations resulting from the use of 7 different loads during bench press.

Keywords: autoregulation; load-velocity relationship; velocity-based training; resistance training; strength training.

INTRODUCTION

Resistance training (RT) has been extensively studied, and the beneficial effects of a well-designed training program on enhancing muscular strength and sports performance are well known (9,13,22). Traditionally, the prescription of the RT sessions was based on the 1 repetition maximum (1RM) and their submaximal percentages, related to the number of repetitions that can be performed (10,23). The main limitation of the traditional method is its inability to account for daily fluctuations in 1RM because of factors like fatigue, sleep quality, and the athlete's adaptation to training (10). Therefore, using this method makes it challenging to monitor an athlete's daily readiness accurately (23). To solve these limitations, velocity-based training (VBT) has proved to be an objective approach that uses the barbell's velocity for efficiently tracking training loads and their impacts. The relationship between relative load and lifting velocity, initially identified by Gonzalez-Badillo and Sanchez-Medina (6), has gained widespread acceptance among researchers and practitioners as a reliable tool for accurately assessing relative loads (e.g., %1RM). Furthermore, by monitoring barbell velocity, it is possible not only to track the athlete's daily readiness but also to assess their fatigue level during every training session (24). Although the advantages of VBT are clear, one of the main challenges is the high cost of the equipment used to measure velocity. The most reliable devices for this purpose are linear position transducers (LPTs) (11) and linear velocity transducers (11), which are quite expensive. Because of their cost, purchasing multiple units may be unrealistic for many organizations, limiting their ability to prescribe resistance training sessions using VBT. For this reason, the scientific community has started investigating athletes' ability to perceive barbell velocity integrating the use of specific devices (1,5,7,16–19,21).

With the aim of addressing this issue and providing more accessible tools for practitioners, perception of velocity (PV) scales have been validated (1,18). The first perception scale (1) showed very broad and general velocity ranges from 1.6 $m \cdot s^{-1}$ to 0.10 $m \cdot s^{-1}$ as the minimum velocity threshold (MVT), which is a value that varies significantly depending on the exercise performed (23). The second validated scale for velocity perception, developed by Romagnoli et al. (18), is specific for the full squat. It features minimum and maximum ranges aligned with the velocities reported for the full squat. In this line, previous studies have reported that athletes can perceive barbell velocity with a certain degree of accuracy (1,2), and subsequently, have shown that, through training and familiarization, the margin of error between the real velocity (Vr) and perceived velocity (Vp) decreases even more (16). However, a closer analysis of the existing literature on velocity perception reveals that studies generally use only 3 loads (40, 60, 80%1RM) (17–19) to investigate velocity perception, with only 1 study using 5 loads (16). Such a limited number of loads does not allow the understanding of how sensitive athletes' velocity perception is to small changes in load, which is crucial in a real training context. For this reason, it remains unclear whether, and to what extent, athletes can perceive smaller velocity variations than those typically observed with the 3 loads commonly used in the literature (16,17,19).

Last, as previously mentioned, barbell velocity is closely linked to %1RM (4,6), making it particularly relevant to explore not only athletes' PV but also their ability to accurately estimate the %1RM, especially when they are already accustomed to and using it in regular RT sessions. Furthermore, it is essential to evaluate the accuracy of these perceptions and determine whether the estimated %1RM aligns with the perceived velocities. For this reason, considering that athletes can accurately perceive barbell velocity and the use of the perception scale as a tool to compensate the potential lack of a sufficient number of LPTs, the aim of the present study was to (a) validate a new velocity perception scale specific for the bench press (Figure 1); (b) assess whether athletes can perceive small changes in load using a total of 7 different loads; (c) determine if athletes are able to perceive not only barbell velocity but also the associated %1RM; (d) determine whether the Vp and perceived %1RM are congruent, and, if not, which of the 2 shows a smaller error compared with the actual load.

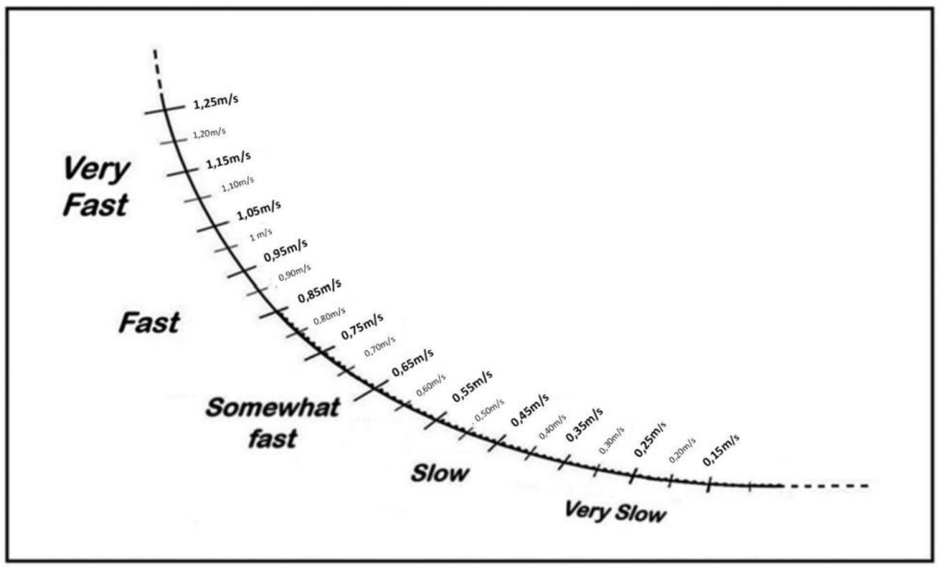

Figure 1. Velocity perception scale for the Bench Press

Methods

Experimental Approach to the Problem

The study design included a total of 7 training sessions, all performed on the bench press using a Smith machine (Multipower Fitness Line; Peroga, Murcia, Spain). The first 3 sessions were used to familiarize the subjects with the new velocity perception scale specific for the bench press, which this study aimed to validate, and with the concept of velocity perception across a wide range of loads. In addition, anthropometric measurements (i.e., height, weight, and age) of the subjects were recorded during the first session. The fourth training session involved an incremental loading test in the bench press exercise until 1RM, during which subjects were further familiarized with the scale and velocity perception across all loads used (from~20%RM to 1RM). Finally, the last 3 sessions were dedicated to testing the accuracy and reliability of the subjects' velocity perception accuracy.

The PV scale validated in this study (Figure 1) is specifically designed for the bench press. The scale includes a minimum of 0.15 $m\cdot s^{-1}$ and a maximum of 1.25 $m\cdot s^{-1}$ velocity values. The lowest value of the scale has been aligned with what has been reported in the literature for the bench press (6). However, the maximum velocity value of 1.25 $m\cdot s^{-1}$ is not the highest velocity recorded in the literature, but rather the velocity typically associated with 30% of 1RM (20). Loads at or below this percentage are rarely used during bench press training, which is why this velocity was selected as the starting point for the scale. Finally, the verbal anchors associated with the velocities, as reported by Romagnoli et al. (18), align with how athletes perceive these velocities when performing the exercise.

Subjects

The present study included 20 healthy males (age: 23.9 years ±3.0; body weight: 77.0 kg ± 8.8; height: 1.78 *m* ± 0.07; 1RM/BW 1.07 ± 0.13). The inclusion criteria were at least 1 year of experience in RT, age between 18 and 35 years, and absence of current or previous injuries that could affect performance during testing sessions. After receiving detailed information about the procedures, risks, and ethical aspects of the study, and a copy of the explanatory information sheet, subjects signed informed consent and data processing forms. The study protocol was approved by the Research Ethics Committee of "Hospitales Univesitarious Virgen Macarena-Virgen del Rocio (Reference:1547-N-19)" and was prepared in accordance with the latest revision of the Helsinki Declaration, which aims to protect the rights, integrity, and well-being of subjects involved in experiments. Participation in the study could be terminated at any time at the request of the subject and/or staff, without needing to provide reasons and without facing any consequences.

Procedures

Familiarization Sessions

The 3 familiarization sessions were designed to help subjects become acquainted with the velocity perception scale and the velocities reached during the execution of the bench press. Each session began with a warm-up involving joint mobility exercises and self-selected loads by the subjects. An initial set on the bench press performed with an unloaded barbell (20 kg) with maximal intent. In the first familiarization session (day 1), subjects performed heavy loads (<0.60 $m \cdot s^{-1}$) to become accustomed to the lower part of the scale. In the second session (day 2), moderate (0.80 $m \cdot s^{-1}$ to 0.60 $m \cdot s^{-1}$) and light (1 $m \cdot s^{-1}$ to 0.80 $m \cdot s^{-1}$ loads) were used, corresponding to the middle portion of the scale. Finally, in the last familiarization session (day 3), subjects were introduced to the upper part of the scale by using light and very light loads (>1 $m \cdot s^{-1}$). During the familiarization with medium and light loads, subjects were asked to perform 4 repetitions for each load, whereas with heavy loads, only 2 or 3 repetitions were required. For each day-specific target velocity, subjects performed 2 different loads falling within the corresponding velocity range, in incremental order. Before reaching the target velocity, subjects completed at least 2 ramp-up sets toward the target. During all familiarization sessions, subjects received auditory feedback from the investigator, regarding the velocity achieved during each repetition. After each set, they were shown the velocity perception scale intended for validation and informed about the velocity attained during the completed set.

Incremental Loading Test in Bench Press

Before the test, subjects performed a dynamic warm-up consisting of mobility, stretching, and body weight exercises. A linear velocity transducer (T-Force System; Ergotech) was utilized to measure mean propulsive velocity, range of motion, and power output. Subjects performed a maximal incremental test on a Smith machine (Multipower Fitness Line; Peroga) with no counterweight mechanism. They were instructed to perform each repetition as fast as possible. The initial load of the test was set at 20 kg. Three repetitions were conducted for light loads (>0.80 $m \cdot s^{-1}$), 2 for medium loads (0.80–0.60 $m \cdot s^{-1}$), and 1 for heavy loads (<0.60 $m \cdot s^{-1}$). Interset recovery periods were set at 3–5 minutes for light, medium, and heavy loads, respectively. Load increments ranged from 10 to 2.5 kg, depending on the barbell velocity. The test concluded when the athlete was unable to complete a single repetition at a given load.

Perception of Velocity Assessment Test

During the final 3 sessions, subjects' PV was evaluated. In each session, subjects completed 2 repetitions at each of 7 different loads proposed, with barbell velocities ranging from 1.10 to 0.20 $m \cdot s^{-1}$. These loads were both randomized and concealed so that subjects remained unaware of the specific load being lifted. Moreover, the loads were structured so that the 4 lightest ones (1.10, 0.95, 0.80, and 0.65 $m \cdot s^{-1}$) were performed first in a random order, followed by the 3 heaviest (0.50, 0.35, and 0.20 $m \cdot s^{-1}$) also in a random order. This progression ensured that excessively heavy loads were not lifted without proper warm-up, but subjects were not informed of this specific randomization procedure. After completing the first repetition of each set, subjects reported the Vp of that repetition. After the second repetition, they reported both the Vp of the second repetition and visualized the values they indicated on the PV scale. Last, they reported the perceived %1RM (%1RMp).

Statistical Analyses

Data were normally distributed, according to the Shapiro-Wilk test ($p > 0.05$). The accuracy levels in velocity perception were calculated as the difference between Vp and Vr, referred to as DeltaScore (18). The reliability of DeltaScore accuracy levels across the 3 testing days was assessed using the Intraclass Correlation Coefficient (ICC: model 2, form 1) and the *SEM*. *SEM* was calculated as *SEM* × (square root of [1 − ICC]) (14). The correlation between Vp and Vr was analyzed using Pearson's r for each of the 3 test days. The magnitudes of Pearson's r were classified as follows: trivial (<0.1), small (0.1–0.3), moderate (0.3–0.5), high (0.5–0.7), very high (0.7–0.9), and nearly perfect (>0.9). A simple linear regression between Vp and Vr was performed for each day to obtain the coefficient of determination (R^2). A 2-way repeated measure ANOVA was used to identify any differences in DeltaScore across the different loads and test days. The levels of agreement between

Vp and Vr were explored using Bland-Altman plots. The accuracy levels in %1RM were calculated as the difference between the %1RMp and the measured %1RM.

The correlation between %1RMp and %1RM was analyzed using Pearson's r for each of the 3 test days. A simple linear regression between %1RMp and %1RM was performed for each day to obtain the R^2. A 2-way repeated measure ANOVA was used to identify any differences between %1RMp and %1RM across the different loads and test days. The %1RMp was converted into velocity using the individual load-velocity relationship, to assess the agreement between the Vp, derived from %1RM, and Vr provided by the encoder, using Bland-Altman plots. This approach also allows for the comparison of accuracy levels between the DeltaScores and DeltaRM: the first derived from the difference between Vp and Vr, and the second from the difference between %1RMp (converted into velocity) and Vr (DeltaRM = %1RMp-Vr). Last, the absolute mean error of the DeltaScores will be calculated. The alpha level was set at $p < 0.05$. Statistical analyses were performed in Microsoft Office Excel (Microsoft Inc., Redmond, WA) and SPSS v25 (SPSS Inc., Chicago, IL). A power post-hoc analysis was conducted for the results identified as significant to estimate the power of our findings. Effect sizes were determined using η^2 when the result was statistically significant, considering 0.2 = small effect, 0.5 = moderate effect, and 0.8 = large effect.

Results

The coefficients of determination from the simple regression analysis (R^2) and the Pearson correlation coefficients (r) from the correlation analysis, for both velocity and %1RM, are reported in Table 1. The results of these analyses reveal very high to practically perfect levels of correlation and coefficients of determination between Vp and Vr, and between %1RMp and %1RM.

Table 1. Pearson correlation coefficients (r) and coefficient of determination (R^2) between Vp- Vr and %1RMp -%1RM)

	Vp-Vr		**%1RMp- %1RM**	
	r	**R²**	**r**	**R²**
Session 1	0.952	0.906	0.897	0.805
Session 2	0.941	0.895	0.914	0.836
Session 3	0.950	0.902	0.922	0.850

Table 1. Vp: Perceived velocity; Vr: real velocity; %1RMp: perceived %1RM; r: Pearson correlation; R²: coefficient of determination

The results of the ICC model 2 form 1 analysis, along with the corresponding SEM, demonstrate that velocity perception is highly consistent across the three days for all seven loads analyzed (table 2).

Table 2. Intraclass Correlation Coefficient (ICC: model 2, form 1) and Standard Error of Measurement (SEM) based on DeltaScore.

Load	ICC (95%IC)	SEM
Lightest (1.10 $m \cdot s^{-1}$)	0.776 (0.621-0.874)	0.05
Very light (0.95 $m \cdot s^{-1}$)	0.799 (0.660-0.887)	0.05

Light (0.80 m·s^{-1})	0.767 (0.606-0.869)	0.06
Medium (0.65 m·s^{-1})	0.791 (0.648-0.883)	0.05
Heavy (0.50 m·s^{-1})	0.781 (0.610-0.865)	0.03
Very Heavy (0.35 m·s^{-1})	0.777 (0.622-0.874)	0.04
Heaviest (0.20 m·s^{-1})	0.785 (0.673-0.879)	0.03
All loads	0.839 (0.804-0.869)	0.04

Table 2. ICC: Intraclass Correlation Coefficient; SEM: Standard Error of Measurement

The 2-way repeated measure ANOVA, conducted to analyze potential differences in DeltaScores based on load and day, revealed a significant effect of load (F (5) = 11.0 $p < 0.01$; $\eta^2 = 0.24$). In contrast, no significant differences were found for day or the load × day interaction ($p = 0.646$; $p = 0.474$). Post hoc analyses revealed that the significant differences related to load were observed in the accuracy levels between all of the first 5 (lighter) loads and the seventh, which was the heaviest. No statistically significant differences were found in the 2-way repeated measure ANOVA conducted to analyze the differences between %1RMp and %1RM based on load, day, or load × day interaction ($p > 0.05$). The results of the Bland-Altman plots are presented in Figure 2.

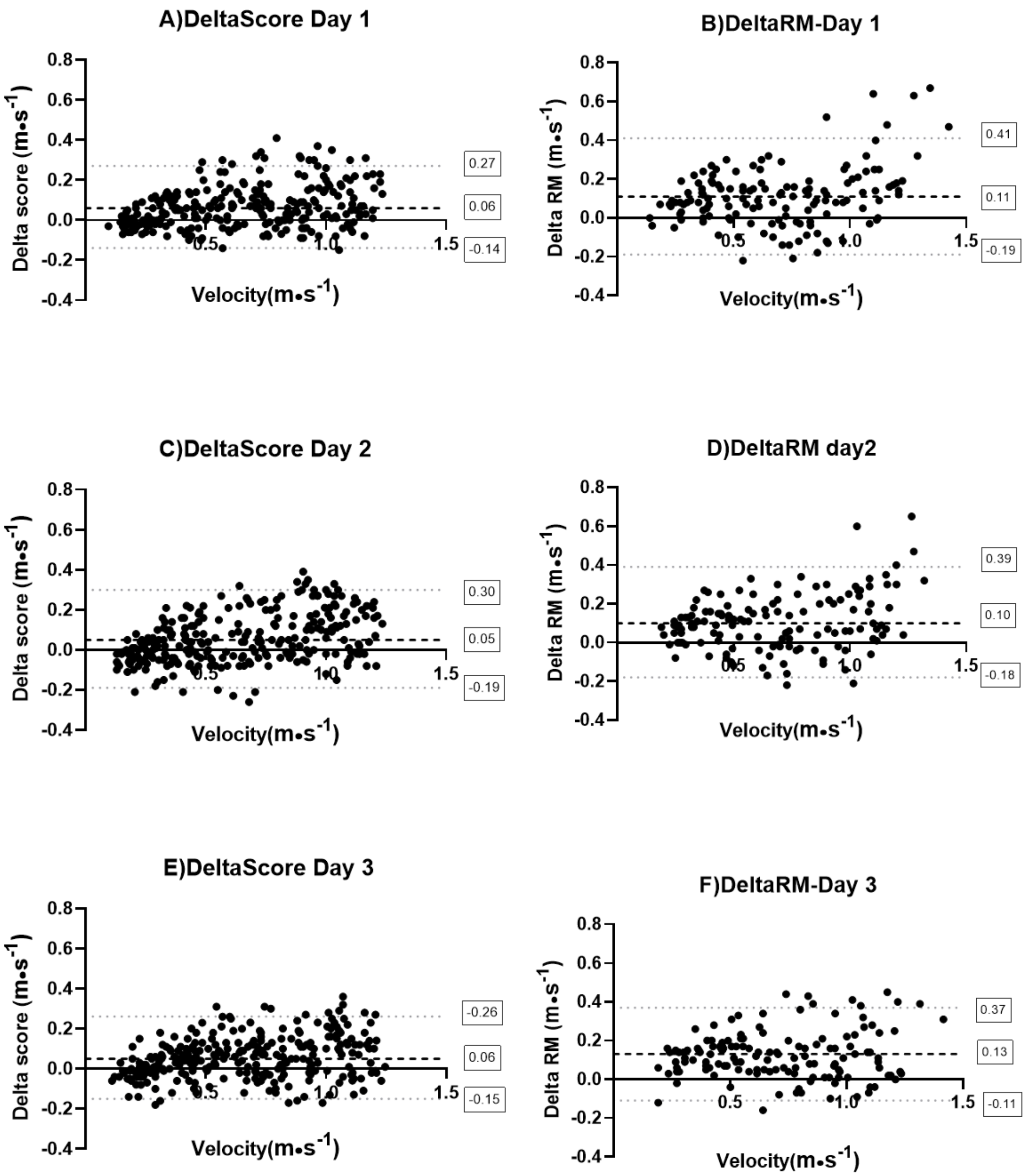

Figure 2. DeltaScore: Differences between perceived velocity and real velocity (Vp-Vr); DeltaRM: Differences between perceived %RM and real velocity(%1RMp-Vr)

The 2-way repeated measure ANOVA, conducted to analyze potential differences in absolute error in DeltaScores based on load and day, revealed a significant effect of load (F (5) = 17.46 $p < 0.001$; η^2 = 0.12). In contrast, no significant differences were found for day or the load × day interaction (p =

0.158; $p = 0.776$). Post hoc analyses revealed that the significant load-related differences in accuracy levels occurred between each of the first 5 loads and the sixth and seventh loads, which were the heaviest. Last, the mean absolute errors, divided by day and load, regarding the DeltaScores are presented in Figure 3.

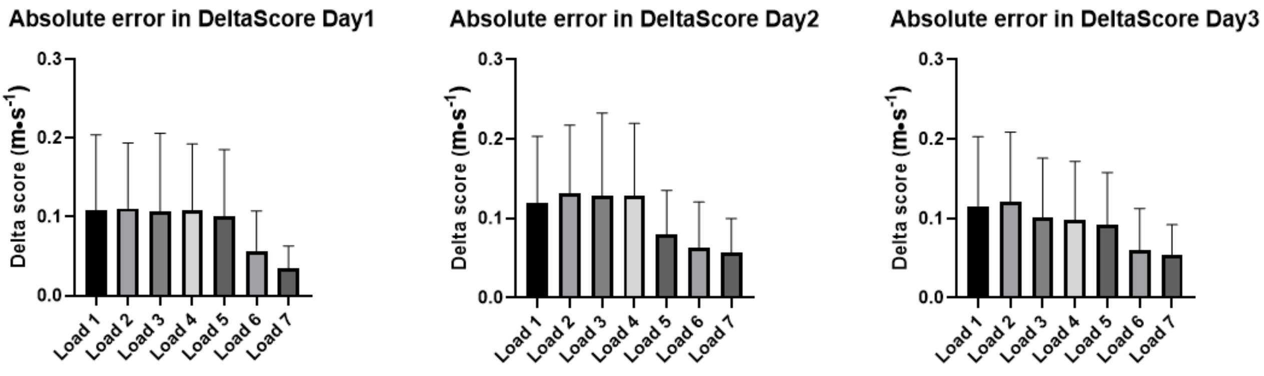

Figure 3. Absolute error in DeltaScore (Vp-Vr) in the three test sessions. Load 1: Lightest (1.10 $m{\cdot}s^{-1}$); Load 2: Very Light (0.95 $m{\cdot}s^{-1}$); Load 3: Light (0.80 $m{\cdot}s^{-1}$); Load 4: Medium (0.65 $m{\cdot}s^{-1)}$; Load 5: Heavy (0.50 $m{\cdot}s^{-1}$); Load 6: Very heavy (0.35 $m{\cdot}s^{-1}$) Load 7: Heaviest

Power Analysis

Post hoc analyses were conducted to determine the statistical power of significant results, specifically regarding the impact of load on DeltaScore. Using G*Power 3.1 software, we set the test family to *F*-test and specified the statistical test as ANOVA: repeated measures, within factors, with an alpha level of 0.05. With an observed effect size of $\eta^2 = 0.24$, the corresponding statistical power was 0.85. Last, based on the reported ICC values, a post hoc power analysis was performed using R (specifically, the *ICC.Sample.Size* package) to estimate the statistical power of the findings. In accordance with the study design and results, an ICC value of 0.77 was used, with a sample size of 20 and 3 repeated measurements, to estimate statistical power. The resulting power was 0.99.

Discussion

Velocity perception as a subjective tool for autoregulation is a relatively new and evolving area of research. Bautista et al. (1,2) were pioneers in this field, developing a PV scale as a valuable tool for monitoring VBT sessions (1). Their studies compared the real mean velocity of a set, measured by an encoder, with the athlete's perceived mean velocity, ultimately validating a general perception scale. More recently, Romagnoli et al. (16–19) introduced the DeltaScore to assess velocity perception (16–19), defined as the difference between the Vp and Vr of each repetition (DeltaScore = Vp − Vr). In the mentioned study, the accuracy of the DeltaScore improved after a familiarization period, highlighting the importance of this phase. Furthermore, they highlighted the importance of using specific minimum and maximum velocity ranges tailored to each exercise when designing velocity perception scales (18). The maximum velocity range should align with the velocity typically associated with approximately 30%1RM for the chosen exercise, as higher velocities are rarely achieved in real training contexts (18). The lowest value presented should correspond to the exercise's MVT, which varies significantly across different exercises depending on the velocity at which the 1RM is reached (e.g., bench press: 0.15 $m \cdot s^{-1}$; prone bench pull: 0.50 $m \cdot s^{-1}$) (23). For this reason, it becomes crucial to (a) familiarize athletes with velocity perception and (b) provide supporting tools, such as highly accurate and precise velocity perception scales, to help athletes perceive barbell velocity correctly and minimize the margins of error. This study was designed with that goal in mind. Based on the aforementioned findings, the primary aim of this study was to validate a velocity perception scale specifically designed for the bench press. Although a general PV scale validated by Bautista et al. (1) already exists, it presents some limitations despite its innovative nature as the first validated scale to utilize athletes' PV. To address these limitations, the following modifications to the previous PV scale were included: (a) both the highest and lowest values displayed on the scale were changed; the highest was lowered from 1.6 $m \cdot s^{-1}$ to 1.25 $m \cdot s^{-1}$ (i.e., 30%1RM) (6) to align it with the maximum velocity typically achieved during bench press training. The lowest value was increased from 0.10 $m \cdot s^{-1}$ to 0.15 $m \cdot s^{-1}$, which corresponds to the MVT typically associated with the bench press (23). These changes were made to help subjects accurately identify barbell velocity during bench press exercise. (b) Because markers spaced by 0.10 $m \cdot s^{-1}$ can represent significant load variation (i.e., 5–7%1RM) (6), the interval between markers was reduced from 0.10 $m \cdot s^{-1}$ to 0.05 $m \cdot s^{-1}$ along the entire scale. In addition, because studies published after the validation of Bautista's scale demonstrated that velocity perception is more accurate at higher loads (18,19), smaller intervals of 0.01 $m \cdot s^{-1}$ were used for velocities starting from 0.85 $m \cdot s^{-1}$ onward. This adjustment aimed to improve the distinction between lower velocities, which are perceived with higher accuracy. (c) The verbal anchor "power zone" previously used was replaced with "somewhat fast" to align with the other anchors, which all referred to Vp rather than a specific training zone. (d) Last, the scale was validated using the DeltaScore rather than the mean velocity of the set. This change allows for more precise information about the Vp during the first repetition, which is typically used to identify the load in VBT sessions. To validate the scale, the reliability of Vp, assessed through the DeltaScore, was analyzed using ICC (model 2, form 1). The results, shown in Table 2, indicate good values (0.77–0.80) for each load tested across the 3 days. In addition, the results did not show significant effects for day or for the load× day interaction, supporting the ICC findings. The only significant result was related to the load, as DeltaScores were significantly lower for heavier loads (i.e., loads 6 and 7) compared with the lighter ones. The DeltaScores for light and moderate loads were similar to each other. These results are further supported by the analysis of the mean absolute error in the DeltaScore (Figure 3). Regarding DeltaScore accuracy, the present study reports slightly improved Bland-Altman plots (Figure 2A, C, E) compared with those previously published by Romagnoli et al. (16), despite their use of a substantially longer familiarization period (i.e., 5 weeks). We hypothesize that this improvement may be attributed to 2 main factors: (a) the different perception scale used, as we argue that an exercise-specific scale like the one we developed may significantly support subject accuracy; (b) the use of a Smith machine in our bench press protocol, whereas Romagnoli et al. (16) employed a free-weight version of the exercise. We hypothesize that using the Smith machine may slightly reduce error in PV estimation, as it minimizes the attentional demand related to movement execution, given the guided nature of the equipment. Last, the results of the Pearson correlation (r) and the R^2 between Vp and Vr showed very good values (Table 1), which are consistent with, although slightly lower than, those previously reported in the literature (1,16,18).

These analyses also fulfilled the second purpose of this study, which was to determine whether subjects could discriminate smaller load variations than those typically reported in the literature, where generally 3 loads were used, compared with the 7 loads used in the present study. The affirmative answer is supported by the fact that the DeltaScores were similar across loads (Figure 3), indicating that subjects were able to perceive the changes in Vr because of small increases in load. Finally, the results related to absolute error in DeltaScore revealed a high *SD*, indicating substantial interindividual variability. Future studies should investigate the underlying mechanisms of these differences. One possible explanation may lie in individual differences in proprioceptive ability, which is believed to vary significantly with factors such as age (8) and training experience (12). Therefore, considering that this study did not account for such differences, future research should explore this possibility. Potential directions for future research include implementing proprioceptive training protocols or conducting comparisons between groups that differ in proprioceptive capacity, such as trained athletes vs. sedentary individuals, or younger vs. older adults (8,12). Moreover, neuroscience literature suggests that the perception of an object's speed is shaped by the integration of proprioceptive signals and external sensory inputs, particularly visual information (3,15). Therefore, future investigations may also explore how visual feedback influences the accuracy of PV.

Beyond these aims, this study also sought to investigate whether athletes could accurately estimate the %1RM performed and determine whether this estimation was more or less precise compared with the velocity perception, 2 aspects which have never been analyzed before. To evaluate the agreement between perceived %1RM (%1RMp) and %1RM, the same analyses used for assessing the agreement between Vp and Vr were applied. First, Pearson correlation (r) and the R^2 yielded very good results, although slightly lower than those corresponding to Vp-Vr (Table 2). In addition, no significant effects ($p > 0.05$) for load, day, or a potential load × day interaction on the accuracy levels of %1RMp were found. Last, Bland-Altman plots show that DeltaScores are systematically more accurate, indicating better agreement than DeltaRM (Figure 2).

Practical Applications

In addition to validating a new PV scale, which could be of significant interest and utility for practitioners, this study has revealed other noteworthy findings. First, subjects were able to detect even small changes in velocity resulting from minor load increments. Second, although they are more accustomed to using %1RM than velocity, our subjects were more accurate in identifying the correct barbell velocity compared with the corresponding %1RM. Moreover, the findings related to the DeltaScore provide a more precise understanding of the margin of error in velocity perception. These findings emphasize 2 important points: (a) the mean error is slightly higher than previously reported in the literature if the absolute error is considered (16); (b) the high SD suggest substantial differences between subjects, indicating that future research should investigate the underlying mechanisms of velocity perception and explore factors that may explain these observed differences.

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Chapter 11: Influence of Visual Feedback on Velocity Perception Accuracy During the Bench Press

This article is currently undergoing internal review and has not yet been submitted to a scientific journal

Title: Influence of Visual Feedback on Velocity Perception Accuracy During the Bench Press

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Abstract: The aim of the study was to investigate the effect of visual input on perception of velocity (PV) during the bench press exercise. Twenty healthy males completed a total of six testing sessions. The first four sessions were used to familiarize the participants with VP and with a specific VP scale for bench press. During the final two testing sessions, conducted in a randomized order, participants performed seven different loads per session, with movement velocities ranging from 1.10 $m \cdot s^{-1}$ to

0.20 m·s^{-1}. In one condition, participants performed the test while blindfolded to remove visual input, whereas in the other condition, they performed the test normally and were instructed to carefully observe the barbell throughout the movement. For each repetition, both the real velocity (Vr), measured by the T-Force system, and the perceived velocity (Vp) (i.e. velocity reported by the subject) were recorded. Pearson's correlation (r) and the coefficient of determination (R^2) between Vp and Vr demonstrated high values across the two conditions (Blind: r=0.94- R^2 =0.88; Non blind: r=0.94; R^2 0.89). PV accuracy was determined using the DeltaScore (Ds), defined as the difference between Vp and Vr (Ds = Vp - Vr) and its absolute value (|Ds|= |Vp-Vr|). A two-way repeated measures ANOVA (load × condition) on Ds revealed significant main effects for both load and condition ($p < 0.05$), but no significant load × condition interaction ($p > 0.05$). For |Ds|, a significant main effect was found only for load, whereas condition and load × condition interaction were not significant ($p > 0.05$). These findings indicate that visual input influences the distribution of error (i.e., whether participants tend to overestimate or underestimate velocity), but does not significantly affect the absolute magnitude of the error.

Introduction

Accurate resistance training (RT) prescription determines improvements in sports performance and enhances health outcomes[1–3]. The most commonly used method for prescribing RT has traditionally been percent-based training (PBT)[4]. PBT uses the percentage of the one-repetition maximum (1RM) to modulate training intensity, and a predetermined combination of sets and repetitions to adjust training volume[5]. Unfortunately, PBT does not take into account daily fluctuations in performance, which represent the main limitation of this training prescription method[5]. To overcome this limitation, in recent years an alternative approach for prescribing and monitoring RT, called velocity-based training (VBT), has been developed[5]. VBT, through the constant monitoring of barbell velocity, typically modulates training intensity based on the velocity of the concentric phase of the first repetition, and training volume based on the percentage of velocity loss (%VL) within each set[5]. Monitoring barbell velocity requires specific devices, such as Linear Position Transducers (LPT), Linear Velocity Transducers (LVT), Smartphone Applications, and Inertial Measurement Unit[6,7]. Among these, LPT and LVT have been recognized as the gold standard in training settings[6]. However, the high costs associated with some devices[8] and the low accuracy of the cheaper ones[6], makes the implementation of VBT in RT session impractical for the majority of strength and conditioning coaches. For this reason, some recent studies have investigated the feasibility of perception of velocity (PV)[8–12], aiming to use it when LPT are not available. PV is the ability to perceive the velocity of first repetition[8]. Usually in the literature, PV accuracy is assessed using a Delta Score (Ds) calculated as the difference between perceived velocity (Vp) and real velocity (Vr) (Ds = Vp - Vr)[9]. Moreover, recently, the absolute value of Ds (|Ds| = |Vr - Vp|) has also been employed to assess PV accuracy[8], in order to prevent the possibility that overestimation and underestimation of velocity might counterbalance each other, thus diminishing the observed magnitude of the error[8]. Concerning the characteristics of PV, it has been demonstrated that PV accuracy improves after a short period of familiarization in which subjects receive constant feedback from LPT and observe the velocity of each repetition on a validated PV scale[8,10,11]. In particular, a recent study showed that after a short familiarization, Ds appears lower at higher loads (80% 1RM) than at lower ones (60% 1RM)[8]. Moreover, PV has been demonstrated to represent a stable parameter across various experimental conditions, including both physical[11] and mental fatigue[10], and to maintain its stability even after a minimum of four weeks following the familiarization phase[8]. Although the results are encouraging, PV accuracy remained insufficient in some condition[8], and considerable variability between subjects was observed[8], with some showing acceptable values, whereas in several cases accuracy remained unsatisfactory[8]. This variability may be attributed to individual differences in the integration of afferent information. In fact, perception is a complex integrative process rather than a simple reading of a single sensory channel[13]. It is the product of the integration of different signals, such as proprioceptive, visual and vestibular, by the Central Nervous System (CNS)[13]. Among these, proprioception represents the fundamental basis of motor control[14]. The term proprioception could be defined as an umbrella concept, encompassing the awareness of passive or active joint movement, the joint position sense, the reproduction of joint angles actively or passively, the ability to detect the level of force production, and changes in movement velocity[15]. Physiologically, proprioception is mediated by various mechanoreceptors located in muscle, tendon and skin[16]. Two of the most fundamental mechanoreceptors are the muscle spindles and the Golgi tendon organs[16]. Muscle spindles are considered the primary receptors for kinesthesia (the sense of movement), they are aligned in parallel with extrafusal muscle fibers and are sensitive both to changes in muscle length (providing information about limb position) and, more importantly, to the rate of these changes (providing information about movement)[16]. Instead, Golgi tendon organs are located at the musculo-tendinous junction, they are positioned in series with the muscle fibers and primarily act as sensors of muscle tension[16]. However, although proprioception has been indicated predominant in the sense of motion, as mentioned above, the CNS integrates with other sensorial afferences to optimize motor control[13]. In particular, studies indicate that the integration of complementary signals of proprioception and vision optimizes the perception of movement velocity and range of motion[14]. Regarding the visual system, investigation in neuroscience has clarified that it is not a passive recorder of reality. Rather, it operates as a Bayesian inference mechanism, interpreting often ambiguous sensory information based on pre-existing expectations named priors[17]. These priors are mediated by the statistical regularities of self-interactions with the environment[17]. Regarding motion perception, it has been demonstrated that in peripheral vision there exists a "centrifugal prior": an intrinsic expectation in the brain that objects move away from the center of the visual field[17]. This prior is so strong that it can generate the illusory perception of movement in physically stationary objects[17]. Thus, considering the priors of the visual system, it can be hypothesized that its intrinsic mechanisms may introduce a systematic bias in the estimation of barbell velocity. Indeed, if PV represents an integration between proprioceptive (internal) signals and a visual (external) signals, and the latter is subject to potential distortions, it is critical to understand whether and how this interaction affects the final accuracy of PV[8]. Therefore, the present study aims to investigate the effects of visual input occlusion on PV during the Bench Press exercise performed on a Smith Machine. We hypothesize that removing visual input, despite also removing visual priors, may result to an overall lower PV accuracy and greater interindividual variability. This hypothesis is supported by previous findings indicating that the complementary integration of visual and proprioceptive information improves the perception of movement velocity[14].

Methods

The study design included six training sessions performing the Bench Press on a Smith Machine (Multipower Fitness Line; Peroga, Murcia, Spain). The first three sessions were used to familiarize subjects with PV across a wide range of loads, during which constant feedback from the LVT (T-Force System; Ergotech) and the new PV scale specific for Bench Press was provided. Moreover, during the first session, anthropometric data (i.e. age, height, body weight) of each participant were collected. In the fourth session, subjects performed an incremental test to determine their 1RM and further familiarized themselves with the entire spectrum of their load velocity profile. In the last two sessions, the effects of visual input on PV have been investigated. The PV test was performed under two different experimental conditions: Blind Condition, in which visual input was completely occluded using a blindfold, and Non-Blind Condition, in which the vision of participants was fully unobstructed. The order of these two sessions was randomized and counterbalanced. Each session commenced with a 5-minute dynamic warm-up that included mobility drills, dynamic stretching, and bodyweight exercises. This was followed by a bench press specific warm-up in which participants executed sets with gradually increasing loads. The protocol consisted of 6–8 repetitions using a 20kg load of the bench press and two additional sets of 3–5 repetitions performed at self-selected intensities. This warm-up sequence and load progression were replicated identically for each participant across all experimental sessions. All sessions were scheduled on non-consecutive days, ensuring a minimum inter-session interval of 48 hours. Throughout all testing procedures, participants were consistently provided with firm verbal cues aimed at promoting maximal performance output. They were repeatedly reminded to execute each repetition with maximal intentional effort during the concentric phase

Sample size justification

An a priori power analysis to estimate the required sample size was conducted using G*Power software (G*Power V 3.1.9.7 Franz Faul, Universit ¨at Kiel, Kiel, Germany). As the primary analysis of the study was a two-way repeated measures ANOVA (load * condition), the following parameters were selected: F test, repeated measures, within factors, a priori, medium effect size ($f = 0.20$), alpha $= 0.05$, power $= 0.80$, correlation among repeated measures of 0.5, and a conservative adjustment considering potential violations of sphericity. Based on these parameters, a total sample size of 18 participants was estimated to be necessary. However, given the overall demanding nature of the protocol and the potential risk of dropouts, a total of 20 participants were recruited.

Participants

The present study included 20 healthy males (age: 23.85 years ± 3.01; body weight: 77.0 kg ± 8.79; height: 1.78 m ± 0.07; 1RM/BW 1.07 ± 0.13). The inclusion criteria were: at least one year of experience in RT, age between 18 and 35 years, and absence of current or previous injuries. After receiving comprehensive information regarding the study's procedures, potential risks, and ethical considerations, along with a copy of the explanatory information sheet, all participants provided written informed consent and authorization for data processing. The study protocol was approved by the Research Ethics Committee of the Hospitales Universitarios Virgen Macarena–Virgen del Rocío (Reference: 1547-N-19) and was conducted in accordance with the latest revision of the Declaration of Helsinki, which ensures the protection of the rights, integrity, and well-being of research participants. Participation in the study could be discontinued at any time, at the request of either the participant or the research staff, without the need to provide justification and without any resulting consequences.

The familiarization and 1RM testing protocol followed the same procedures described by Dello Stritto et al. (2025). The details are reported below. The familiarization phase consisted of three separate sessions intended to ensure that participants developed a clear understanding of the velocity-perception scale and the movement velocities typically produced during the bench press exercise. During the first session (day 1), participants trained with high relative loads that elicited bar-velocities below 0.60 $m \cdot s^{-1}$, enabling them to experience the lower end of the scale. The second session (day 2) focused on moderate (0.60–0.80 $m \cdot s^{-1}$) and light (0.80–1.00 $m \cdot s^{-1}$) loads, corresponding to the middle range of the scale. In the third and final session (day 3), very light and light intensities were used, generating bar-velocities above 1.00 $m \cdot s^{-1}$ and thereby introducing participants to the upper range of the scale. For moderate and light intensities, participants completed four repetitions per load, whereas for heavy intensities only two to three repetitions were performed to avoid undue fatigue. Throughout all sessions, researcher provided real-time auditory feedback on the bar-velocity achieved for each repetition. After every set, participants were presented with the velocity-perception scale previously validated and informed of the actual velocity recorded for that set.

Incremental Loading Test in Bench Press

Before testing, participants completed a dynamic warm-up that included mobility drills, stretching exercises, and bodyweight movements. Mean propulsive velocity (MPV) and range of motion (ROM) were recorded using a linear velocity transducer (T-Force System; Ergotech). Participants then undertook a progressive maximal test on a Smith machine (Multipower Fitness Line; Peroga, Murcia, Spain) without a counterbalance system. They were instructed to execute the concentric phase of every repetition with maximal intentional velocity.

Testing began with a load of 20 kg. For velocities exceeding 0.80 $m \cdot s^{-1}$, three repetitions were performed; for velocities between 0.80 and 0.60 $m \cdot s^{-1}$, two repetitions were completed; and for velocities below 0.60 $m \cdot s^{-1}$, only a single repetition was required. Rest intervals were fixed at 3 minutes for light and moderate loads and increased to 5 minutes once heavier loads were used. Load increments varied between 10 kg and 2.5 kg, depending on the velocity recorded in the preceding set. The protocol was terminated when the participant was no longer able to successfully perform one repetition with the prescribed load."

PV assessment test

During the final two sessions, PV was assessed under the two experimental conditions, which were administered in a randomized and counterbalanced order. In one session, participants performed the experimental protocol while blindfolded, thereby receiving no visual input during the execution of the movement (Blind Condition). In the other session, participants performed the same protocol without a blindfold (Non-Blind Condition). The protocols were conducted under conditions of maximum safety: a Smith machine was used, ensuring that the loads were constrained by the equipment, and at least two spotters were present during each execution. In each session, participants completed two repetitions at each of seven different loads, with barbell velocities ranging from 1.10 to 0.20 $m \cdot s^{-1}$. These loads were both randomized and concealed so that participants remained unaware of the specific load being lifted. Moreover, the loads were structured so that the four lightest ones (1.10, 0.95, 0.80, and 0.65 $m \cdot s^{-1}$) were performed first in a random order, followed by the three heaviest (0.50, 0.35, and 0.20 $m \cdot s^{-1}$) also in a random order. This progression ensured that excessively heavy loads were not lifted without proper warm-up, but participants were not informed of this specific randomization procedure. After completing the first repetition of each set, participants reported the velocity perceived (Vp) of that repetition. Following the second repetition, they reported both the Vp of the second repetition and visualized the values they indicated on the PV scale.

Statistical Analysis

Data were normally distributed, according to the Shapiro-Wilk test ($p > 0.05$). The accuracy levels in velocity perception were calculated both as the difference between Vp and Vr (Ds= Vp-Vr) [18] and as its absolute difference (|Ds| = |Vr-Vp|)[8]. The correlation between Vp and Vr was analyzed using Pearson's r for each test. The magnitudes of Pearson's r were classified as follows: trivial (<0.1), small (0.1–0.3), moderate (0.3–0.5), high (0.5–0.7), very high (0.7–0.9), and nearly perfect (>0.9). A simple linear regression between Vp and Vr was performed for both conditions to obtain the coefficient of determination (R^2). A two-way repeated measure ANOVA was used to identify any differences in Ds and |Ds| across the different loads and condition. The levels of agreement between Vp and Vr were explored using Bland-Altman plots. The alpha level was set at $p < 0.05$. Statistical analyses were performed in Microsoft Office Excel® (Microsoft Inc., Redmond, WA, USA) and SPSS v25 (SPSS Inc., Chicago, IL, USA).

Results:

The coefficients of determination from the simple regression analysis (R^2) and the Pearson correlation coefficients (r) from the correlation analysis, for both blind and non-blind conditions are reported in Table 1. The results of these analyses reveal very high to practically perfect levels of correlation and coefficients of determination between Vp and Vr.

Table 1. Pearson correlation coefficients (r) and coefficient of determination (R^2) between Vp - Vr and %1RMp -%1RM)

	Vp-Vr	
	r	**R^2**
Blind Condition	0.938	0.884
Non-Blind Condition	0.941	0.895

The two-way repeated measure ANOVA, conducted to analyze potential differences in Ds based on load and condition, revealed a significant effect for condition (F (1) = 6.5 p=0.01; η^2=0.15) and load (F (6) = 5.94 p=0.01; η^2=0.14). In contrast, no significant differences were found for the load × condition interaction (p=0.841;). Post hoc analyses revealed that the significant differences related to load were observed in the accuracy levels between all of the first five (lighter) loads and the seventh, which was the heaviest. The results of the Bland-Altman plots are presented in Figure 2. Ds distribution across all seven loads in both blind and non-blind conditions is presented in Figure 3.

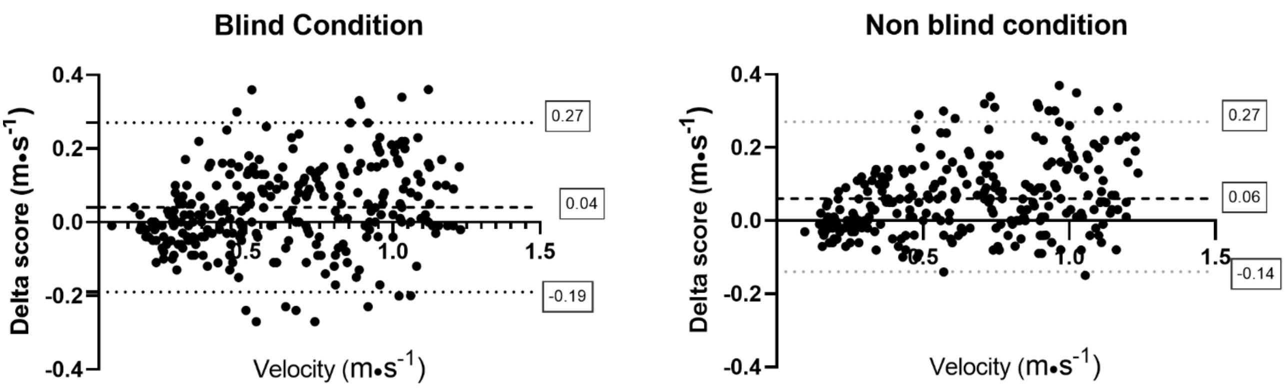

Figure 2. DeltaScore (Ds): Differences between perceived velocity and real velocity (Vp-Vr)

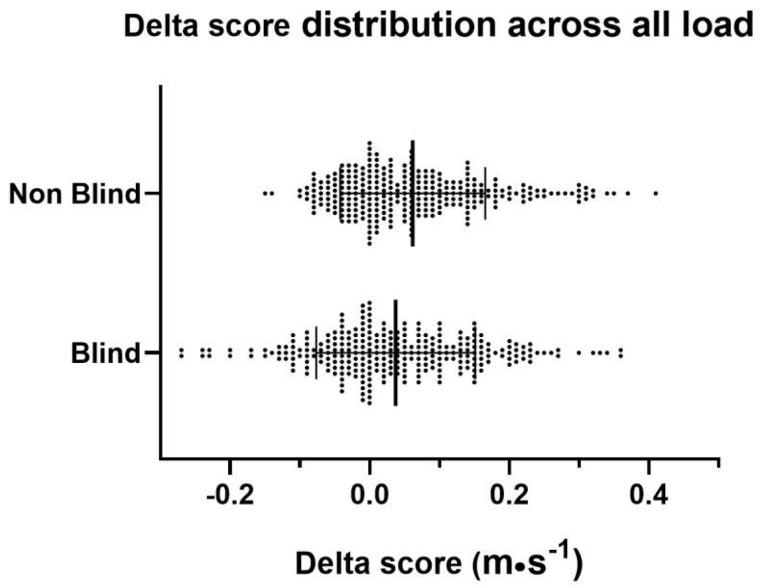

Figure 3. Distribution of DeltaScore (Vp-Vr) across all the seven loads.

The two-way repeated measure ANOVA, conducted to analyze potential differences in |Ds| based on load and condition, revealed a significant effect of load ($F(6) = 11.81$ $p<0.001$; $\eta^2=0.24$). In contrast, no significant differences were found for condition or the load × condition interaction ($p=0.607$; $p=0.142$.). Post hoc analyses revealed that the significant load-related differences in accuracy levels occurred between each of the first five loads and the sixth and seventh loads regardless of the condition analyzed. Lastly, the mean absolute errors, divided by day and condition, regarding the |Ds| are presented in Figure 4.

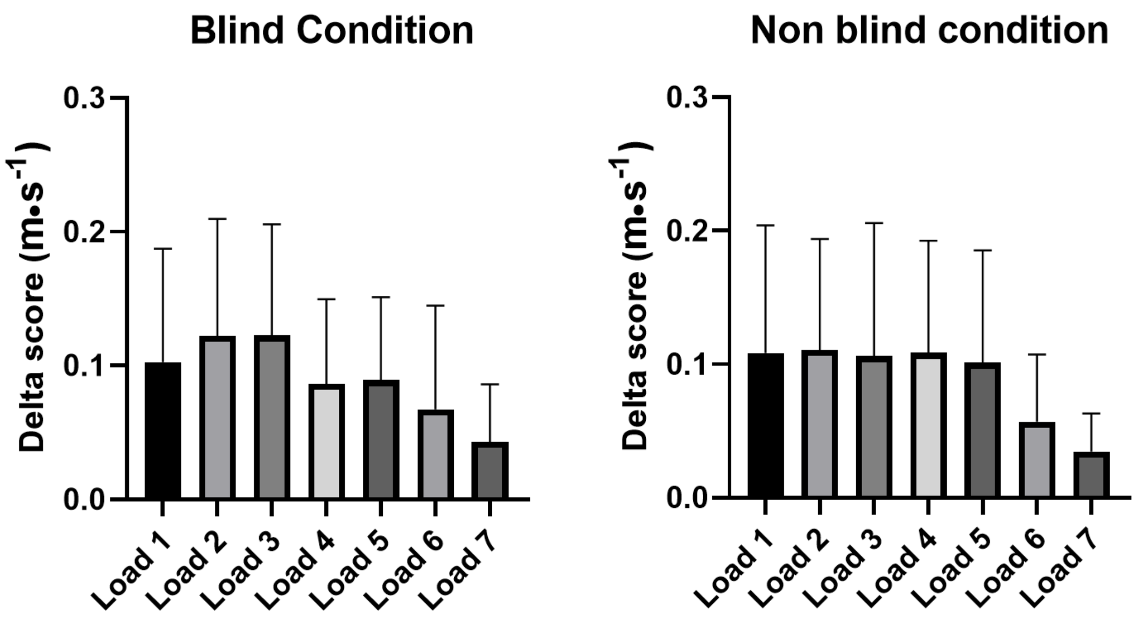

Figure 4. Absolute error in DeltaScore (Vp-Vr). Load 1: Lightest (1.10 m·s^{-1}); Load 2: Very Light (0.95 m·s^{-1}); Load 3: Light (0.80 m·s^{-1}); Load 4: Medium (0.65 m·s^{-1}); Load 5: Heavy (0.50 m·s^{-1}); Load 6: Very heavy (0.35 m·s^{-1}) Load 7: Heaviest (0.20 m·s^{-1})

Discussion

The main aim of this study was to investigate the effect of visual input on PV accuracy and variability in Bench press exercise. No significant differences in PV accuracy were found between the Blind and the Non-Blind condition. However, the distribution of the error changed significantly. In fact, although |Ds| did not vary significantly between the conditions, indicating consistency in the magnitude of error, Ds changed significantly, suggesting a change in the direction of the error. In particular, in the Blind-condition, a greater tendency to underestimate the velocity as well as greater interindividual variability were found. These results suggest that the visual input may be crucial for stabilizing the PV, reducing interindividual variability rather than impacting the magnitude of error. These results seem to align with the multisensory integration paradigm[13,14]. Indeed, The CNS does not rely on a single channel; rather, it continuously integrates information from multiple sources to generate the most reliable perception possible[13,14]. Within this framework, muscle proprioception, serves as the key source of kinesthetic information, although this internal signal may be subject to individual interpretation[13]. Vision acts as a perceptual anchor that, despite being susceptible to its own biases (e.g. centrifugal prior), provides a complementary information that facilitates the calibration and interpretation of internal proprioceptive signals[17]. Indeed, it can be hypothesized that, in the absence of an external visual signal serving as an objective reference, athletes may rely more heavily on internal cues, such as the "sense of effort" arising from the efferent copy of the motor command[16]. Without visual confirmation of a rapid and explosive movement, a given perceived level of effort may be interpreted as less effective, leading to an underestimation of the produced velocity and, consequently, of PV. Thus, the absence of visual input forced subjects to rely solely on a subjective interpretation of the proprioceptive signal, without being able to use objective visual information[19]. Although visual input appears to reduce differences between subjects, high interindividual variation in PV persists in both conditions, consistent with previous literature[8]. These outcomes suggest that PV does not rely solely on visual-proprioceptive integration, but is also modulated by other factors, such as attentional focus[20]. Concerning the attentional focus, the literature on motor control has extensively demonstrated that an external focus (directed toward the outcome of the movement, e.g., "move the barbell as quickly as possible") is superior to an internal focus (directed at the movement of body segments, e.g., "contract the pectorals") for both performance and motor learning[20]. Thus, it can be hypothesized that external focus may also lead to a more accurate and consistent perception of velocity, as attention is directed specifically toward the variable intended to be perceived. Another factor could be the athlete's level of experience, which may affect the sense of effort. [21]. Effort perception has been previously associated with afferent feedback from peripheral physiological systems[16]; However, more recent theoretical models highlight its complex nature, suggesting a predominant role for purely central signals[22]. From this perspective, effort perception is interpreted as the conscious awareness of the corollary discharge of the motor command, a cognitive process independent of feedback from the body[22,23]. Consequently, it can be speculated that different athletes producing the same velocity may do so with different motor commands, and thus differing perceived effort, ultimately affecting their final estimation. Lastly, the role of cognitive and personality traits cannot be excluded. As demonstrated by D'Amour et al.[24], an individual's tendency to rely on external cues ("field dependence") may also modulate movement perception[24]. In conclusion, the results of this study, for the first time, suggest vision as a key factor for PV, alongside proprioception. Considering that, as mentioned above, other factors such as attentional focus[20], effort perception[16], personality traits[24], and cognitive aspects[24] may affect PV accuracy, future studies should focus on the remaining factors to determine if and how they effectively influence PV.

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General conclusion:

This doctoral thesis and the associated research focused on both subjective and objective aspects of performance and its monitoring. The common thread linking the different studies is the use of movement velocity as a key tool for training prescription, within the framework of Velocity-Based Training (VBT).

The work can be divided, as outlined in the aim, into two main sections. The first addresses the objective aspects of performance and its monitoring (i.e., the effects of mental fatigue and the accuracy of 1RM prediction), while the second focuses on subjective aspects, exploring the use of velocity and velocity loss perception as a tool for training monitoring and its reliability under different conditions.

The first study investigated the possibility of predicting the one-repetition maximum (1RM) through load–velocity profiles in the free-weight back squat, and whether sex-specific differences might influence this prediction. The findings showed that, under highly standardized and controlled conditions, the 1RM can be accurately estimated using the minimum velocity threshold (MVT). Moreover, the study highlighted that males and females exhibit different MVT values, a difference that must be considered when using load–velocity profiling. Finally, to achieve an accurate prediction, it is necessary to avoid using very light loads (<30% 1RM) and loads close to maximal intensity (>90% 1RM).

The second study investigated the effect of mental fatigue on barbell velocity, examining both the velocity of the first repetition as an indicator of training intensity and the velocity loss across repetitions as an indicator of training volume. Additionally, the study explored whether males and females respond differently to mental fatigue. The results showed that both sexes experienced a significant decline in performance in terms of volume and intensity. However, while no significant sex differences were found in the reduction of training volume, males exhibited a greater decrease in intensity-related performance. Based on these findings, it is recommended to avoid mentally fatiguing activities prior to resistance training sessions or to adopt strategies that can mitigate the effects of mental fatigue, such as listening to music or consuming caffeine.

The third study aimed to validate a new linear encoder (Velocity Matters) available on the market, tested during free-weight bench press and back squat exercises. The validation of this device was of particular interest due to its low cost compared to other commercially available alternatives. The results showed that Velocity Matters systematically underestimated barbell velocity in both the bench press and the squat. The device demonstrated acceptable accuracy only at higher squat loads, while in the bench press it presented occasional “phantom repetitions.” Therefore, its use can be recommended only for high-load squat sets, whereas it is not advised for bench press monitoring.

The fourth study investigated the stability over time of perception of velocity (PV) and perception of velocity loss (PVL). The study covered a four-week period. After a familiarization phase consisting of four sessions conducted over two weeks, participants showed consistently good accuracy in PV at 80% 1RM, but not at 60% 1RM, where the margin of error occasionally exceeded acceptable limits (>0.09 m/s). PVL, on the other hand, consistently showed acceptable levels of error. Importantly, these levels of accuracy remained stable over the four-week period.

The fifth study investigated whether and how physical and mental fatigue could negatively affect PV and PVL, using protocols designed to replicate realistic training conditions. In line with the hypotheses and previous literature, neither physical nor mental fatigue negatively influenced PV or PVL. Based on these findings, PV and PVL can be considered reliable parameters for training prescription, even under fatigue conditions, particularly when using high relative loads (80%1RM) and velocity losses of 20% or greater.

The sixth study validated a perception scale specifically designed for the bench press exercise. Previous literature had already emphasized the importance of using exercise-specific scales to help athletes develop familiarity with PV. However, no bench press–specific perception scale had been available to date. Through the validation process, we also examined whether participants were able to distinguish relatively small differences in velocity across seven different loads. The results showed that participants could accurately perceive even small changes in barbell velocity, confirming that the scale is a useful tool for improving familiarity with velocity perception in the bench press.

The seventh and final study aimed to identify a possible mechanistic determinant of velocity perception by removing visual input during velocity perception tests. The results showed that velocity perception is influenced by the absence of visual input. Specifically, removing visual information reduced interindividual variability, thereby improving the stability of perception, although it did not enhance overall accuracy. In particular, when visual input was removed, participants tended to underestimate the perceived velocity to a greater extent.

Based on the results summarized from the studies presented, several highly relevant insights can be drawn.

Considering the first part of this dissertation, it is evident that sex-specific differences are critical to account for when using VBT. These differences are particularly relevant when predicting 1RM through load-velocity profiles. Females exhibited a lower MVT than males, which significantly affected the accuracy of these predictions. Accounting for sex differences is also important during actual VBT sessions, especially under conditions of mental fatigue, as males and females appear to respond differently. Despite these observed differences, it is important to emphasize that performance declines under fatigue occur in both sexes, highlighting the necessity of implementing strategies to mitigate the effects of mental fatigue.

Regarding the second part of the dissertation, which focused on subjective aspects related to velocity perception, the findings suggest that both PV and PVL are stable parameters following familiarization for at least four weeks. This is highly relevant, as it implies that in real training contexts, the familiarization process does not need to be repeated for at least a month. Furthermore, these parameters remain stable not only over time but also under conditions of physical and mental fatigue, which athletes commonly experience during training. These results support the notion that PV and PVL are highly valid metrics for training prescription, especially at high loads.

However, despite the extensive research conducted on PV and PVL, certain aspects remain unclear and warrant investigation in future studies. The studies presented consistently revealed substantial inter-individual variability in PV, with some participants being consistently more accurate than others. Future research should address two main questions: first, whether and how this inter-individual variability can be reduced, for instance, by slightly modifying the familiarization protocol; second, the underlying factors explaining such variability. Additionally, while it is known that the margin of error remains stable for up to four weeks, it is unclear when a decline in velocity perception capacity begins. Future studies should explore longer timeframes to identify when accuracy decreases, thereby providing coaches and athletes with guidance on when familiarization with PV and PVL should be repeated.

Finally, and importantly, the mechanistic bases of velocity perception and its accuracy remain largely unknown. The last study presented in this dissertation investigated the role of vision as a potential mediator, demonstrating that visual input can reduce error dispersion. Future research should explore additional factors, such as attentional focus, effort perception, personality traits, and cognitive aspects, to determine whether and how they effectively influence PV accuracy.

Appendix

Scientific Production

Published papers:

- **Dello Stritto** Emanuele, Romagnoli Ruggero, Nocchi Michele and Piacentini Maria Francesca (2025). How does load selection and sex influence 1RM Prediction using the minimal velocity threshold during free weight back squat? *Sports* 2025, *13*(7),224; https://doi.org/10.3390/sports13070224; Clarivate Journal impact factor 2.9
- **Dello Stritto** Emanuele, Gramazio Antonio, Romagnoli Ruggero and Maria Francesca Piacentini (2025). Temporal Stability and Practical Relevance of Velocity and Velocity-Loss Perception in Back Squat. *Applied Sciences*, *15*(13), 7252. https://doi.org/10.3390/app15137252; Clarivate Journal impact factor 2.5
- Quagliarotti Claudio, Coloretti Vittorio, **Dello Stritto** Emanuele, Cuccurullo Sarah, Acalai Jessica, Lepers Romuald, Fantozzi Silvia, Cortesi Matteo and Piacentini Maria Francesca; Does Smartphone Use Affect a Subsequent Swimming Training Session? Preliminary Results in Amateur Triathletes. *Sensors*, *23*(13), 5837. https://doi.org/10.3390/s23135837; Clarivate Journal Impact Factor 3.5

Accepted papers:

- **Dello Stritto** Emanuele, Sánchez-Valdepenas Juan, Romagnoli Ruggero and Piacentini Maria Francesca (2025) Validation of a Velocity Perception Scale for the Bench Press: Accuracy in velocity perception and %1RM perception across multiple loads; Journal of strength and conditioning research; Clarivate Journal impact factor 3.0

Submitted papers:

- **Dello Stritto** Emanuele, Romagnoli Ruggero, Quagliarotti Claudio, Gramazio Antonio and Maria Francesca Piacentini. Mental Fatigue Impairs Training Performance in Resistance-Trained Males and Females: A Velocity-Based Approach. Journal of strength and conditioning research
- **Dello Stritto** Emanuele, Gramazio Antonio, Romagnoli Ruggero, Quagliarotti Claudio and Maria Francesca Piacentini. The Impact of Mental and Physical Fatigue on Perceptual Load Monitoring in Resistance Training: A Reliability Study of Perceived Velocity and Perceived Velocity Loss. International Journal of sport physiology and performance
- **Dello Stritto** Emanuele, Gramazio Antonio, Romagnoli Ruggero, Quagliarotti Claudio, Guerriero Aristide and Maria Francesca Piacentini. Exploring validity of the "Velocity Matters" Linear Position Transducer in the Back Squat and Bench Press. Sensors

Papers currently under internal revision:

- **Dello Stritto** Emanuele, Sánchez-Valdepeñas Juan, Gramazio Antonio, Grassadonia Filippo Maria, Romagnoli Ruggero, Piacentini Maria Francesca. Influence of Visual Feedback on Velocity Perception Accuracy During the Bench Press

Conference presentations

- Poster presentation: **Dello Stritto** Emanuele, Romagnoli Ruggero and Piacentini Maria Francesca (2023). Differences in Load-Velocity and Load-Power relationship between Males and Females in Back Squat; European College of Sport Science 2023.

- Poster presentation: **Dello Stritto** Emanuele, Romagnoli Ruggero and Piacentini Maria Francesca (2023). Differences between individual and generalized regression models using first and second-degree polynomials on back squat in males and females. Società Italiana di Scienze Motorie e Sportive 2025

- E-poster presentation: **Dello Stritto** Emanuele, Romagnoli Ruggero and Piacentini Maria Francesca (2023). 1RM prediction using different models and MVT in female athletes; Strength and Conditioning Society- 6th annual conference 2023

- Oral presentation: **Dello Stritto** Emanuele, Romagnoli Ruggero, Quagliarotti Claudio and Piacentini Maria Francesca (2024). Is the perception of barbell velocity during the back squat a stable parameter under different fatiguing conditions? European College of Sport Science 2024

- Poster presentation: **Dello Stritto** Emanuele, Romagnoli Ruggero and Piacentini Maria Francesca (2024). Perception of Velocity (PV) and Perception of Velocity Loss (PVL) for Resistance Training Autoregulation. Società Italiana di Scienze Motorie e Sportive 2024.

- Oral presentation: **Dello Stritto** Emanuele, Gramazio Antonio, Romagnoli Ruggero, Quagliarotti Claudio and Maria Francesca Piacentini (2025). Mental Fatigue Impairs Training Performance in Resistance-Trained Males and Females: A Velocity-Based Approach. European College of Sport Science 2025

- Oral Presentation: Fuk Andrea, Villanova Simone, Filipas Luca, Gallo Gabriele, Cabboi Luigi, Gramazio Antonio, **Dello Stritto** Emanuele, Bazzucchi Ilenia, Conti Alessandra, Lamberts Roberts, Piacentini Maria Francesca (2025). Physiological Changes at the Moderate-to-Heavy intensity domain transition and 5-min Time-Trial Performance Decline in Running Ater Prolonged Cycling. European College of Sport Science 2025

- Poster presentation: Gramazio Antonio, **Dello Stritto** Emanuele, Romagnoli Ruggero and Piacentini Maria Francesca (2025). Can the sight of the load influence the Velocity perception and the Velocity loss perception? Società Italiana di Scienze Motorie e Sportive 2025

Co-Tutored Master Thesis (LM-68)

- Thesis Title: Differenze nei profili carico-velocità e carico-potenza tra uomini e donne nel Back Squat

  Student: Pellegrino Cecere

- Thesis Title: Studio pilota sulla percezione della velocità di spostamento del bilanciere in condizioni di affaticamento fisico e mentale

  Student: Guglielmo Ippoliti
- Thesis Title: Effetti della fatica mentale sulla performance e sulla percezione della velocità nel back squat

  Student: Sarah Cuccurullo
- Thesis Title: Confronto dei profili Carico-Velocità e Carico-Potenza fra atleti professionisti di Rugby Union ed una popolazione di controllo di non atleti

  Student: Valerio Nulli
- Thesis Title: Previsione dell'1RM tramite il profilo carico-velocità nel free weight back squat: differenze tra sesso e modelli di regressione

  Student: Michele Nocchi
- Thesis Title: Percezione della velocità del bilanciere in condizioni di affaticamento fisico e mentale

  Student: Antonio Gramazio
- Thesis Title: Differenze di Genere nel Velocity Based Training

  Student: Alessandro Adamo
- Thesis Title: Confronto fra Adattamenti dell'Allenamento: Protocollo Tradizionale di Resistance Training vs. Velocity-Based Training

  Student: Andrea Flati
- Thesis Title: "Correlazione tra profilo carico-velocità dry-land e in-water e prestazione di gara nello stile crawl"

  Student: Mirko Montagna
- Thesis Title: Influenza dell'input visivo nella percezione della velocità di spostamento del bilanciere durante la panca piana

Student: Filippo Maria Grassadonia

- Thesis Title: Effetto della fatica fisica e mentale sulla percezione della velocità

  Student: Gianmarco Rotondi

Research period abroad

Universidad Pablo de Olavide - Centro de Investigación en Rendimiento Físico y Deportivo (Seville, Spain). [2 February - 30 June 2024]