Testing Maximal and Strength-endurance Performance

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Chapter 12:
Testing maximal and strength-endurance performance

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Muscle force refers to the tension generated by muscles when they contract. Although researchers are keen to understand muscle force capacity, we currently lack the instruments to directly measure the actual forces produced by individual muscles during the execution of functional tasks. This muscle force, resulting from the activation of muscle fibres, can manifest in various types of muscle actions, such as concentric (shortening), eccentric (lengthening), and isometric (static) contractions. Consequently, we rely on measuring the external manifestation of muscle force during those actions. This practical application of muscle force can be assessed using various dynamometers, such as force platforms or linear position transducers (LPTs).

This chapter offers a general overview of the external manifestations of muscle force. We provide a more in-depth analysis of the external manifestations of muscle force that can be assessed through the recording of lifting velocity. Specifically, we will explore the different testing protocols and metrics available, as well as the main methodological factors to consider when evaluating both maximal-strength and strength-endurance capacities through the recordings of lifting velocity. Velocity-based training (VBT) emerges as a quick and fatigue-free method to obtain reliable and valid indicators of these strength manifestations.

12.1 External manifestations of muscle force

Based on Newton's second law, external force during dynamic actions is calculated as the product of mass and acceleration. In static actions, external force is directly proportional to the deformation caused in the object to which the force is applied, as there is no movement or acceleration involved. In both dynamic and static actions, the force applied is measured in Newtons. That being said, when assessing dynamic actions, measuring lifting velocity can offer more meaningful insights into an individual's strength performance than directly measuring force. This is not only because LPTs (the gold standard for VBT) are more practical than force platforms (the gold standard for force measurements), but also because lifting velocity directly reflects the force applied relative to the mass being lifted (see Chapter 3 for details). Therefore, it is not surprising that kinematic devices, such as LPTs, are increasingly used in both research and practice for evaluating various external manifestations of muscle force (Harris et al. 2010)

The external manifestations of muscle force can be categorized based on the types of muscle actions involved: (i) static force, (ii) dynamic force, and (iii) reactive force. In the following sections, we describe the primary examples of muscle force that can be assessed within each category (**Figure 12.1**). It seems reasonable to evaluate different external manifestations of muscle force because force requirements are task-dependent and can vary significantly in terms of (i) the maximum amount of force to be exerted, (ii) the time available to apply force, (iii) the speed at which the force needs to be exerted, and (iv) the duration that a given force must be maintained.

Figure 12.1. *Main external manifestations of muscle force. 1RM, one-repetition maximum; RSI, reactive strength index; DJ, drop jump; CMJ, countermovement jump.*

12.1.1 Static force

Static force refers to the force exerted by muscles when they contract without causing any visible movement, maintaining a constant muscle length and joint position. This type of force is typically measured during isometric exercises, where the muscle generates tension against an immovable object. Isometric exercises are widely used in both sports and rehabilitation settings, not only for assessing muscle strength capacity but also for improving force production at specific joint angles (Lum and Barbosa 2019). While they have strong practical applications, we will only mention several key points about them as they fall outside the primary scope of VBT. There are three primary external manifestations of muscle force typically measured using isometric exercises: (i) maximal isometric force, (ii) the force-time relationship, and (iii) muscular endurance.

(A) *Maximal isometric force* is the highest amount of force that a muscle or group of muscles can generate without visible movement (**Figure 12.2**). It is typically assessed using a dynamometer or force sensor (e.g., force plate), with the subject exerting maximum effort for 3-5 seconds in a stable posture. Research has demonstrated that maximal isometric force can be measured with high reproducibility (Maffiuletti et al. 2016), and it often shows strong correlations with maximal dynamic strength indicators, such as the one-repetition maximum (1RM) and the theoretical maximal force (F_0) (Cuk et al. 2014). This makes it a reliable and valuable measure in both sport and rehabilitation contexts.

Figure 12.2. *Assessing maximal and time-dependent force variables during a maximal voluntary isometric contraction. MIF, maximal isometric force; RFD, rate of force development.*

(B) *Force-time relationship* refers to the pattern of force generation by muscles over time. It is typically measured during maximal isometric contractions, where subjects are instructed to rapidly increase force production from the onset of the contraction. Two key variables are used to evaluate a subject's ability to rapidly increase force production: (i) the rate of force development (RFD), and (ii) the initial force at specific time intervals (**Figure 12.2**). The RFD (N/s) represents the slope of the force-time curve. It is calculated by measuring the change in force over specific time intervals, and the maximal RFD is identified as the highest value of RFD observed during the initial phase of the contraction, typically within the first 200 milliseconds. The initial force (N) represents the force achieved at specific time intervals during the initial phase of the contraction (e.g., 50 or 100 milliseconds from the onset of the contraction). Both variables are highly ecologically valid because, in most actions, the time available to apply force is limited. However, obtaining these variables with acceptable reproducibility is challenging (Maffiuletti et al. 2016), which limits their practical use. Lifting velocity against submaximal loads, which is closely related to RFD capacity due to the limited time available to apply force, could be a more reliable metric for indirectly assessing this critical strength attribute.

(C) *Strength-endurance* is the ability to sustain force production over an extended period. This ability can be assessed using both maximal and submaximal isometric tasks (**Figure 12.3**). In maximal tasks, subjects perform a maximal isometric contraction for a fixed duration (e.g., 20 seconds), with performance evaluated by measuring the decrease in force production from the peak

isometric force (typically reached within the first 5 seconds) to the force value at the end of the task. In submaximal tasks, subjects are instructed to maintain a submaximal force output (e.g., 60% of peak isometric force) for as long as possible, with performance evaluated by the duration they are able to sustain the submaximal force. The submaximal isometric endurance task could reflect the more traditional method of measuring muscular endurance during dynamic actions, which involves evaluating the maximal number of repetitions completed to failure. In contrast, the maximal isometric endurance task is more closely related to the novel approach of assessing lifting velocity during repeated dynamic efforts performed at maximal intended velocity.

Figure 12.3. *Assessing strength-endurance performance through maximal (upper-panel) and submaximal (lower-panel) isometric tasks. MIF, maximal isometric force.*

12.1.2 Dynamic force

Dynamic force refers to the force generated by muscles during movement, where the muscle length changes through eccentric and concentric actions. This type of force can be assessed under isoinertial and isokinetic conditions. In isoinertial conditions, the load remains constant, such as when lifting a fixed weight. In contrast, isokinetic conditions involve maintaining a constant movement speed using specialized equipment like an isokinetic dynamometer. These types of assessments help evaluate the ability to produce force across various loads and speeds, offering a comprehensive understanding of an individual's muscular capabilities and performance. The primary external manifestations of muscle force typically assessed during isoinertial and isokinetic dynamic conditions are detailed below.

12.1.2.1 Isoinertial strength assessment

This is the most commonly used type of assessment in practice due to its simplicity, low cost, and the valuable information it provides on strength manifestations. Essentially, it requires only standard training equipment, such as barbells and weight plates, along with a measuring device to assess mechanical performance variables (e.g., force, velocity, and power). This is the main type of assessment when applying VBT. The primary external manifestations of muscle force typically assessed during isoinertial exercises (e.g., squat or bench press) using velocity recordings include: (i) maximal dynamic force, (ii) submaximal dynamic force, (iii) dynamic force deficit, (iv) force-velocity (F-v) relationship, and (v) repetitive efforts with maximum intent.

(A) *Maximal dynamic force* represents the highest force value (N) achieved during an exercise performed with the maximum load that can be lifted. While this variable is feasible to be measured, the assessment is often simplified by determining the maximum load (kg) that can be lifted once with proper technique, known as the one-repetition maximum (1RM). As detailed in Chapter 7, the 1RM, which typically represents the maximal dynamic force capacity, can be directly measured or estimated through the recording of lifting velocity. It is important to note that when the lifting phase is performed at maximal intended velocity, individuals will progressively display lower force values as the load moves further from the 1RM. This is because the ability to exert force is inversely related to the velocity of muscle shortening. Therefore, although it can be affirmed that individuals will have varying force values corresponding to different loads (velocities), their maximal dynamic force will always be attained against the 1RM load.

(B) *Submaximal dynamic force* represents the ability to apply force against resistances lower than the 1RM. One of the simplest and most reproducible method to measure this capacity involves recording lifting velocity against various submaximal (< 1RM) loads. An increase in the velocity at which a given load is lifted clearly indicates that the individual has improved their ability to apply force against that load. The advantages of recording lifting velocity over other mechanical variables, such as force or power outputs, have been detailed in Chapter 3.

(C) *Dynamic force deficit* represents the difference in force output between a submaximal load (< 1RM) and the maximal load (1RM) that can be lifted. For example, a peak force deficit of 400 N would be obtained when an individual produces 1500 N against the 1RM but only 1100 N against a submaximal load (e.g., 80% 1RM). Dynamic force deficit is load-dependent, with greater differences expected for progressively lighter loads. This metric is crucial because many resistance training (RT) programs not only aim to increase maximal dynamic force capacity but, more importantly, the ability of individuals to express most of their maximal force capacity when exercising with submaximal loads. Therefore, a common goal of RT should be to minimize the dynamic force deficit. Although it has been less explored compared to other VBT applications, an effective and efficient approach to determine the dynamic force deficit consists of assessing the velocity corresponding to different relative loads (%1RM). Lifting a given %1RM at higher velocities indicates a lower dynamic force deficit. This is supported by a previous study showing that a 4-week RT program, which included ballistic exercises such as vertical jumps and bench press throws loaded at 40%1RM, resulted in increased velocities at submaximal %1RM post-training (Pérez-Castilla and García-Ramos 2020).

(D) The *force-velocity (F-v) relationship* has been extensively used to characterize the mechanical limits of the neuromuscular system which can be summarized through three parameters: the theoretical maximal force that limbs could produce over one extension at null velocity (F_0), the theoretical maximal velocity at which they could extend against no constraints (v_0), and the maximal power output they can develop over one extension ($P_{max} = F_0 \cdot v_0/4$). It can be assessed by recording force and velocity outputs against two or more loads, and then modelling the recorded data through a linear regression model (Jaric 2016). Graphically, F_0 and v_0 correspond to the force axis and velocity axis intercepts of the linear F-V relationship, respectively, and P_{max} corresponds to the apex of the parabolic power-velocity relationship (**Figure 12.4**). The parameters of the F-v relationship have been shown to be effective for guiding load prescription to maximize ballistic performance (Jiménez-Reyes et al. 2017) and as criteria for returning to play following a hamstring injury (Mendiguchia et al. 2016). However, the challenge of obtaining reliable F-V relationship parameters under specific circumstances has led to the proliferation of a simplified load-velocity (L-V profile), which provides similar indicators of maximal force, velocity, and power capacities (see Section 12.2.2 for details).

Figure 12.4. *Force-velocity and power-velocity relationships obtained sprinting against five different resistance levels during the leg cycle ergometer exercise. F_0, maximal theoretical force; v_0, maximal theoretical velocity; P_{max}, maximal power.*

(E) *Repetitive efforts with maximum intent* are a crucial strength attribute to evaluate, as success in many athletic endeavours critically depends on the performer's ability to sustain maximum mechanical performance throughout the event. Therefore, it is essential for athletes to

develop high mechanical capacities (i.e., F_0, v_0, and P_{max}) and, equally important, to maintain these maximal capacities for as long as possible while minimizing the impact of fatigue. Traditionally, muscular endurance during dynamic actions has been assessed by counting the number of repetitions performed to failure with a submaximal load. However, the proliferation of velocity measuring devices is contributing to the creation of new tests and metrics, such as mean set velocity (MSV), mean velocity maintenance (MVM), and mean velocity decline (MVD), which provide more informative data with less time-consuming and fatiguing tasks (see Section 12.3 for details). Briefly, we no longer need to conduct sets to failure to count repetitions; instead, we can analyse the decrement in mechanical performance during a single or multiple sets performed with maximal lifting intent.

12.1.2.2 Isokinetic strength assessment

Isokinetic testing has been widely used in laboratory settings to provide detailed information on strength production during both concentric and eccentric actions (Dvir and Müller 2020). This technology allows for a thorough assessment of muscle function, as it enables the evaluation of force production during the lengthening phase of muscle contraction, which is crucial for understanding overall muscle performance. This method employs specialized equipment that measures muscle performance at a constant speed. While the equipment required for isokinetic testing is more sophisticated and costly than standard training tools, the data obtained is invaluable for assessing muscle imbalances and monitoring rehabilitation progress. However, this assessment method will not be further discussed in this chapter as it does not pertain to the core concept of VBT.

12.1.3 Reactive force

Reactive force refers to the force generated by muscles in response to a sudden stretch, commonly observed during plyometric activities. It measures the muscle's ability to swiftly switch from an eccentric (lengthening) action to a concentric (shortening) action, which is crucial for explosive movements such as jumping, sprinting, and changing direction. This concept is closely linked to the activity of muscle spindles, which detect rapid stretches and trigger a reflexive contraction, enabling the muscle to quickly transition from eccentric to concentric action.

One of the most commonly used exercises to assess reactive strength ability is the drop jump (DJ), which evaluates the reactive strength index (RSI) by dividing the jump height by the ground contact time. A higher RSI indicates better reactive strength, reflecting a greater ability to generate force rapidly after landing. A modification of the RSI, used for the countermovement jump (CMJ), is calculated by dividing the jump height by the push-off time. These metrics are crucial because they account for both the final output and the time required to achieve it. However, caution should be exercised, particularly using the CMJ, as these indices can be acutely influenced by factors such as jump strategy (Pérez-Castilla et al. 2021b).

12.2 Protocols for assessing maximal strength using velocity recordings

Evaluating an athlete's ability to generate force in a rested (non-fatigued) state is crucial, as it significantly impacts their overall performance potential. Traditionally, the 1RM has served as the benchmark for assessing this capacity. However, relying on the 1RM is problematic not only because it demands a physically, technically, and psychologically challenging testing protocol, but even more importantly because changes in 1RM do not adequately reflect the full range of

adaptations occurring along the F-v continuum. Consequently, it is essential for coaches and researchers to monitor and document changes in force generation under various loading conditions to gain a more comprehensive understanding of an athlete's strength profile.

The two methods most commonly employed in scientific research to generate a comprehensive strength profile include: (i) documenting changes in lifting velocity with the same absolute loads, and (ii) analysing the load-velocity (L-V) relationship to derive key variables from this relationship. The basic characteristics of these testing procedures, along with their advantages and disadvantages, are detailed in the subsequent sections.

12.2.1 Testing the same absolute loads

A common goal of many RT programs is to foster adaptations that enable individuals to generate more force under the same absolute load, or in other words, achieve higher velocities while lifting the same absolute load. Recording lifting velocity against the same absolute loads has been shown to effectively distinguish between athletes of different competitive levels (González-Badillo et al. 2015), detect fatigue during and after RT sessions (Pareja-Blanco et al. 2017a), and identify strength changes following various RT programs (Pareja-Blanco et al. 2017b). One of the most crucial aspects of using velocity recordings to assess strength potential is ensuring consistent absolute loads across athletes and over time.

A primary challenge in comparing strength performance across individuals with varying maximal strength levels is that using constant absolute loads can result in assessing their force production at different points on the F-v relationship. For instance, a 60 kg load during a barbell back squat would be a light load for a *strong* subject with a 1RM of 200 kg (30% 1RM), but the same absolute load would be considered heavy for a *weak* subject with a 1RM of 80 kg (75% 1RM). Some studies have attempted to address this issue by testing lifting velocity against relative loads, adjusting for each individual's 1RM or body mass, but this approach has its flaws.

Consider the same two subjects from the earlier example. Instead of using a consistent absolute load (i.e., 60 kg), researchers decide to test their lifting velocity performance at the same percentage of their 1RM (e.g., 75% 1RM). Here, the weaker subject would lift 60 kg, while the stronger subject would lift 150 kg. In this scenario, the weaker subject might demonstrate a higher lifting velocity, yet this does not accurately reflect a superior strength potential. At most, this suggests that the weaker subject has a lower dynamic force deficit, as detailed in section 12.1.2. Therefore, while comparing lifting velocities at the same %1RM should not serve as an absolute measure of strength potential, it can be useful for determining the percentage of a subject's maximal strength that can be expressed during submaximal lifts.

The practice of assigning loads based on a percentage of body mass, which is common in loaded jumps assessments, can be even more problematic. For instance, García-Ramos et al. (2016) evaluated international-level female swimmers performing squat jumps with additional resistance of 25, 50, 75, and 100% of their body mass and correlated the mechanical outputs (force, velocity, and power) with their swimming start performance. However, this method is impractical, as in many sports, including swimming, external loads do not vary with an athlete's body mass. Sports like football, basketball, and tennis require athletes to move their own body mass, but the external loads encountered during gameplay do not increase for heavier athletes. Therefore, assigning

different external loads based on body mass during strength assessments does not seem advisable, as it fails to reflect the actual demands of competition.

The information provided above highlights the necessity of testing velocity against consistent absolute loads to assess differences in strength potential. It is important to recognize, however, that these loads may align with different sections on the F-v relationship for various athletes or even the same athlete as their strength evolves due to training or detraining. Additionally, testing multiple loads can lead to discrepancies where differences in performance might appear for some loads but not others, possibly due to random noise. To give coaches clearer insights, the data from various loads should be integrated, and ideally, it should offer distinct information about changes in force capabilities at different segments of the F-v relationship.

The most sophisticated approach for evaluating individual changes in strength performance involves calculating the average velocity achieved against all absolute loads that are consistent between both pretest and posttest (Pareja-Blanco et al. 2017b; González-Badillo et al. 2022). Typically, subjects undergo testing against multiple incremental loads, usually ranging from 20 kg up to their 1RM across 6 to 11 increments. The velocities for these common loads are then aggregated to generate a single velocity value, which is intended to represent the overall strength performance across the entire incremental loading test. Additionally, separate analyses are often performed to calculate the average velocity for the common loads moved faster or slower than a specific velocity threshold (e.g., 1 $m \cdot s^{-1}$) to differentiate changes in a subject's capacity to apply force against light and heavy loads, respectively.

However, this approach has several limitations. Firstly, the averaged velocity value is disproportionately influenced by changes in performance against lighter loads compared to heavier ones because a fixed percentage change in velocity results in a more significant absolute difference (in m/s) for lighter loads. Secondly, the procedure is time-consuming and fatiguing because it typically involves testing 6 to 11 load increments. Thirdly, comparisons across different studies and individuals are challenging unless the exact same absolute loads are used to compute the average test velocity. The assessment of the L-V profile, as discussed in the next section, is expected to address all these issues.

However, we would like to highlight a unique benefit of the testing procedure that involves recording velocity against individual loads: its exceptionally high reliability. Studies using a LPT to measure lifting velocity performance against submaximal loads have consistently demonstrated very high intra- and inter-session reliability. This level of consistency is observed in various exercises, including different forms of the squat, deadlift, bench press, bench pull, and shoulder press. Notably, this high reliability has been confirmed for exercises performed with both free-weights and on a Smith machine. Consequently, it is unequivocal that this testing procedure is a valuable tool for assessing an athlete's strength profile. While monitoring the L-V profile addresses some of the limitations of testing the same absolute loads, the extrapolation needed to derive variables of interest from the L-V relationship introduces variability, making it a less reproducible testing method. Therefore, when deciding on their testing procedure, coaches and researchers should weigh the greater informative value of L-V profile variables against the greater reproducibility expected for velocity outputs collected against individual loads.

12.2.2 Testing the load-velocity (L-V) profile

The F-v relationship has traditionally been used to comprehensively assess the mechanical properties of the human musculoskeletal system in producing force during various multi-joint isoinertial and isokinetic tasks (Jaric 2015). The mechanical limits of the neuromuscular system are often described by (i) theoretical maximal force capability (F_0), (ii) theoretical maximal velocity achievable without external constrains (v_0), and (iii) maximal power (P_{max}) that can be developed. The F-V testing procedure provides more valuable information than standard testing under a single mechanical condition because it distinguishes between maximal force, velocity, and power capacities, whereas force, velocity, and power outputs recorded under individual loads depend on each other and do not reveal the individual maximal mechanical capacities.

Previous studies have shown that the outcomes of the F-v relationship (i.e., F_0, v_0, F-V slope, and P_{max}) can be used to create individualized RT programs to enhance ballistic performance and manage injuries (Mendiguchia et al. 2016; Jiménez-Reyes et al. 2017). However, the reliability and validity of the parameters derived from the F-v relationship remain questionable (Lindberg et al. 2021). A primary challenge in exercises performed against gravity (e.g., squats or bench press) is obtaining accurate measurements of v_0 due to the significant extrapolation required from the experimental points to the velocity axis. For instance, in loaded jumps, the lightest experimental point (i.e., unloaded jump) is typically located in the middle portion of the F-v relationship (Cuk et al. 2014; García-Ramos et al. 2017).

To address the aforementioned issue, the L-V relationship has been recommended as a simple and potentially more reproducible method for assessing maximal neuromuscular capacities (Pérez-Castilla et al. 2021a). Unlike the F-V relationship, which typically considers the system's weight (in N), the L-V relationship method requires only the external load lifted (in kg), reducing the extrapolation needed to reach the velocity axis and potentially improving the reproducibility of v_0. The L-V relationship can be modelled using a simple linear regression to obtain analogous outcomes to those derived from the F-v relationship: (i) theoretical maximal load (L_0; load at 0 $m \cdot s^{-1}$; a proxy for F_0), (ii) theoretical maximal velocity (v_0; velocity at 0 kg), and (iii) area under the L-V relationship line ($A_{line} = F_0 \times v_0 / 2$; a proxy for P_{max}) (**Figure 12.5**).

Figure 12.5. *Representation of a load-velocity relationship and the calculation of its main outcomes. The regression equation and Pearson's correlation coefficient (r) are depicted. L_0, load-axis intercept; v_0, velocity-axis intercept; A_{line}, area under the load-velocity relationship line.*

Emerging evidence has confirmed the high reliability, sensitivity, and validity of the L-V relationship variables (L_0, v_0, A_{line}). Pérez-Castilla et al. (2021a) demonstrated high between-session reliability for L-V relationship variables in the bench press throw exercise (CV ≤ 2.36%), with nearly perfect correlations between L_0 and bench press 1RM (r = 0.98) and between A_{line} and P_{max} (r = 0.96), though the correlation between v_0 and peak velocity at 14 kg was lower (r = 0.59). Similar findings were reported by Pérez-Castilla et al. (2022) for two squat exercise variants, showing high between-session reliability (CV = 2.58% to 9.01%) and high concurrent validity between L_0 and squat 1RM ($r \geq 0.87$) and between A_{line} and P_{max} (r = 0.98). Furthermore, Iglesias-Soler et al. (2021) found that L_0 and v_0 were sensitive enough to detect changes in neuromuscular performance during the bench press and squat exercises following a five-week RT program with

traditional or cluster set configurations. The L-V relationship variables have also shown positive correlations with rowing performance (Pérez-Castilla et al. 2023a) as well as swimming performance and in-water force production (Miras-Moreno et al. 2024).

The L-V relationship has been typically determined using a linear regression model applied to data from multiple external loads (i.e., "multiple-point method"). However, since the L-V relationship is approximately linear during multi-joint tasks, the intermediate loads should not meaningfully influence the outcomes of the relationship. Accordingly, several studies have shown very high concurrent validity for L-V relationship variables obtained using the 2-point method (data of only two loads used for the L-V relationship modelling) compared to the multiple-point method in exercises such as the countermovement jump (Pérez-Castilla et al. 2023b) and bench pull (Miras-Moreno et al. 2022, 2023). Therefore, the 2-point method can significantly reduce testing time and minimize fatigue induced by the testing protocol while still providing reliable and valid L-V relationship outcomes. The key methodological aspects for implementing the 2-point method are detailed in Chapter 13.

In summary, the most common procedure to evaluate changes in neuromuscular performance before and after a training intervention involves comparing the velocity achieved with the same absolute loads or the average velocity attained with light (e.g., > 1.0 $m \cdot s^{-1}$) and heavy (e.g., < 1.0 $m \cdot s^{-1}$) loads (Pareja-Blanco et al. 2017b; González-Badillo et al. 2022). However, assessing L_0 and v_0 through the L-V relationship offers a less arbitrary and more comprehensive indicator of an individual's capacity to apply force at low and high velocities, respectively. A third variable, the area under the L-V relationship line ($A_{line} = L_0 \cdot v_0/2$), likely serves as an indicator of P_{max}. The L-V relationship variables have two important advantages over the F-v relationship parameters: (i) they can be obtained with higher reliability (especially v_0), and (2) only velocity outputs, not force outputs, need to be recorded. However, a limitation worth noting is that L-V relationship variables do not have a clear physiological meaning, unlike the maximal mechanical capacities of muscles to produce force, velocity, and power determined through the F-v relationship modelling.

12.2.3 Non-ballistic vs. ballistic exercises

Since the seminal work of Newton et al. (1996), the consensus has been that ballistic exercises (e.g., loaded jump and bench press throw) produce greater force, velocity, power, and muscle activation than their traditional RT equivalents (e.g., squat and bench press). These mechanical differences are more pronounced with lighter loads and gradually diminish, eventually vanishing as the loads near the 1RM. Additionally, it is possible that the braking phase characteristics of traditional exercises performed at maximal intended velocity with light loads can introduce measurement noise, as evidenced by the higher reproducibility of lifting velocity in the bench press throw compared to the bench press (Garcia-Ramos et al. 2015). Given the superior magnitude and consistency of mechanical outputs, it is evident that coaches and researchers should prioritize ballistic exercises for assessing strength performance with light loads.

An alternative solution proposed by researchers to avoid underestimating an individual's true neuromuscular potential when lifting light and medium loads is to report the mean mechanical values exclusively from the propulsive phase, excluding the braking phase identified by barbell acceleration lower than gravity (Sanchez-Medina et al. 2010). For instance, during the bench press

exercise performed at maximal intended velocity with 20%1RM, the propulsive and braking phases account for 72% and 28% of the total lifting phase duration, respectively (Sanchez-Medina et al. 2010). While using mean propulsive values might be more appropriate than traditional mean values that consider the entire lifting phase for assessing mechanical performance with light and medium loads in non-ballistic exercises, it is more reasonable to select exercise variants that allow individuals to express their full potential throughout the entire range of motion. Due to the limitations of LPTs in detecting the end of the propulsive phase during ballistic exercises (see Chapter 3 for details), the peak velocity variable should be prioritized when assessing performance in ballistic exercises. When lifting heavy loads (> 70% 1RM), the braking phase contribution is minimal, making non-ballistic exercise variants preferable and allowing for reporting either mean or peak velocity.

In summary, strength performance with light to moderate loads should ideally be assessed using ballistic variants and reporting peak velocity, while performance with heavy loads should be assessed using non-ballistic variants, allowing for the reporting of either mean or peak velocity. A significant technological advancement would be if LPTs can accurately determine the exact point of bar release during ballistic exercises, enabling the computation of mean mechanical performance for the entire propulsive phase. Note that the current inability of LPTs to precisely determine the release point has led to incorrect conclusions, such as the assertion that the bench press throw provides lower power than the traditional bench press (Loturco et al. 2017).

12.3 Protocols for assessing strength-endurance using velocity recordings

Evaluating an athlete's ability to sustain mechanical performance over an extended period is crucial, as success in many athletic endeavours depends on maintaining peak performance throughout the event. For example, in many sports, athletes need to sustain explosive movements such as jumps, kicks, sprints, and changes of direction throughout the entire game. Traditionally, the maximal number of repetitions completed to failure (MNR) with a submaximal load, performed without any pauses between successive repetitions, has been used to assess this capacity. However, relying on MNR is problematic not only because it involves a fatiguing testing protocol that can interfere with training goals (Gonzalez-Badillo et al. 2016; Pareja-Blanco et al. 2017b), but also because it is insensitive to detecting different patterns of velocity decline during the set. Therefore, to gain a comprehensive understanding of an athlete's strength-endurance profile, coaches and researchers should monitor performance changes throughout the set, ideally using testing procedures that do not require individuals to reach muscular failure.

The proliferation of velocity monitoring devices is contributing to the creation of new tests and metrics, providing more informative data with less time-consuming and fatiguing tasks. Sets to failure and counting repetitions are no longer required. Instead, lifting velocity can be monitored during sets performed with maximal intent but submaximal effort (i.e., not to failure), allowing for the computation of various variables related to the individual’s strength-endurance performance. The basic characteristics of these testing procedures, along with the key velocity metrics that can be computed, are detailed in subsequent sections.

12.3.1 Testing procedures

The novel VBT approach involves assessing lifting velocity during repeated dynamic efforts performed at maximal intended velocity. While reaching muscular failure is not necessary, it is

crucial that the exercise's physical demands are taxing enough to induce fatigue, as indicated by a decline in lifting velocity. To ensure valid assessments of strength-endurance using velocity recordings and effectively manage the physical demands of the repeated dynamic task, four main methodological factors should be considered: (i) the number of sets, (ii) the number of repetitions, (iii) the load lifted, and (iv) the rest periods.

12.3.1.1 Number of sets

Strength-endurance capacity can be assessed using testing protocols that involve single or multiple sets. Naturally, the physical demands increase with the number of sets performed. Note also that in RT, individuals are typically advised to complete multiple sets per exercise to optimize strength adaptations. Therefore, when assessing strength-endurance capacity, it is reasonable to instruct individuals to perform multiple sets of an exercise. This approach provides a more realistic representation of a typical RT session and allows for a thorough examination of lifting velocity behaviour over an extended period. However, a challenge with implementing multiple sets is that data from subsequent sets can be confounded if the number of repetitions in each set is variable. Thus, practitioners are encouraged to evaluate strength-endurance capacity under multiple sets only when the number of repetitions performed in each set is fixed.

12.3.1.2 Number of repetitions

When assessing strength-endurance capacity using velocity recordings, there are two approaches for prescribing the number of repetitions: (i) *fixed repetitions*, where individuals are instructed to perform the same number of repetitions per set (e.g., 10 repetitions), and (ii) *flexible repetitions*, where individuals continue performing repetitions until their velocity drops below a predetermined threshold (e.g., mean velocity < 0.40 $m \cdot s^{-1}$). Velocity metrics are particularly valuable for assessing strength-endurance performance during non-failure RT sets with a fixed number of repetitions (see section 12.3.2 for details). Since comparisons based on velocity metrics (e.g., MSV, MVM, and MVD) can be compromised if the number of completed repetitions differs, it is important that individuals do not reach failure before completing the prescribed number of repetitions. In such cases, strength-endurance performance should be evaluated by counting the number of repetitions completed rather than relying on velocity metrics.

The flexible repetitions scheme is only valuable for assessing strength-endurance performance by counting the number of repetitions performed above a velocity threshold in the first training set. This is because when the number of repetitions varies in each set, data from subsequent sets can be confounded. For example, imagine subject A performs 15 repetitions above a velocity cutoff of 0.40 $m \cdot s^{-1}$ in the first set, while subject B performs only 6 repetitions. If a second set is performed after a brief rest period, the difference in the number of repetitions between subjects A and B may decrease. However, this could be partially explained by the greater volume of repetitions performed by subject A in the preceding set. Therefore, when the number of completed repetitions is variable, regardless of whether the sets are performed or not to failure, the only unbiased indicator of strength-endurance performance is obtained in the first set.

12.3.1.3 Load lifted

Based on the desired level of effort (i.e., proximity to failure), practitioners should find an optimal balance between the load and the prescribed number of repetitions. This balance is crucial, as the load must be sufficient to induce fatigue (evidenced by a decline in lifting velocity) but not so

taxing that subjects cannot complete the prescribed sets and repetitions before reaching muscular failure. Unlike maximal strength testing, where using the same absolute loads is recommended, strength-endurance performance should be assessed using relative loads (%1RM). Note that the same absolute load would be less demanding for stronger individuals, resulting in greater maintenance and smaller declines in lifting velocity when a fixed number of repetitions is prescribed. As a result, using absolute loads makes it challenging to determine whether an improvement in velocity metrics is due to increased maximal force capacity, strength-endurance capacity, or both. By having individuals lift the same relative load, practitioners can assess their strength-endurance capacity independently of their maximal strength levels.

Two approaches can be used to prescribe loads for comparing strength-endurance performance across individuals or within the same individual over time: (i) using the same %1RM or (ii) using the same initial velocity. Using the same %1RM can be problematic as it requires a direct 1RM test or an estimation with inherent error. More importantly, it does not allow for direct comparisons of mean set velocity (MSV), as this variable is typically greater for individuals with faster starting velocities. However, mean velocity maintenance (MVM) and mean velocity decline (MVD) are not significantly affected by small variations in starting velocity. Despite the variability in lifting velocities between subjects at different %1RMs, strength-endurance assessments can be simplified by prescribing a load based on the initial velocity achieved before fatigue sets in (e.g., load linked to an initial mean velocity of 0.70 $m \cdot s^{-1}$). This initial velocity can be chosen based on generalized L-V relationships (see Chapter 7 for details) to approximate the load to the desired %1RM.

12.3.1.4 Rest periods

Lifting velocity performance is significantly influenced by the duration of both inter- and intra-set rest periods (Jukic et al. 2020; Janićijević et al. 2023). Therefore, maintaining consistent rest periods is crucial when assessing strength-endurance performance, as shorter rest periods are expected to result in greater declines in lifting velocity. Although not commonly practiced, alternative set structures incorporating short rest periods within a set could also be valuable for assessing this capacity (see Chapter 6 for details). This approach is justified as it mirrors the intermittent high-intensity actions and brief rest periods typical in many sports, making it a potentially more ecologically valid set structure for assessing strength-endurance capacity.

12.3.2 Key velocity metrics

Six variables can be used to assess strength-endurance performance based on the monitoring of lifting velocity during sets not performed to failure (**Figure 12.6**): (i) mean set velocity (MSV), (ii) mean velocity maintenance (MVM), (iii) mean velocity decline (MVD), (iv) repetitions above the threshold, (v) fastest set velocity ($V_{fastest}$), and (vi) last repetition velocity (V_{last}).

Figure 12.6. *Mean velocity during three sets of 10 repetitions and computation of key velocity metrics. Vfastest, velocity of the fastest repetition of the set; Vlast, velocity of the last repetition of the set, MSV, mean set velocity; MVM, mean velocity maintenance; MVD, mean velocity decline. An absolute threshold of ≥ 0.65 $m \cdot s^{-1}$ was used to quantify the repetitions performed above the threshold.*

12.3.2.1 Mean set velocity

Mean set velocity (MSV) refers to the average lifting velocity across all repetitions performed within a set. It provides an overall measure of strength-endurance performance by considering the entire set, but it has important limitations. For instance, its value is heavily influenced by the starting velocity, making it ineffective for comparing performance across individuals who do not begin the set at the same velocity. Additionally, it is impractical if the number of repetitions varies, as MSV could be lower for an individual who is able to complete more repetitions.

12.3.2.2 Mean velocity maintenance

Mean velocity maintenance (MVM) represents the ability to sustain a consistent velocity across multiple repetitions within a set. It is calculated as MVM (%) = (MSV × 100) / $V_{fastest}$, where MSV is the mean set velocity and $V_{fastest}$ is the fastest velocity of the set. MVM is a good indicator of how well an individual maintains their initial performance level across the set. Small variations in the starting velocity of the set are not expected to significantly influence its value, making it a robust indicator of the ability to maintain maximal mechanical performance. However, it is not a reliable indicator of overall fatigue during multi-set testing procedures, as its value can be misleadingly inflated when $V_{fastest}$ progressively decreases with an increasing number of sets. Note in Figure 12.6 that the best MVM outcome is achieved in set 3, even though the subject is more fatigued, as indicated by a lower $V_{fastest}$.

12.3.2.3 Mean velocity decline

Mean velocity decline (MVD) quantifies the reduction in velocity from the beginning to the end of a set. It is calculated as MVD (%) = (V_{last} – $V_{fastest}$) / $V_{fastest}$ × 100), where V_{last} is the velocity of the last repetition of the set and $V_{fastest}$ is the fastest velocity of the set. MVD provides insight into the level of fatigue experienced at the end of the set. Similar to MVM, small variations in the starting velocity of the set are not expected to significantly influence its value, making it a reliable indicator of performance decline. However, similar as MVM, it is not a good representative of fatigue during multi-set testing procedures when $V_{fastest}$ decreases with the increase in the number of sets. Note that the best value in Figure 12.6 occurs during set 3.

12.3.2.4 Repetitions above the threshold

Repetitions above the threshold refer to those performed at a velocity exceeding a predetermined minimum velocity. This metric helps identify the repetitions that meet a specific performance criterion, such as the number of repetitions performed before the lifting velocity falls below an absolute (e.g., 0.40 $m \cdot s^{-1}$) or a relative threshold (e.g., 20% velocity loss). While the previously mentioned variables require a fixed number of prescribed repetitions, this metric can be effectively used with both fixed and flexible repetition approaches.

12.3.2.5 Fastest set velocity

This variable enables the assessment of an individual's ability to maintain high mechanical outputs throughout an RT session involving multiple sets performed with the same absolute load. A decrease in $V_{fastest}$ indicates incomplete recovery from the preceding effort. Additionally, the behaviour of $V_{fastest}$ during an RT session is crucial for computing other metrics such as MVM and MVD. Previous studies have shown that in RT sessions characterized by a gradual decline in $V_{fastest}$, using $V_{fastest}$ from each specific set can overestimate mechanical performance (MVM and MVD) compared to using $V_{fastest}$ from the first set or the entire RT session (Jukic et al. 2023; Janićijević et al. 2023; Janicijevic et al. 2024).

These findings have important practical applications when using velocity loss thresholds to prescribe the volume of repetitions. In RT sessions with a gradual decline in $V_{fastest}$, if the $V_{fastest}$ of each particular set is considered, prescribing repetitions based on a fixed velocity loss threshold (e.g., performing repetitions until velocity drops more than 20%) may lead to varying levels of fatigue. Specifically, when using a fixed velocity loss threshold to prescribe the number of repetitions, the degree of fatigue at the end of the set is expected to be higher (i.e., closer proximity to failure) when sets are initiated at a lower velocity.

12.3.2.6 Last repetition velocity

During multi-set RT testing procedures, changes in $V_{fastest}$ serve as a general indicator of fatigue at the start of each training set, while V_{last} provides similar insight into the fatigue state at the end of each set. When using fixed absolute load and repetitions in multi-set testing procedures, $V_{fastest}$, MSV, and V_{last} offer complementary and valuable information regarding recovery capacity across different sets. On the other hand, MVM and MVD are better suited to assessing the ability to maintain performance within a single set. Note that MVM and MVD do not account for potential fatigue that may already be present at the start of a set during multi-set testing unless the $V_{fastest}$ from the first set is factored into their calculations for subsequent sets.

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