Velocity-Based Strength Training: An Integrative Analysis of Methodological Evolution, Training Advantages, and Limiting Factors

Maolin Du, Hongbo Li*

Linyi University, Linyi, 276000, China
**Corresponding author: lihongbo@lyu.edu.cn*

Abstract: *Velocity-based strength training has made full use of the continuous development of sports biomechanical measurement technology and is now an end in itself, not merely a way to monitor load. The basis of the above method is to construct an individual load-velocity profile and dynamically adjust the velocity-loss threshold; thus, it is a closed-loop adaptive control scheme based on real-time feedback and not the traditional open-loop training decision-making method. Another advantage of training is that it can selectively activate high-threshold motor units and change their firing frequency; thus, fatigue will be reduced and recovery will be improved by stimulating the high-velocity part of the force-velocity curve to enhance athletic performance. The application effect of this method is limited by factors that affect the external validity of the load-velocity relationship, by the different responses of various people to the threshold of velocity loss, and by the equipment used. The three dimensions of the theoretical framework for this method in this paper are the development of the method, the strengths and weaknesses of training, and the general application range and individualisation of the program.*

Keywords: *Velocity-Based Strength Training, Load-Velocity Profile, Velocity Loss Threshold, Neuromuscular Adaptation, Closed-Loop Control*

Introduction

With the development of all kinds of strength-training methods, so too has also improved the accuracy of sports biomechanical measurement technology. The first way to reduce the size and number of weights is to decrease the speed of movement. With the development of measurement technology, many high-speed sensors have appeared that can record changes in the speed of load movement every millisecond, and thus power can be regulated dynamically rather than after the fact. A custom load-velocity curve has been added, velocity-loss limits have been set, and now a real-time feedback device can be employed to switch between open-loop preset and closed-loop adjustment of the strength-training method according to velocity. Although it has been shown that this can improve neuromuscular adaptation and regulate fatigue at different times in sports, there are also deficiencies; among them are confounding factors that affect external validity, individual differences in response, and dependence on equipment. The three places for systematic integration are the improvement of methods, the strengths and weaknesses of training, and the theoretical foundation to clarify the internal logic and application scope of this method.

1. Methodological Paradigm and Evolutionary Logic of Velocity-Based Strength Training

1.1 Historical Tracing and Technological Iteration of Velocity-Dependent Training

There have been changes in the development of velocity-based strength training and an increase in the accuracy of sports biomechanical measurement technology. The first measurements of motion speed were carried out offline with timers and high-speed cameras, but these methods have the problems of data latency and loss of some information; therefore, they are not suitable for real-time speed control during training. Gradually add a linear position transducer and an inertial measurement unit to the training, and both the sampling frequency and the responsiveness of load-movement velocity have reached the millisecond level. With the development of technology, the speed variable is no longer a late indicator of the effect of training but has become an early warning signal. Measurement tools are small and inexpensive, so velocity-dependent training has been applied to many areas of all-round training more and more frequently, and now it has established good technical foundations and is being developed as a training method.

Obtain the velocity information in real time and begin to develop a new kind of training decision-making logic. The main motivating factor of traditional strength training is external load-weight, and movement speed is an indirect result determined by both the magnitude of the load and a person's neuromuscular state; thus, it lacks direct control. Velocity-dependent training can increase the speed of movement to some extent, and people are able to adjust the weight they lift or the number of repetitions according to changes in speed during exercise. The change from a "load-dominated" model to a "velocity-dominated" model shows that the quality of velocity-based training has improved; it is now an independent mode of training, and thus the epistemology for building the load-velocity relationship model in the following section has been established.

1.2 Principles for the Construction of the Load-Velocity Profile

Load and speed of movement are inversely related; therefore, this is the basis of the concept of velocity-based strength training. At a high load during a certain movement, there is usually a decrease in the maximum voluntary contraction velocity of the concentric phase. Most of the time, the relationship at the individual level is a stable linear or quadratic function. To construct the load-velocity curve, one needs to measure and fit the corresponding velocity at various load levels, and the slope and intercept of this curve can reveal the distribution characteristics of a person's strength and velocity traits along the force-velocity curve. Given that these people are different, velocity-based training should be based on accurate measurement of the neuromuscular condition of each individual; otherwise, using the average data of the group will result in a large prediction error[1].

As a necessary link in the transmission of the load-velocity relationship to training practice, the theoretical basis of the velocity loss threshold is that there is a stable dose-response relationship between the extent of velocity reduction and the accumulation of metabolic stress and neuromuscular fatigue. When the movement speed reaches a certain level because it has been sustained for a long time, a considerable change has occurred in the strategy of motor unit recruitment; adding more repetitions beyond this point will result in an imbalance between the effect of fatigue and training stimulus. The velocity-loss threshold is used to convert the static relationship shown in the load-velocity profile into a dynamic regulation factor; thus, training intensity and training volume can be adjusted according to changes in a person's condition at that time, and the problem of traditional percentage-based loading that does not consider individual differences in condition on any given day has been solved.

1.3 Adjust the Training Decision-Making Structure in Response to New Information

Real-time velocity feedback has changed both the direction and the form of the flow of information in strength training. The old way was to have other people observe how the coaches trained and determine whether one was tired; now this is out of date and impractical to verify. Velocimetry is used to obtain information on the speed of a person promptly and accurately, and then, according to various goals for exercise, changes can be made in the motor output and load in real time. Based on the above feedback, some changes have been made to turn the previously implicit knowledge gained through experience into explicit operating rules that can be repeated and verified, and thus the uncertainty in training decisions has been reduced.

Given the change in circumstances, closed-loop control will be introduced to adjust the training plan at this time. Based on the above, the reference input will be the target velocity or the velocity loss threshold; the controlled quantity is the movement speed, and the trainee's neuromuscular system functions as both the actuator and the sensor, so real-time feedback forms an error-correction loop. A fixed protocol has only preset load and repetition numbers in open-loop mode, but a closed-loop structure can be changed instantly according to how far the actual output is from the goal in each unit of action to improve the alignment of the training stimulus with the desired adaptive effect. With the change in the structure of decision-making, the content of training will be adjusted, and the basic regulatory logic of the training process will be reformed to meet the different needs of individuals more closely.

2. Training Advantages of Velocity-Based Strength Training and their Physiological Mechanisms

2.1 Selection Promotion of Neuromuscular Adaptability

At a certain rate, the training needs to be carried out to achieve the desired effect on the neuromuscular system. If the goal of the exercise is to increase the speed of concentric contraction, then the central nervous system will increase the recruitment and firing frequency of high-threshold motor units to a certain extent. The method of recruitment is to obtain a large number of troops quickly and organise the motor units according to the combined effect of rate coding and the size principle. It should not be confused with the traditional kind of strength training that aims to increase maximum strength; instead, the goal of velocity-based training is to reduce the time taken to reach peak electromyographic activity and thus improve the foundation for rapid force generation at the neural level.

The first is that the velocity term will change how muscle contractile properties and neural drive are related in neuromuscular adaptation. At high speeds of contraction, both the rate of cross-bridge formation and the kinetics of calcium release are closely related; thus, there is an increase in the proportion of fast-twitch muscle fibres in the fibre-type composition. Motor units that are often under the influence of high-speed load stimuli will increase the speed of axonal conduction and change the structure of motor endplates to improve the efficiency of rapid force generation through neural plasticity. According to the velocity-dependent mechanism of neuromuscular adaptation, velocity-based training is not only a modification of the quality of traditional exercise but also establishes a new synergistic adaptive pathway for neural drive and muscle contractile properties[2].

2.2 Quantitative Management Efficiency of Fatigue and Recovery

A velocity-loss threshold is an index of fatigue that can be measured non-invasively, and it is based on the fact that a decrease in the speed of movement is associated with changes in neuromuscular function. As the number of repetitions increases, there are many reasons for a decrease in the speed of the concentric phase, such as a reduction in the central drive, a slowdown in the speed of muscle fibre contraction, and the accumulation of metabolic waste products. The traditional way to determine training volume is to feel how tired one is after exercising or to set a fixed proportion of the maximum number of repetitions; on the other hand, the velocity loss index can directly show changes in neuromuscular function during training and is not affected by fluctuations in a person's physical condition on any given day. Therefore, velocity-based training can change the extent of fatigue in one set more precisely.

A velocity parameter can be used to show the degree of recovery in this way. Measure the running speed at a certain load before training or at different times during training to obtain an objective reference for how much the neuromuscular system has recovered. When a person moves at a lower speed than expected for the given load, it is often because the central nervous system is still fatigued and has not yet regained the ability to recruit motor units. Therefore, based on the above, the training load can be adjusted dynamically according to the results of speed measurement, and if fatigue is about to reach a dangerous level, it will be reduced or stopped early. Quantification of the management function for velocity parameters in fatigue and recovery can be employed to adjust training load more accurately and individually according to speed, moving away from the old method of strength training.

2.3 Kinetic Optimisation Pathway for the Transfer of Sport-Specific Performance

Change the kinetic parameters to find out how much the velocity-based training effect on power in sports is increased. The quality of the execution of sports-specific movements, such as jumping, sprinting and changing direction, will directly affect the rate of force development and the output capacity in the high-velocity region of the force-velocity curve. The original purpose of strength training was to increase maximum strength, but it has not been able to improve both the slope of the force-velocity curve and the force produced at high speeds. Directly increase the output level of movement speed in velocity-based training to solve the problem of a high-velocity end to the force-velocity curve and aim to move the force-generation capacity to a higher-velocity region. Therefore, the training effect will be closer to what is actually required for movement in sports.

The Foundation for the Transfer of Sport-Specific Performance is the Synergistic Optimisation of Neural Drive Patterns and Muscle Contractility. Velocity-based training can increase the firing frequency of a motor unit in a short amount of time, and it is a type of neural adaptation that meets the high-speed force-production demands of jumping and sprinting. At the same time, changes in the conditions of high-velocity contraction, such as a shorter cross-bridge cycle duration and improved energy-storage efficiency of elastic components, also increase the muscular mechanical performance during the stretch-shortening cycle. When the pattern of neural drive and muscle contraction needed to respond to the training stimulus is in harmony with the mechanical demands of sports activities, then the transfer efficiency of the training effect is relatively high. Given that velocity-based training and the kinetic parameters of sport performance are closely related, both are very effective ways to increase the power of athletes in many sports.

3. Limiting Factors and Boundary Definition of Velocity-Based Strength Training

3.1 Interference Factors in the External Validity of the Load-Velocity Relationship

All sorts of external factors can affect the stability of the load-velocity relationship, and together they form the theoretical limit of velocity-based training at the level of external validity. The Shape of the motion at a certain speed determines how much force a joint can provide; as this force increases, the proportion of force contributed by different joints also changes, so the usual linear relationship between velocity and force cannot always be used. As the load in exercises such as squats and bench presses increases, for all sorts of reasons, there are changes in joint angles, patterns of muscle coordination and moment arm lengths; thus, there is a large variation in velocity decay curves among different people. Changes in the physiological condition of the test subjects from one day to the next, such as alterations in sleep quality, levels of glycogen storage and arousal state of the nervous system, etc., can lead to changes in the load-velocity profile without changing the structure of the neuromuscular system; thus, the generalizability of load prediction equations obtained from a single test is limited[3].

Another reason there is no general load-velocity relationship is that the measurement environment and the range of normalisation are limited. The criteria for determining the amplitude of movement, the identification of the start of the concentric phase, and the time window for velocity sampling will all directly affect both the magnitude and the sign of the change in velocity. All the measurement devices have different sampling frequencies, filtering algorithms, sensor locations, etc., so the research results obtained by various devices and laboratories cannot be directly compared or integrated. More significantly, the load-velocity relationship is usually obtained by means of standardised single-set incremental load tests, and fluctuations in fatigue accumulation, the recovery state during the inter-set period, and exertion intention in actual training can lead to deviations in velocity performance from the predicted curve. Based on the above reasons, it can be concluded that the application effectiveness of the load-velocity relationship as a theoretical basis for velocity-based training is limited by the extent of the difference between testing conditions and training environments.

3.2 Heterogeneity of the Inter-individual Velocity Loss Threshold

As the main reason for the size of the training, the ideal value of the velocity loss threshold is not the same for everyone. At different times in training, people are more sensitive to the velocity-loss threshold; that is to say, the degree of impairment in neuromuscular function due to metabolic stress at a certain reduction in speed varies among highly trained athletes and those with traditional training backgrounds. After many years of strength training, neural adaptations have occurred that help well-trained people maintain a relatively stable pattern of motor unit recruitment at low speeds, and at the same time, untrained people will show a considerable change in their recruitment strategy even after a slight reduction in speed. Another reason is that the proportion of muscle fibre types is also relatively large; people with a high proportion of fast-twitch fibres can maintain a relatively high force output under conditions of high-velocity loss, but those with a large proportion of slow-twitch fibres will experience a significant reduction in the speed of force development even at a relatively small amount of velocity loss.

The corresponding relationship between the velocity loss threshold and the training goal is also special. Those who want to increase their speed will only be able to achieve a small reduction in speed before there is no change in neuromuscular adaptation. If the threshold for velocity loss is too high for trainees whose main goal is to increase explosive power, then the neural drive pattern will change to that of a slow-velocity contraction mode in the next repetitions, and thus the directionality of the training stimulus and its desired adaptation will be lost. Due to changes in the training stage, fatigue and other reasons, the ideal velocity loss range for the same person will be different at different times. The different responses of individuals to velocity-loss training show that a single threshold for the whole group is not suitable for everyone; therefore, to make velocity-based training effective for all people, more detailed individualisation of training needs to be introduced.

3.3 Equipment Dependence and Technical Constraints of Application Scenarios

There is a technical bottleneck in the spread of velocity-based training for measurement equipment because such equipment is needed. The sampling frequency, resolution and signal processing method of the high-precision measurement system will directly affect the accuracy of the velocity data; if the sampling rate is too low or the filter is not good, there will be phase shifts or amplitude distortions in the feedback information at different times and places. Linear position transducers and inertial measurement units are based on different measurement principles, so there will be systematic errors in the presentation of absolute velocity values and their trends. Therefore, when analysing the data and setting the threshold, one should take into account device particularity. High-precision measuring equipment is expensive and has a high technical threshold; thus, it has been difficult to apply velocity-based training in the training of elite athletes. There is also the problem that the low-precision option has low reliability and poor validity; therefore, it does not meet the decision-making reliability requirements of fine regulation.

The other reason for the large number of uses is equipment dependence. To measure the speed of linear motion, such as that in barbell squats and bench presses, it is relatively simple; therefore, cable-based transducers or linear encoders can be employed for this purpose, but to observe the speed of jumping, sprinting and multi-planar changes in direction, more complex multi-sensor fusion techniques are needed. Changes in the temperature, vibration and electromagnetic noise of the training environment can all affect the stability of the sensors and lead to loss of data collection. The Presentation form and the delay time of the real-time feedback will also affect the efficiency of closed-loop regulation; if the feedback is too late, the trainee will be making control decisions based on old data and will lose the real-time advantage of closed-loop control. Based on the requirements of the equipment and the technical constraints of the application environment, if high-precision measurement cannot be achieved, then this way of velocity measurement for training will have a relatively low level of reliability. This is the end of the range for the application of the above method.

Conclusion

The three parts of this paper will be the development of velocity-based strength training, its advantages and problems. Velocity-dependent training has changed in form over time, and according to the level of its development, it has gone from being load-dominated to velocity-dominated; a load-velocity profile has been put forward as the theoretical basis for individualisation, and at the same time, feedback has been added to the closed-loop control system of training decisions. To enhance the speed of neuromuscular adaptation and improve motor unit recruitment and firing at the level of the training effect on training benefits, provide an objective and quantitative control index for fatigue and recovery through the velocity-loss threshold, and systematically optimise kinetic parameters to increase the efficiency of power transmission in sports are the goals. At the level of limiting factors, the external validity of the load-velocity relationship is affected by the specificity of the movement pattern and the degree of standardisation in measurement; the threshold for velocity loss is not the same for everyone and varies according to training level and type of muscle fibres, and equipment accuracy and contextual applicability also limit the scope of application of this method. In the future, we will learn about all kinds of load-velocity relationships of different types of motion, develop dynamic adjustment algorithms for the velocity-loss threshold, and study regulatory compensation strategies under the conditions of low-precision equipment.

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