A coach’s guide to velocity-based training: Definitions and diagnostics

THOMPSON, Steve <http://orcid.org/0000-0001-7674-3685>, FERNANDES, John, DORRELL, Harry, GREIG, Leon and BISHOP, Chris

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Abstract

Velocity-based training (VBT) utilizes the measurement of velocity to help inform and influence testing, monitoring, programming, autoregulation, and feedback strategies within strength and conditioning (S&C) practice. This review focuses specifically on the definitions and underpinning principles of VBT, as well as load-velocity profiling, while undertaking an in-depth evaluation of the literature and translating this information into practical recommendations for S&C coaches. There is a detailed evaluation of the different ways to construct a load-velocity profile (LVP), providing examples of simplicity, time efficiency, increased accuracy, and optimizing training prescriptions and manipulations. New approaches, such as combining ballistic and non-ballistic exercises and methods of extrapolation have been explored. Additionally, this paper highlights practical considerations regarding data analysis, specific exercises, statistical modeling, number of loads, and extrapolation methods. A worked example of utilizing LVP data within excel has also been presented. Finally, there is a focus on one repetition maximum prediction, the benefits and challenges of implementing such an approach, and the most appropriate ways of collecting reliable and valid data.

Introduction

Strength and conditioning (S&C) coaches are tasked to improve the physical performance of their athletes through effective training solutions created via effective needs analyses, athlete profiling, program development, and coaching and reflective practices (103). Ingrained in this process is the need for efficient strategies that meticulously plan long-term preparation for a major event in an athlete's calendar while ensuring flexibility to unplanned deviations due to uncontrollable factors (e.g., injury, fatigue, personal stressors, etc.) (11,19,46). Long-term planning for an athlete combines methods of periodization (e.g., block or undulating) and programming (percentages of one repetition maximum (1RM) (%1RM) or repetition maximums) to (19) map out training cycles and target specific physiological adaptations in preparation for competition (19). Despite the possibilities for rigorous planning, programming at the start of a training block alone could lead to sub-optimal progression and insufficient preparation for competition, particularly in multi-faceted sports with long and congested competitive schedules (e.g., soccer, rugby, basketball, etc.). For example, an individual's strength capabilities can fluctuate in response to psychological and physiological stressors (Figure 1), and research has suggested that confounding variables such as fatigue, poor sleep, high levels of stress, specific training phases, and improper nutrition, can all impact an athlete's ability to lift consistent loads continuously (7,18,23,67,77,96). Therefore, practitioners must find strategies to help circumvent some potential limiters to performance.

Insert figure 1

Alternative options to %1RM, such as repetition maximum targets or zones, are common within applied S&C and the literature (112). These methods, however, can elicit excessive levels of neuromuscular fatigue, stunt physiological adaptations, and be ineffective for long-term programming. This is likely due to the 'training to failure' nature of this method (12,13,20,47,100,112). Therefore, the restrictions of traditional programming often require coaches to seek alternative strategies to optimize physiological adaptations and maximize readiness to train.

Combining non-flexible programming with additional methods designed to account for fluctuations in strength could enable more effective prescriptions during an athlete's competitive preparation. These methods are often referred to as autoregulation, where flexible practices are utilized to adjust volume or intensity in accordance with an athlete’s psychological and physiological status (e.g., readiness, fatigue, neuromuscular function) and provide an additional tool for S&C coaches to utilize (50,102). Examples of autoregulatory practices are subjective exertion scales (e.g., ratings of perceived exertion, repetitions in reserve), prediction equations from sets to failure, autoregulatory progressive resistance exercise (APRE), or flexible non-linear programming (FLNP) (63,73,76,117). All these methods have facilitated greater strength and power adaptations compared to periodization alone (44,73,76), though they are not without limitations. For example, many of the scales used are subjective, resulting in a need for accurate judgment to yield meaningful data. In addition, APRE relies on training to failure, which can increase the fatigue present in athletes, while FLNP lacks supporting evidence within the literature (106). As a result, more objective and less invasive methods of autoregulation have been explored both within the literature and practice, such as velocity-based training (VBT), specifically load-velocity profiling (47,106,108,115). Therefore, the aim of this article is to provide an in-depth and applied evaluation of load-velocity profiling and the underpinning principles of VBT while providing coaches with practical examples and recommendations to implement within their practices.

Definitions

VBT involves the measurement and analysis of the velocity (vector quantity) in each phase of movement (e.g., concentric phase) of an external load (typically barbell) or biomechanical system to better understand intensity and volume to inform and improve training. The most common metrics used in practice are mean velocity, mean propulsive velocity, or peak velocity (Table 1) (115). VBT requires the utilization of technology (e.g., linear position transducer (LPT), inertial measurement unit (IMU), camera-based system, or smart device application) to measure and calculate velocity data that can then be used to customize athlete mechanical output for an exercise and assist with training prescriptions (109,116).

Nevertheless, VBT is often misrepresented as a direct training method when it perhaps best represents an overarching set of guiding principles designed to enhance a training environment (47,108). For example, statements and questions such as “we are doing VBT” or “can VBT improve our practice?” are heard from practitioners and coaches, leaving the relevant details of how, what, and when unanswered (108). Instead, coaches should look at VBT as an umbrella of overarching strategies that can be flexible, multi-dimensional, and adapted to any training environment. Furthermore, at the heart of these guiding principles are several objective applications (e.g., LVPs, velocity loss) for quantifying training effort, monitoring fatigue, profiling individuals, and assisting with program design (4,106,115).

Insert table 1

Insert figure 2

Three main velocity metrics are most commonly available to coaches (Table 1). Mean velocity or mean propulsive velocity is thought to be more suited to ‘strength-based’ non-ballistic exercise (e.g., back squat, bench press, deadlift), while peak velocity seems to be more appropriate for ‘power-based’ ballistic exercise (e.g., power clean, jump squat, bench throw) (115). Furthermore, when performing more complex movements such as weightlifting exercises, mean velocity could be impacted by phases such as the first pull, which is often a slower and more variable portion of the lift (62).

It is important to consider the mechanical context and the reliability of each metric before employing specific metrics for different training modalities. First, literature has identified minimal differences between the three metrics when considering reliability, irrespective of exercise modality (ballistic *vs.*

non-ballistic) (6,39). Second, peak velocity, dictated by sampling rate, only provides a snapshot of neuromuscular function and mechanical output within an exercise and could be influenced by erroneous data, movement variability, technique, filtering processes, or measurement error (6,109,111). As a result, perhaps both mean velocity and mean propulsive velocity could provide a more robust and in-depth understanding of velocity characteristics of an individual within both ballistic and non-ballistic exercises. Additionally, coaches might want to consider alternative metrics such as eccentric velocities, velocities over given time points (e.g., 50-200 ms), or velocity up to the sticking region as potential alternatives to the three traditional options. However, literature validating the reliability and sensitivity of these alternative metrics is still limited, specifically using VBT technology.

Physiological and mechanical underpinnings

Velocity (v) is the rate of change of displacement (s) (both vector quantities) but can also be integrated from acceleration (a) and time (t), directly linking to Newton's second law of motion. Newton's second law states the change in momentum (m) of an object is equal to the impulse applied to it and is equivalent to the instantaneous sum of force being equal to its mass multiplied by its acceleration (F=ma) (49,83,107). Mechanical principles dictate that F=ma can be extended or rearranged to underpin many other metrics. For example, a fundamental kinetic principle that describes the movement of objects, impulse-momentum, can be equated as follows:

$$\boldsymbol{F} = \boldsymbol{m} \times (\boldsymbol{v_1} - \boldsymbol{v_2})/(\boldsymbol{t_1} - \boldsymbol{t_2}) \qquad \text{eq.1}$$

$$\boldsymbol{F} \times (\boldsymbol{t_1} - \boldsymbol{t_2}) = (\boldsymbol{m} \times \boldsymbol{v_1}) - (\boldsymbol{m} \times \boldsymbol{v_2}) \qquad \text{eq.2}$$

$$\boldsymbol{F} \times \Delta \boldsymbol{t} = \boldsymbol{m} \times \boldsymbol{v}$$

eq.2

Power (P) (a scalar quantity) represents the rate of mechanical work a system can perform with respect to force and is a commonly utilized metric within S&C when rearranged to reflect the interaction between force and velocity:

$$\boldsymbol{W = F \times s}$$

eq.3

$$\boldsymbol{P = \frac{(F\ x\ s)}{t}}$$

eq.4

$$\boldsymbol{P = \frac{F\ (v \times t)}{t}}$$

eq.5

$$\boldsymbol{P = F \times v}$$

eq.6

Both examples above culminate in force and velocity being integral parts of the equation, underpinning the mechanical principles of major aspects of S&C (114). Thus, utilizing velocity to inform training directly links biomechanics and physiology (107). The interaction between force and velocity underpins the basic principles of VBT (e.g., LVP) and is directly linked to specific physiological mechanisms that underpin performance (111). A direct, inverse relationship between single-joint muscular force and velocity exists, reflecting the complex interaction between a muscle fiber's shortening proteins, actin and myosin (8,16,28,52). As the velocity of muscle shortening increases, the time available for cross-bridges between actin and myosin to form reduces, and thus, muscular force must decrease (1,2,27,51). Similarly, as muscle shortening velocity decreases, force can increase, highlighting the existence of the force-velocity relationship (30). When considering multi-joint actions, the inverse relationship still exists but has been reported as more quasi-linear (properties of a linear relationship but with some curvature of the best-fit line) (10). Therefore, this direct link between mechanical output (velocity) and neuromuscular function provides a unique opportunity for practitioners to manipulate training, evaluate readiness, and analyze athlete capabilities.

The load-velocity relationship and profile

When performing resistance exercises, force can be analyzed with respect to an external weight (e.g., barbell) or the whole-body system (center of mass). VBT centers on the former, utilizing mathematical models to estimate the interaction between external load and movement velocity, which is analogous to the force-velocity relationship (16,72,111). When performing exercises that start and end with zero acceleration (e.g., isotonic or isokinetic), mean net force must also equal zero, resulting in mean force equating to system weight (body weight in addition to any external load) as force and acceleration are directly proportional (see equation 1) (30). Therefore, when profiling resistance exercises (e.g., back squat, bench press, deadlift), mean force and load can be interchangeable, permitting the creation of comparable relationships. Given that VBT technologies (e.g., LPT, IMU, camera systems) are typically cheaper and more accessible than force-plates, administering LVPs could be a more feasible approach than force-velocity profiling to assist with programming and prescription (109,116). Importantly, coaches must be aware of the differences between force-velocity analysis on a force plate and load-velocity analysis from a barbell. Any mechanical calculations (e.g., force, velocity, acceleration) derived from an LVP would be related directly to the barbell, as opposed to the center of mass (CoM) if a force plate was used (65,80). Additionally, the method by which key variables are calculated (e.g., power output) differs significantly, with research reporting an overestimation of power output in jumping tasks when employing the barbell method (95% limits of agreement fell between 28 and 63% overestimation) (4,57,80). Therefore, while important information could still be pulled from barbell velocity, coaches must be cautious of any inferences made related to the CoM.

The relationship between load and velocity can be applied to create an LVP an integral underpinning application of many other VBT strategies, including autoregulation (47). The protocol for creating an LVP typically entails measuring barbell velocity during multiple loads across a full load spectrum (0-100% 1RM), much like a 1RM protocol (75,111). Upon completion of the LVP, load (kg or %1RM) is often plotted against velocity (Table 1), followed by the application of a statistical model (e.g., linear regression) to quantify the relationship between the two metrics (Figure 3) (24,43,78). Predictive equations can then be applied to estimate either velocity or load across the full spectrum, providing key information on relative effort, fatigue, and acute fluctuations in strength (115).

Insert figure 3

Over two decades of LVP research has been conducted, in which many exercises, including the back squat (6,74,99,111), front squat (104), deadlift (9,79,97), hex-bar deadlift (68), bench press (38,85,98), pull-up (81), bench pull (42,98), military press (3), power clean (48,82,111), bench press throw (39), and loaded jump squat (88), have been investigated. Near-perfect (r and R^2 values of > 0.9) inverse relationships have been reported across all exercises investigated (9,15,38,40,42,81,99,104). Similarly, strong inter- and intra-day and inter-set reliability has been observed across many of these exercises, with intraclass correlation coefficients (ICCs) of 0.79-0.97, coefficient of variations (CVs) of 1.4-10.0% and standard error of measurements (SEMs) of 0.02-0.07 $m{\cdot}s^{-1}$. Therefore, this evidence provides coaches with more confidence to implement such methods within their day-to-day practices (6,14,26,33,42,95). Despite this, a large percentage of this research has been performed in upper-body (namely, bench press) Smith-machine exercises (22,33,69,70,87,91,95). While smith-machines serve a specific purpose and are often used in general health and fitness settings, they are not commonly utilized in strength and conditioning contexts nor often located in such facilities, thus limiting transferability of Smith-machine-based data to free-weight exercises. In addition, coaches must refrain from cross-comparisons between smith-machines and free-weight data as peak velocity, maximum load lifted, and electromyographical muscle activity have been reported to differ between the two methods (17,90,101). Finally, LVPs are specific to exercise and sex, meaning that superfluous research studies in one exercise (e.g., bench press) limit transferability to other, more commonly used, exercises within typical S&C programs such as the back squat, deadlift, and weightlifting derivatives (Table 2). The same is true between sexes, with men typically presenting higher velocities than women in different exercises (41,113). Coaches can also improve reliability of LVP data by providing immediate feedback after each repetition (59).

Insert table 2

Building the profile

Load-velocity profiling is designed to improve athlete monitoring but should complement traditional methods, such as 1RM testing, enhancing the amount of insight into an athlete's neuromuscular capabilities (108). Where possible, coaches should employ individualized profiles given more reliable and valid estimations of relative load can be made in comparison to generalized (pooled) profiles (5,6,21,111). Large variability in velocity between individuals at the same relative load is also evident, indicating a generalized profile could be sub-optimal for groups of athletes (95,111). Despite this, early research has highlighted the potential for group-based or "generalized" profiles for testing, monitoring, and autoregulation (43). Indeed, recent research by Dorrell et al. (21) found no differences in performance improvements when employing group-based *vs.* individualized profiles. Thus, generalized profiles or normative data from research could be an option for practitioners who are time-poor and perhaps are not able to undertake somewhat lengthy LVP protocols.

When plotting load-velocity data, coaches must adhere to the underpinning assumptions and principles of regression. For example, coaches must identify the predictor (independent - *x-axis*) and outcome (dependent – *y-axis*) variables and then rearrange accordingly when predicting x from y (see below for example). Despite this clear and important methodological process, some researchers have violated this assumption in attempts to predict load or 1RM (69,89). Contextually, when collecting load-velocity data, the load (kg or % 1RM) would always represent the independent variable given the manipulation applied to load during the incremental protocol to capture the associated velocity (dependent variable). In addition, the construction of the profile must be exercise, athlete, and scenario-specific, with coaches required to make several decisions to ensure the LVP data will reflect the needs of the athlete at the time (Figure 4).

Insert figure 4

Figure 4 outlines the typical choices required prior to undertaking an LVP. These relate to identifying key exercises, selecting the most appropriate statistical model, deciding on the number of data points (or loads lifted) to complete the profile, and whether a combination of ballistic and non-ballistic exercises is warranted. The following sections provide suggestions to guide the reader through this process based on practical experience and the literature.

Key exercise and variable selection

As LVPs are exercise-specific (Table 2), practitioners must identify key lifts to avoid excessive testing and maximize impact within a program. It is recommended that these exercises are typically compound lifts that form the foundations of most S&C programs but could include a combination of ballistic and non-ballistic, and upper and lower body exercises (e.g., back squat, power clean, jump squat, bench press, and inverted row), dependent on the key physical capacities that need developing for the sport and individual (6,42,60,69,111). Figure 4 guides decision-making for both upper-body (blue boxes) and lower-body (red boxes) exercises. In addition, coaches must decide how they wish to determine load when administering LVPs. S&C coaches have reported the use of one of three methods, each with their own benefits and drawbacks (108):

1. Loads as a % 1RM (most common)
2. Loads in kg or lbs
3. Loads as a % of body mass or relative strength (least common)

Methods 2 and 3 enable coaches to administer LVPs without prior knowledge of 1RM or testing. Loads can be selected using common sense based on the estimated maximum load an individual might lift or their known body mass. Nevertheless, these two approaches could impact accuracy of prescription if wanting to set target velocities or autoregulate load on a regular basis. Retrospective analysis would be required to estimate % 1RM if desired for prescriptions. Alternatively, method 1 would enable data to be collected at applicable relative loads, making the transition to programming more seamless. This method, however, does require a valid assessment of an individual's 1RM, which could entail collecting a traditional 1RM prior to the LVP or a legitimate estimation based on training and previous testing data. Finally, the velocity metric (see Table 1) needs to be determined as outlined in this article and is likely dictated by the type of exercise being profiled (e.g., strength or power).

Statistical modeling

The mathematic model applied to LVP data provides coaches with an assessment of the strength of the relationship between the two variables (explained variance - R^2) and an equation that can be used to predict 1RM or provide specific velocity targets for training prescription or load manipulation. Typically, LVP data is modeled with linear regression (see Figure 2), given the seemingly linear and inverse nature of the relationship (5,54,66,86), with research reporting practically perfect R^2 values (> 0.95), good levels of reliability (CV < 10%), and 1RM predictions with minimal predictive error (40,54,58,98,99). Importantly for coaches, however, these data have been collected in smith-machine exercises, which, as previously suggested, lacks practical representation with typical S&C environments and does not transfer to free-weight derivatives. In fact, when performing LVPs in free-weight exercises using a linear regression, predictive error is present (systematic bias = 7.15-38.3 kg, 5.7-20.4%; SEEs = 10.6-17.2 kg; CVs = 3.3-12.8%; TEE = 9.1-13.7 kg) (5,25,66,71,97). As such, it has been hypothesized that a potential contributing factor to this predictive error is the lack of sophistication when applying a first-order polynomial (e.g., linear) model (110). It could be theorized, therefore, that the relationship between load and velocity during this type of activity is better fitted with a second-order polynomial (e.g., quadratic) to account for the slight curvature of the line (Figure 5). As previously mentioned, the R^2 value can be misleading, often indicating practically perfect relationships, but when used to extrapolate down to 1RM, large differences are evident (Figure 6) (5). Coaches must, therefore, use both pieces of information (R^2 and predictive equation) when assessing the quality of an LVP and a method of prediction.

Insert figure 5

A paucity of research supports the suggestion that lower-body, free-weight exercises are better modeled using a second-order polynomial – an extension of a linear regression that applies a curved line to a model to evaluate the relationship between two variables (68,110); however, additional research is required to provide greater confidence that this method can accurately predict 1RM.

Thompson et al. (110) reported systematic biases of 1.17-0.80 kg *vs.* 2.38-9.36 kg when comparing quadratic *vs.* linear, respectively, highlighting the potential of using such a method for accurate 1RM predictions in free-weight lower-body exercise (see calculated example in Figure 5). Interestingly, research has advocated against using quadratic equations due to statistical complexity (31,47). In this context, utilizing simpler mathematical modeling (linear) over the optimal one (quadratic) is unacceptable. To highlight how to perform both models, a worked example has been produced:

$$Linear\ Model: y = ax + b \qquad x = \frac{y - b}{a} \qquad \text{eq.7}$$

$$Quadratic\ model: y = ax^2 + bx + c \qquad x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \qquad \text{eq.8}$$

As previously stated, when predicting 1RM, the equation must be rearranged to solve *x*, not simply swapped so that load is the outcome variable (on the *y-axis*). Equations 7 and 8 show how this can be done. If wishing to do this in Microsoft Excel, for example, the formulas in Table 3 can be inputted.

Insert table 3

Once the formulas from Table 3 have been inputted into Excel, the following steps can be completed to solve *x* for both the linear and quadratic models (see Figure 6 for reference):

For linear modeling, using the rearranged equation 7 and the a and b coefficients from the LINEST function, the formula in cell H14 (figure 6) would be =(H15-H13)/G13, with H13 and G13 being the coefficients and H15 the *y* value input to solve *x*.

For quadratic modeling, using the rearranged equation 8 and the a, b, and c coefficients from the LINEST function, the approach could follow four simple steps:

1. Cell H5 (b^2-4ac): =H4^2-(4*G4*(I4-H9))
2. Cell H6 (-b-SQRT(D)): =-H4-SQRT(H5)

3. Cell H7 (2a): =G4*2
4. Cell H8 (solve x) = H6/H7

Insert figure 6

Number of data points

The number of loads collected during an LVP can be dictated by several factors, including number of athletes testing, time allowance for profiling, exercise performed, and statistical model employed (108). Statistical theory and relevant research indicate that more paired data will increase the accuracy of modeling LVP data (4). By doing so, there would be a stronger relationship between the two variables, potentially creating a more reliable profile. In addition, if looking to extrapolate data to predict 1RM, having a larger spread of loads, with some data points closer to the true maximum value, will ensure more reliable and valid predictions (4). Nevertheless, the more loads performed, the longer the profile will take to complete, and the closer proximity to 1RM, the greater the neuromuscular fatigue produced, which has been reported as a limitation and potential reason against adopting load-velocity profiling by S&C coaches (108). Therefore, coaches need to accept a trade-off between number of loads and efficacy of the profile. Research has shown accurate 1RM predictions in the free-weight back squat from just four loads (difference from actual 1RM = 1.17 kg, standard error of the estimate = 1.62 kg) (110), suggesting this could be a suitable, time-efficient starting point for coaches.

To solve logistical challenges with multiple-point profiles, the two-point method (creating an LVP from just two loads) has been created, which was originally devised by Jaric et al. (55,56) and later developed by Garcia-Ramos et al. (31,34,35). It has been hypothesized that because multi-joint force- and load-velocity profiles are almost perfectly linear (e.g., R^2 typically > 0.90), the number of the experimental points should not impact the reliability and validity of the data (31,56), with high reliability and validity in the bench press, prone bench-pull, and seated row exercises (32,34,94) being reported. For example, Garcia-Ramos and Haff et al. (34) found mean differences of 0.6-3.6 kg and test-retest CVs of 3.1-5.1% when predicting bench press 1RM from the two-point method compared to a direct assessment. Additionally, two multicenter studies investigated the validity of the two-point method for profiling and predicting F-v characteristics (e.g., force at theoretical zero velocity - F_0; velocity at theoretical zero force - V_0, maximum power P_{max}) in the bench press (CVs = 2.91-6.65%; ICCs = 0.76-0.98), bench throw exercises (CVs = 3.58-6.19%; ICCs = 0.72-0.96), squat (CVs = 2.41-5.61%; ICCs = 0.64-0.93) and jump squat (CVs = 2.09-7.30%; ICCs = 0.64-0.93) (36,37,92,93). Therefore, this data shows practitioners the potential practical utility of the two-point method, and the accuracy in predicting load from only two velocity data points. However, coaches should be aware of the limitations of extrapolating data from just two loads (discussed next) and consider whether this method is truly necessary from a logistical and statistical perspective.

When applying the two-point method, the loads selected impact the reliability and validity of the data (35,37). It has been suggested that the use of two distal points (e.g., 0 and 75 kg, 20 and 80% 1RM, or 20 kg and a load that represents 0.55 $m \cdot s^{-1}$) are the most effective ways of producing the profile (35,37,92). Additionally, the two-point method is bound by the statistical model applied to it (i.e., linear regression), meaning the 'goodness of fit' or amount of explained variance (R^2 value) will always be 100%. Previous literature utilizing the two-point method for predicting 1RM has only found positive results in upper-body Smith-machine-based exercises, limiting any practical cross-over to lower-body or free-weight exercises, and thus, coaches should use with caution. In fact, when utilizing a free-weight bench press, a predictive error of almost 10 kg has been reported (71). Despite this, the two-point method could potentially be useful for estimating key F-v characteristics vital for assessing neuromuscular adaptations and key performance improvements that could relate to sporting performance. This could be applied to pre-post training interventions as a marker of performance improvement and a proxy measure of physiological adaptations. Importantly, coaches should choose the number of loads based on their environment. If one-on-one or coaching small groups, multiple-point profiles, particularly in free-weight exercises, should be collected. A minimum of four points seems a sensible number to collect an in-depth and valid profiles in lower-body exercises (110), with a more feasible opportunity to undertake a profile from just two data points in upper-body exercises (Figure 4). More research is needed, however, to investigate the effectiveness of the two-point method in free-weight and lower-body strength exercises.

Ballistic vs. non-ballistic exercises

The majority of LVP literature focuses on non-ballistic, compound exercises (e.g., bench press, back squat, deadlift, bench pull), with a smaller proportion investigating ballistic exercises (e.g., jump squat, bench throw, power clean) (5,36,38,42,48,61,66,68,88,104,105,111). As previously suggested, coaches should identify key exercises to LVP. Furthermore, those profiles should include loads across the spectrum to maximize reliability and accuracy of prediction (31). As a result, it is important to consider the phases of a non-ballistic exercise and the impact these could have on mechanical output (i.e., velocity), particularly in lighter loads. The concentric portion of non-ballistic exercises contains two main phases: a propulsion phase (minimum displacement to maximal velocity) and a braking phase (maximal velocity to maximal displacement) (figure 7) (29,64,107).

Insert figure 7

This braking phase, depending on the load being lifted, will account for a different amount of the concentric portion of the lift, whereby the athlete must “brake” to prevent the body from leaving the ground or letting go of the barbell (Table 4) (107). It has been implied that the impact of this braking phase could create variability in mechanical output, potentially impacting the reliability and underestimating the validity of velocity data at lighter loads (64,84,107,110). Therefore, it has been proposed that lighter loads (up to 50-60% 1RM) should utilize a ballistic counterpart (e.g., jump squat) when performing LVPs in a non-ballistic exercise (e.g., back squat) (107,110). This threshold has been suggested more for practical reasons of performing very heavy ballistic movements such as jump squats that could impact individuals from a landing perspective, for example. It is this combined method that will provide a true reflection of an individual’s force-velocity characteristics, minimize output variability, and provide practically representative velocity values at lighter loads given that athletes will often jump at 0-60% 1RM, but very rarely squat with those loads (107,110). Additionally, this method has been reported to be common in practice amongst high-level S&C coaches but is yet to be fully investigated in the literature (108).

Insert table 4

Coaches must think sensibly about their environments upon making decisions regarding profiling their athletes. It is simple for research to present a "best practice" approach for any method within S&C, however, best practice in one environment might not be feasible in another, and thus, coaches must only strive for what is practically and logistically appropriate for their athletes. VBT and LVPs can be very flexible, offering available methods for all practitioners in all environments, and coaches may wish to consider implementing guidance provided in sources such as this review to identify the most appropriate approach.

Extrapolation method

A typical approach for predicting an individual's 1RM is to collect a baseline LVP up to and including 1RM and then to perform submaximal profiles at the start of a week or a session to predict maximal strength on that given day and adjust loading accordingly (45,110). This method requires a point of extrapolation or an outcome value (i.e., velocity at 1RM - V_{1RM}) that can be used as a reference point for the model to predict. Several methods are available to practitioners for identifying the V_{1RM} for predicting 1RM (47,115). The most common and likely most appropriate method would be to collect an individualized maximal load and minimal terminal velocity during an incremental, full profile and then utilize this in all subsequent predictive models. Nevertheless, the reliability of the individualized V_{1RM} has been questioned, with research showing poor reproducibility, particularly in free-weight exercises (5,6,66,111).

Alternative V_{1RM} solutions have been suggested, including utilizing normative data (115) (e.g., 0.25 $m \cdot s^{-1}$ for back squat) as the reference point within the predictive model. This could be a quicker and simpler option for practitioners to employ but the between-participant variability of velocity data must be considered and the impact this could have on the validity of the predictions. Similarly, Hughes et al. (53) investigated extrapolating down to predict the load at theoretical 0 velocities (LD_0), and then the difference between LD_0 and a pre-determined 1RM was calculated and removed to identify V_{1RM} (58). A predictive error of ~ 4 kg was reported, with between-session reliability CVs of ~ 8%, and thus, could be a viable option; however, this model is reliant on the data being truly linear, and thus, further investigation is required.

The poor reliability of velocity at heavier loads creates challenges for coaches wanting to predict 1RM from load-velocity data (111). However, Thompson et al. (110) developed a model that removes the reliance on the V_{1RM}, culminating in very accurate predictions when combined with quadratic modeling (systematic bias = 0.60-1.17 kg, SEE = 1.62-4.06 kg, SMD = -0.06-0.04). This method applied a predictive model of interpolation (predicting a value within the dataset) to estimate the velocity of 80% 1RM, given this has been reported to be the heaviest, reliable load in the free-weight back squat (80% 1RM CV = 5.4-5.7% vs. V_{1RM} = 11.8-19.4%) (6,111). Once 80% 1RM is predicted, the model then simply extrapolates to 100% 1RM to provide the daily maximum for any given session (Figure 8) (110). Despite these positive results, this method requires further investigation across multiple populations and exercises to see if the same predictive validity occurs. There are many options for coaches to choose from when identifying an appropriate reference point for a predictive model to utilize, and despite many researchers suggesting 1RM prediction is not possible in free-weight exercises (47), it can be done accurately with the correct combination of number of data points, statistical model, and extrapolation method, and thus, coaches should not be discouraged if they see value in such a method.

Insert figure 8

Practical Applications

This review has provided definitions surrounding VBT, identified the benefits of implementing VBT, and detailed the different aspects of load-velocity profiling. Coaches must consider the research, practical and logistical appropriateness of different methods, and why they desire to utilize LVPs when making their decisions on protocols and procedures. The following list serves as a recommended approach to profiling, including specific factors and choices for practitioners to consider based on the literature. When performing an LVP, practitioners must ensure several important criteria are met to maximize the reliability and validity of the data collected:

- Individuals must be habituated with velocity-based techniques (i.e., moving the load (irrespective of the mass with maximal intent). This should occur before collecting any LVP data.
- Maximal intent and velocity must be performed across all loads to maximize reliability and validity of the LVP.
- Specific feedback can help improve reliability of velocity outputs across the load spectrum and should be provided in unit form (e.g., "1.50, 1.52, 1.51" $m \cdot s^{-1}$) after each repetition.
- Reliable and valid technology must be employed (refer to work by Weakley et al. (116))

Similarly, coaches must consider the following when building, collecting, and analyzing LVP data:

- When measuring velocity over the concentric phase of an exercise, coaches should utilize measurements of mean velocity for all exercise modalities.
- Only profile key exercises, given the exercise-specific nature of LVP data. The exercises selected for profiling should frequent most training blocks to ensure continuity of data collection.
- Load-velocity data is individualized, and therefore, where possible, individualized LVPs should be administered.
- The load used as the predictor (independent) variable should ideally be %1RM; however, kg/lbs or $kg \cdot kg^{-1}$/$lbs \cdot lbs^{-1)}$ could be suitable and quicker alternatives.

- The more loads incorporated in the incremental protocol, the more valid the profile will be. If time is a restriction, however, methods such as the four-point or two-point are available.
- When more than two loads are collected, practitioners should use a quadratic (second-order polynomial) equation to model the data, particularly when predicting 1RM.
- Many extrapolation / V_{1RM} / reference points are available. Coaches should use the most reliable method when predicting 1RM (e.g., 80% 1RM reference method). Conversely, V_{1RM} could also be used if required, along with normative data if time is restricted. Coaches must be aware of the associated measurement error when using these methods.
- Ballistic counterparts should be incorporated in lighter loads to maximize velocity output, remove the impact of the braking phase, and provide a true and useable representation of an individual's load-velocity characteristics.

Figure 1. Theoretical example of the weekly fluctuations that could occur across the course of a training intervention based on standard deviation. The thick black dotted line indicates the planned increase in 1RM, with the red shaded area indicating – 2 x SD, orange – 1 x SD, yellow + 1 SD, and green + 2 SD.

Figure 2. Graphical representation of the different velocity metrics taken from back squat data. The dotted blue line represents mean velocity, the solid red line represents peak velocity, and the dashed green line represents mean propulsive velocity.

Figure 3. An example of a load-velocity profile showing mean velocity being measured across nine different relative loads.

Figure 4. Practitioner decision tree for undertaking a load-velocity profiling. The grey boxes represent the decisions required prior to undertaking a profile, with the green boxes being general decisions not specific to any exercise or model. The blue boxes represent suggestions for upper-body free-weight exercise, and the red boxes represent suggestions for lower-body free-weight exercise

Figure 5. Comparison of upper (black) and lower (red) body exercises with first- (black) and second order (red) polynomial models applied, respectively, highlighting the difference in shape of the profile between upper and lower body exercises. Data was taken from (40,42,79,99) to produce the figure.

Figure 6. A worked example of linear and quadratic modeling of LVP data to predict 1RM from real back squat data using the LINEST function in Microsoft Excel. The green cells are for inputting collected load and velocity data. The red cells and dashed line represent the quadratic model, while the blue cells and dotted line represent the linear model. The two "velocity (y input)" cells represent the reference velocity to predict load from. In this example, it is 0.24 $m \cdot s^{-1}$, representing velocity at 1RM.

Figure 7. Example 1RM predictive model using 80% 1RM. Figure adapted with permission from Thompson et al. (110).

Figure 8. Phases of a non-ballistic exercise. The eccentric and concentric portion of a back squat, including propulsive (positive displacement, positive acceleration) and braking phases (positive displacement, negative acceleration). Figure adapted with permission from Thompson et al. (107)

Table 1. Definitions of common velocity metrics used when implementing VBT applications.

Table 2. Exercise-specific load-velocity profile data for common upper and lower body resistance exercises.

Table 3. Excel formula examples for applying linear and quadratic modeling to load-velocity data using the specific LINEST function in Microsoft Excel. The function provides the necessary a, b, and c coefficients for both models to predict x or y variables.

Table 4. Percentages of the propulsion phase with respect to the full concentric phase for common resistance exercises.

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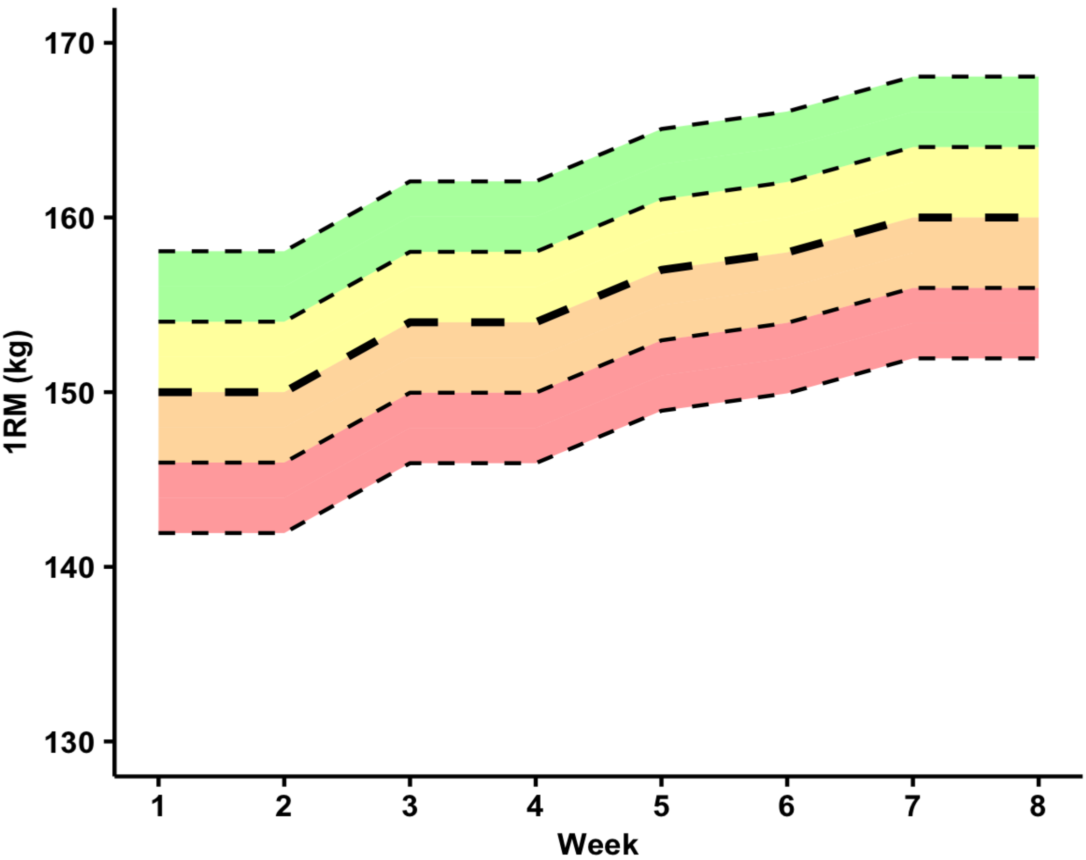
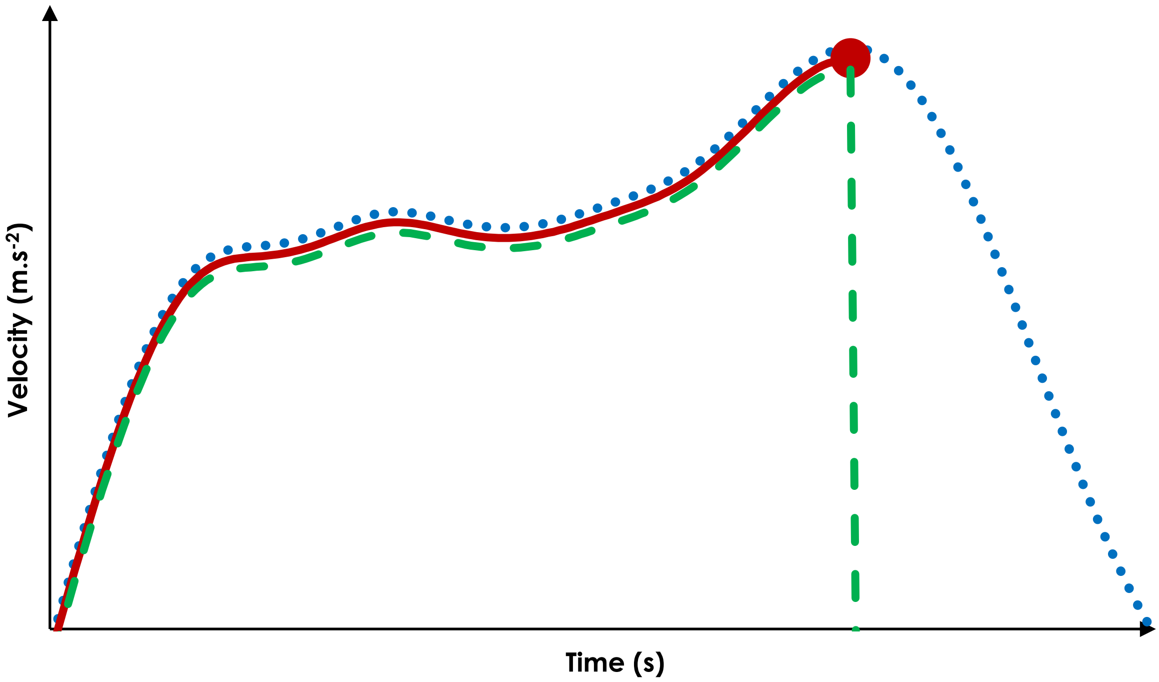
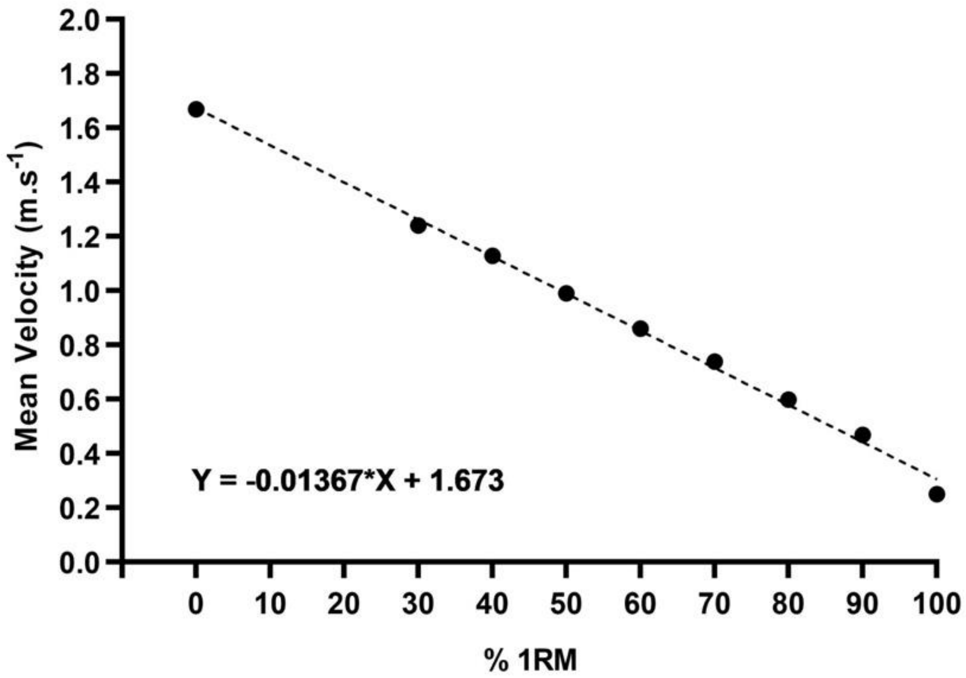

170
160
150
140
130
1RM (kg)
1
2
3
4
5
6
7
8
Week

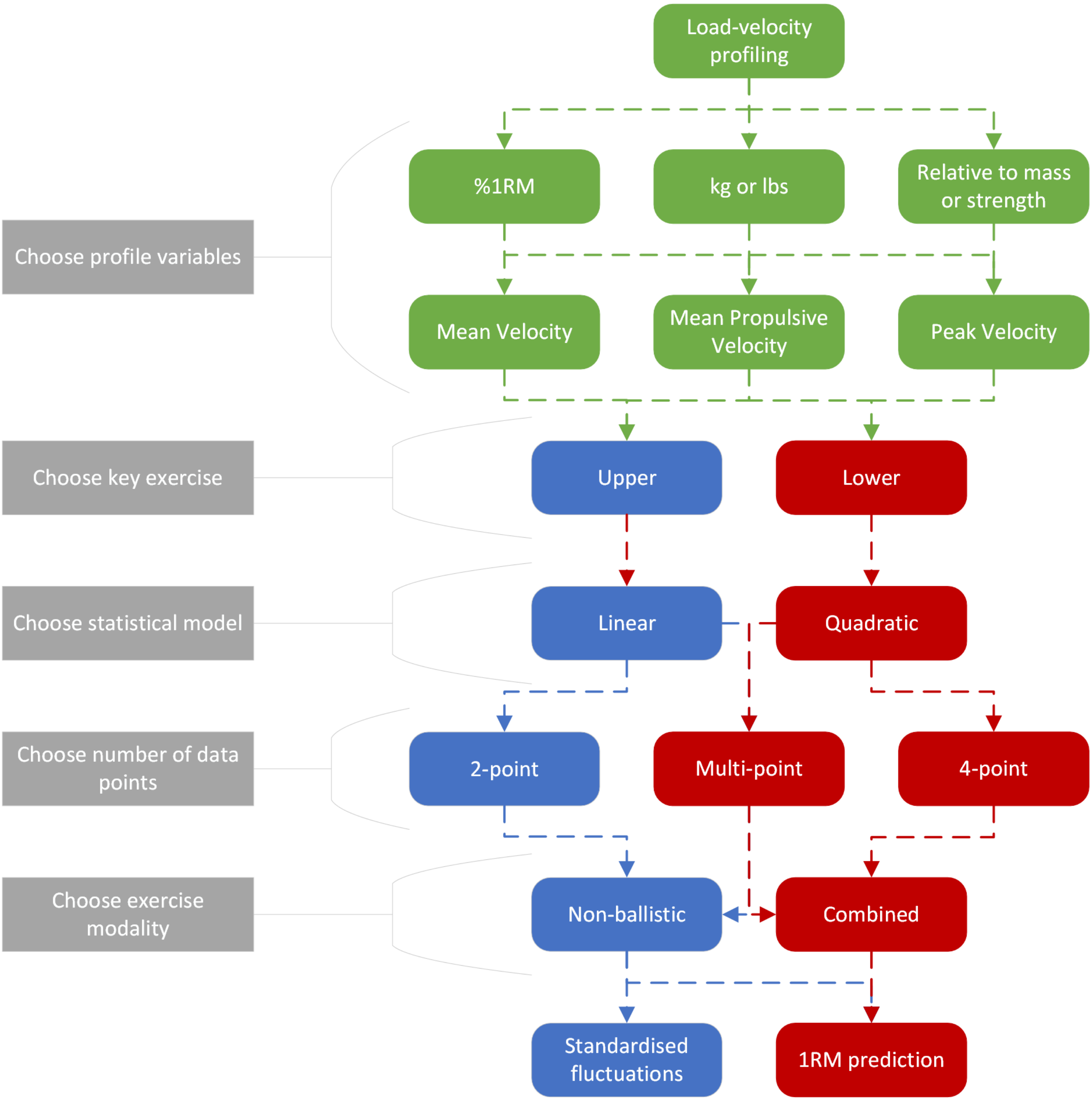

Velocity (m.s^{-2})
Time (s)

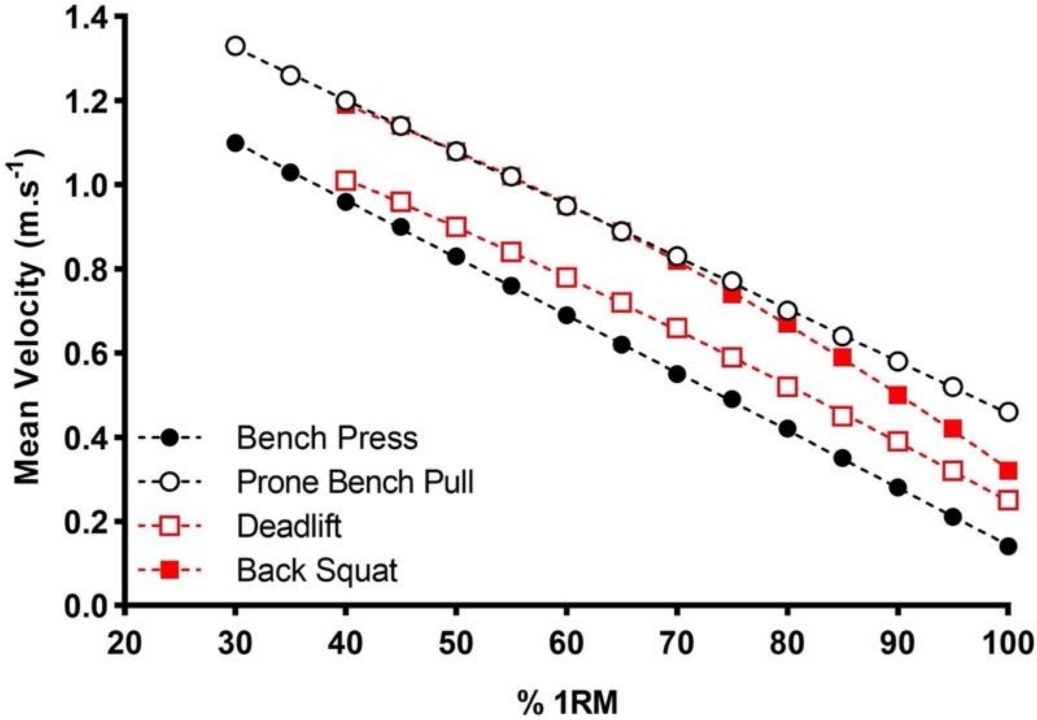

Mean Velocity (m.s-1)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Y = -0.01367*X + 1.673
0
10
20
30
40
50
60
70
80
90
100
% 1RM

848

849

850


Load-velocity profiling
%1RM
kg or lbs
Relative to mass or strength
Choose profile variables
Mean Velocity
Mean Propulsive Velocity
Peak Velocity
Choose key exercise
Upper
Lower
Choose statistical model
Linear
Quadratic
Choose number of data points
2-point
Multi-point
4-point
Choose exercise modality
Non-ballistic
Combined
Standardised fluctuations
1RM prediction

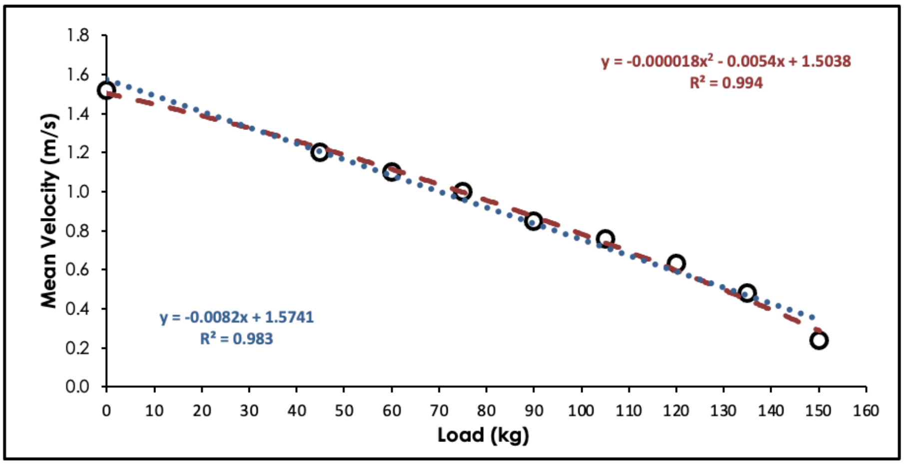

Mean Velocity (m.s-1)
% 1RM
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
20
30
40
50
60
70
80
90
100
Bench Press
Prone Bench Pull
Deadlift
Back Squat

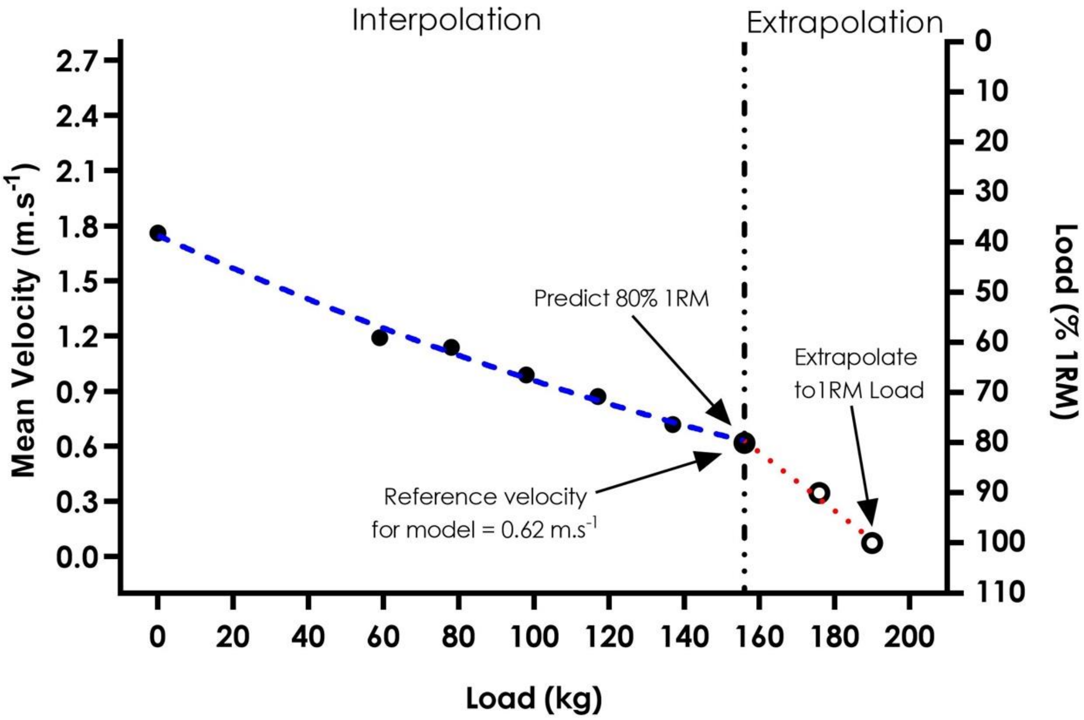
Load (kg) (x)	Velocity (y)	% 1RM
150	0.24	100
135	0.48	90
120	0.63	80
105	0.76	70
90	0.85	60
75	1.00	50
60	1.10	40
45	1.20	30
0	1.52	0

Quadratic Modelling			
a	b	c	
-0.000018	-0.0054	1.5038	
b^2-4ac	0.00012		
-b-SQRT(D)	-0.00556		
2a	-0.00004		
Load (x outcome)	154.43	Predicted 1RM	
Velocity (y input)	0.24		

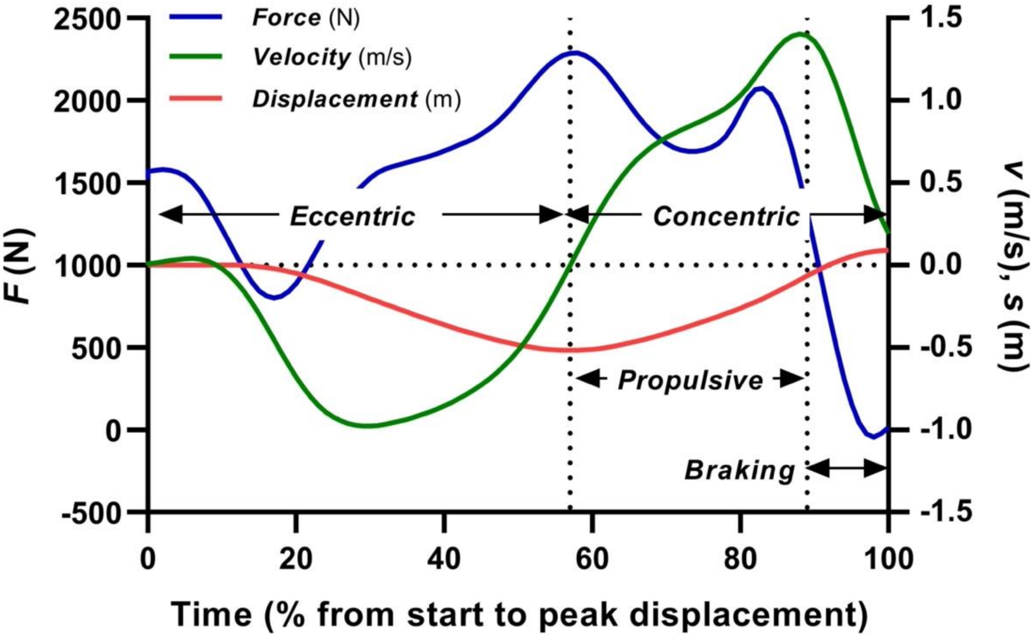
Linear Modelling		
a	b	
-0.0082	1.5741	
Load (x outcome)	162.93	Predicted 1RM
Velocity (y input)	0.24	

Lift	1RM (kg)	Difference (kg)	Difference (%)
Quadratic	150	4.43	2.96
Linear	150	12.93	8.62





Interpolation
Extrapolation
Mean Velocity (m.s-1)
Load (% 1RM)
Load (kg)
Predict 80% 1RM
Extrapolate
to1RM Load
Reference velocity
for model = 0.62 m.s-1


Force (N)
Velocity (m/s)
Displacement (m)
Eccentric
Concentric
Propulsive
Braking
F (N)
v (m/s), s (m)
Time (% from start to peak displacement)
2500
2000
1500
1000
500
0
-500
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0
20
40
60
80
100

Velocity Metric	Description
Mean Velocity	*The average velocity recorded across the full concentric phase.* Typically suited to non-ballistic, strength exercises such as back squat, bench press, deadlift.
Mean Propulsive Velocity	*The average velocity recorded during the propulsive phase.* The propulsive phase occurs between minimum displacement and maximal velocity. It can also be defined as the portion of the concentric phase during which the acceleration is greater than gravity (9.81 $m.s^{-2}$) and is a suitable alternative for non-ballistic exercise.
Peak Velocity	*The instantaneous maximum velocity recorded during the full concentric phase.* Typically suited to ballistic, explosive, or weightlifting exercises such as jump squat, snatch, power clean, or bench press throw.

Load (% 1RM)	**Mean Velocity (m.s^{-1})**								
	Bench Press (37)	**Bench Press** (88)	**Bench Press** (39)	**Shoulder Press** (50)	**Prone Bench Pull** (41)	**Bent Over Row** (70)	**Back Squat** (20)	**Deadlift** (9)	**Deadlift** (80)
30	1.40	1.20	1.10		1.33	1.42	1.15		
35	1.31	1.13	1.03		1.26		1.08		
40	1.22	1.05	0.96	1.15	1.20	1.28	1.03	1.02	1.01
45	1.14	0.98	0.90	1.07	1.14		0.97	0.97	0.96
50	1.05	0.91	0.83	0.98	1.08	1.22	0.92	0.91	0.90
55	0.96	0.83	0.76	0.90	1.02		0.87	0.85	0.84
60	0.87	0.76	0.69	0.82	0.95	1.08	0.81	0.80	0.78
65	0.79	0.68	0.62	0.74	0.89		0.74	0.74	0.72
70	0.70	0.61	0.55	0.66	0.83	0.97	0.68	0.68	0.66
75	0.61	0.54	0.49	0.58	0.77		0.60	0.62	0.59
80	0.52	0.46	0.42	0.50	0.70	0.83	0.53	0.57	0.52
85	0.44	0.39	0.35	0.43	0.64		0.46	0.51	0.45
90	0.35	0.31	0.28	0.35	0.58	0.74	0.37	0.45	0.39
95	0.26	0.24	0.21	0.27	0.52		0.29	0.39	0.32
100	0.18	0.16	0.14	0.19	0.46	0.63	0.24	0.33	0.25

Model type	Microsoft excel formula	Explanation
Linear	=LINEST(*velocity column, load column*, TRUE, FALSE)	LINEST function creates the a and b coefficients based on the known y's (velocity column) and known x's (load column) The first TRUE means the b coefficient (intercept of the line) is not set to zero The second TRUE would return additional data such as standard error of the estimate, sum of squares, R2 value etc
Quadratic	=LINEST(*velocity column, load column* ^{1,2},TRUE,FALSE)	^{1,2} ensures a second order polynomial is applied to the line, returning a, b, and c coefficients

Load (% 1RM)	**Propulsion Phase (%)**					
	Bench Press (102)	**Bench Press** (100)	**Bench Press** (74)	**Prone Bench Pull** (100)	**Shoulder Press** (50)	**Deadlift** (80)
30	76	76	73	85		
35	79	79	76	86		
40	81	81	79	87	84	81
45	83	83	81	88	87	82
50	86	85	84	89	89	84
55	88	88	86	89	91	86
60	91	90	88	90	93	88
65	93	92	90	91	94	91
70	95	94	92	92	96	93
75	98	97	94	93	97	96
80	100	99	95	94	98	99
85	100	100	97	95	99	100
90	100	100	98	96	100	100
95	100	100	99	97	100	100
100	100	100	100	98	100	100