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Velocity-based training in mid- and late-stage rehabilitation after anterior cruciate ligament reconstruction: a narrative review and practical guidelines

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ABSTRACT

Resistance training is critical for strength development and physical recovery after anterior cruciate ligament reconstruction (ACLR). Traditional percentage-based training (PBT) methods, which often focus on maximal strength and training to failure, are not able to objectify rapid force development. Velocity-based training (VBT), using movement velocity as a metric for training intensity, offers a promising alternative. This article promotes the use of VBT in ACLR rehabilitation, emphasising its potential to enhance neuromuscular recovery and return-to-sport outcomes. A narrative review of current literature focuses on mid- and late-stage rehabilitation to examine how VBT can address PBT limitations and improve functional recovery and sports performance. VBT provides several advantages, including real-time feedback, individualised load adjustments and better alignment with daily physiological variations. It facilitates the accurate training load prescriptions, enhances motivation and reduces unnecessary fatigue. Monitoring load–velocity profiles and velocity-loss thresholds enables more effective strength and hypertrophy adaptations without reaching muscular failure. In midstage rehabilitation, VBT not only helps to restore muscle strength and hypertrophy using submaximal loads and individualised velocity profiles but also addresses unwanted neuroplasticity following ACLR by providing augmented feedback and facilitating an external focus. In late-stage rehabilitation, VBT focuses on improving explosive strength and power, crucial for sports performance. Despite its benefits, VBT application in rehabilitation is limited by a lack of data on injured populations and specific exercises, such as open-chain single-joint movements. Integrating VBT allows practitioners to enhance traditional rehabilitation protocols, potentially leading to better clinical outcomes and providing a more personalised rehabilitation process.

WHAT IS ALREADY KNOWN ON THIS TOPIC

- ⇒ Resistance training is a critical component of rehabilitation following anterior cruciate ligament reconstruction (ACLR), essential for restoring muscle strength and joint stability.
- ⇒ Traditional percentage-based training methods have limitations in addressing neuromuscular fatigue and rate of force development.
- ⇒ Velocity-based training (VBT) has been recognised as a potential alternative or complement to traditional resistance training approaches.

WHAT THIS STUDY ADDS

- ⇒ VBT offers a personalised and dynamic approach to mid- and late-stage ACLR rehabilitation, allowing real-time load adjustments and reducing unnecessary fatigue, thereby increasing general and specific performance.
- ⇒ The load–velocity profile and velocity-loss thresholds provide more precise strength and hypertrophy adaptations without requiring maximal effort or muscular failure.
- ⇒ Practical guidelines for integrating VBT in ACLR rehabilitation are proposed, with emphasis on enhancing neuromuscular recovery, explosive strength and return-to-sport readiness.

INTRODUCTION

Resistance training after anterior cruciate ligament reconstruction (ACLR) is absolutely essential, not only for the impact of the rehabilitation process itself but also for long-term joint health.[1] A well-structured muscle strengthening programme is crucial for restoring muscle strength and joint stability, preventing future injuries and achieving a safe return to sport. In the short term, it aids in regaining full knee function and range of motion, while in the medium and long term, it plays a vital role in minimising the risk of complications like osteoarthritis, which is a common consequence of inadequate recovery.[2] Furthermore, a significant percentage of athletes fail to achieve a full recovery and return to their preinjury performance levels with current rehabilitation methods. Persistent issues, such as pain, muscle weakness and decreased function, highlight the need to explore more effective rehabilitation approaches. This demonstrates that conventional methods may not ensure a complete, 'ad integrum' recovery, necessitating the integration of new, innovative rehabilitation strategies approaches to enhance outcomes and reduce complications.

Resistance training is essential for developing strength and other physical abilities after ACLR.[3] The manipulation of key training variables significantly shapes the stimuli provided and the resulting neuromuscular adaptations.[4] To develop strength and power, various training methods, such as weightlifting or ballistic training, can be used in rehabilitation.[4] Among all the training variables influencing post-training physiological adaptations, intensity is considered the most important.[3] Rehabilitation approaches have focused on traditional methods centred on muscle strengthening through percentage-based training (PBT), where loads are adjusted according to a percentage of the patient's maximal strength or one repetition maximum (1-RM).[4] Although this approach has been shown to be effective in restoring strength capacity, it has its limitations, particularly for ACLR patients.[3 4] One of the main limitations is that 1-RM loads produce a metabolic training effect but compromise the neuromuscular training effect. It is difficult to get an insight into neuromuscular fatigue. The lack of adaptation in rehabilitation intensity and load to the patient's neuromuscular state, combined with the use of near 1-RM loads, hinders strength gains and negatively affects rate force development (RFD).[5] This component is too often overlooked. It is an essential element in sporting movements and that is often deficient in the final phases of ACLR rehabilitation and return to sport.[4 6] Despite the support of recent research, consideration of velocity in resistance exercises remains almost non-existent in current after ACLR rehabilitation practice.[7] However, force and velocity are intimately linked, and the different forms of the force–velocity relationship provide valuable insights into muscular capabilities and how muscles respond under varying loads and velocities.[8] Given the same ability to generate force, the athlete capable of generating this force fastest will be more powerful and, therefore, potentially more successful on the field.[9]

Recently, velocity-based training (VBT), which is a method of resistance training that enables the accurate and objective prescription of resistance training intensities and volumes,[9] has emerged as a promising training paradigm, offering an alternative or complement to traditional practices.[9 10] VBT uses velocity as a metric to provide objective feedback, estimate strength, measure fatigue and develop load–velocity profiles, based on the load–velocity relationship (LVR), which is an extension of the more classic force–velocity relationship, for accurate load prescription.[9] Unlike PBT, VBT focuses on the velocity of the movement rather than the load lifted, allowing more dynamic and specific adaptation to individual needs.[9 10]

By providing a synthesis of current knowledge, this article aims to enlighten physiotherapists, coaches and athletes on the potential of VBT to enrich midstage and late-stage rehabilitation protocols, with the goal of promoting a safe, effective and return to sport.

VBT may hold potential in the early phases of rehabilitation as a tool to address unwanted neuroplasticity caused by task-oriented exercises with an internal focus, promoting external focus and enhanced coordination through augmented feedback. The constrained action hypothesis supports the theoretical benefits of restoring automatic control processes and improving movement efficiency.[11] However, its scientific efficacy in this context remains to be conclusively demonstrated, particularly given that the primary focus in early postoperative rehabilitation typically focuses on quadriceps activation and basic neuromuscular recovery.[7 12–16]

In light of these considerations, it becomes essential to explore how rehabilitation methods can evolve to address the limitations of traditional PBT. This article will first analyse the shortcomings of PBT after ACLR rehabilitation, particularly in relation to muscle recovery and return-to-sport outcomes. We will then introduce VBT as a promising addition, detailing its mechanisms and advantages in mid- and late-stage rehabilitation. Finally, we will offer practical guidelines for integrating VBT into ACLR rehabilitation protocols to enhance muscle function recovery, optimise performance and reduce long-term complications.

VBT compared with traditional methods

Challenges of PBT

PBT has long been the best strategy for muscle strength and power training and has been widely used by practitioners.[17] This traditional method is based on the value of the maximum load that the individual is capable of lifting once during a dynamic concentric action, using a correct lifting technique.[18] Once this so-called 1-RM is determined, the resistance training programme is periodised into training cycles, depending on the neuromuscular adaptations sought, where the relative loads of each training session are determined by a percentage of this 1-RM.[19] The intensity of each training session is, therefore, ideally planned in advance.

Although this training method is widely used, it has some notable limitations.[20] First, the value of the 1-RM can vary by almost 20% daily.[21] This variability is due to factors directly linked to training, such as residual posttraining fatigue, the time and quality of recovery.[22] Other factors, related to individual stress, including lifestyle, psychological state, stress management and various life events (eg, psychological fatigue, burnout from excessive training loads, chronic stress related to competition pressure, sleep deprivation, anxiety and emotional distress), make resulting training prescriptions inappropriate and not in phase with the targeted neuromuscular adaptations.[9] Second, it is an opinion widely shared that training to failure is the best stimulus for maximal hypertrophy and strength gains, but this craze is not supported by recent scientific literature.[5] This type of training places unnecessary metabolic, mechanical and hormonal stress on the body, creating an unfavourable anabolic–catabolic balance. In the long term, this is likely to lead to a significant reduction in the RFD.[7 14] Third, recent studies have questioned the ability of the PBT method to determine the level of effort induced by each repetition of the training session.[23] This training variable, for a given relative load (ie, %1-RM), represents the ratio of the actual number of repetitions performed to the maximum number of repetitions that could be performed on that day.[23] The PBT method assumes that all individuals experience the same degree of effort when performing an exercise with a load defined as a percentage of their 1-RM.[24] This standardised approach typically assumes a fixed structure, such as five sets of a maximum of eight repetitions (5×8 RM). However, there is no difference in hypertrophy stimulus between loads ranging from 30% to 90% of 1-RM. 8–12RM also seems to cause mainly sarcoplasmic hypertrophy, which correlates extremely low to strength gains.[25] Meta-analysis shows that 20%–25% velocity loss (VL) is the optimal VL threshold to improve hypertrophy.[5] Statistically, there is not more hypertrophy with deeper VL thresholds.[26] Going deeper into VL than 30% causes a lot of neuromuscular fatigue and causes a shift to a slower phenotype.[27] This, of course, does not help the selective inhibition and atrophy following ACLR. With the PBT, clinicians tend to create too much VL and fatigue in sets with the goal of inducing hypertrophy. This is not effective because they may generate especially sarcoplasmic hypertrophy and compromise RFD, mechanical delay through neuromuscular fatigue and a shift to a slower phenotype. This adaptability can make the method feel more tailored, and for many practitioners, such flexibility is already a common practice, raising questions about the necessity of a strictly fixed approach. However, physiological reality and individual capacities vary greatly from one person to another.[28] Two individuals following the same programme may not produce the same degree of effort. One individual may reach muscular failure precisely at the eighth repetition, in accordance with the plan, while another may be able to do a few extra repetitions or may fail before reaching eight repetitions. These differences can be attributed to several factors, such as an inaccurate estimate of 1-RM at the start of the training cycle, fatigue levels or variations (strength, endurance, flexibility, recovery, stress, illness or changes in training intensity or volume) in general fitness.[29]

The implications of these variations are significant: if the degree of effort is not adequately calibrated for each individual, the expected neuromuscular adaptations may not be optimal.[23] As a result, the PBT method does not allow the principle of individualised training to be rigorously respected. This principle is fundamental to the design of adapted training programmes. It helps to take into account individual differences that affect performance and recovery, such as physical condition, fatigue levels and recovery capacities.[5] Training that includes the principles of individualisation then makes it possible to optimise gains in muscular strength and hypertrophy while respecting the individual's current capabilities, which is all the more important for an individual who has undergone an ACLR.[29]

VBT benefits

To overcome the limitations of PBT training, velocity-based approaches have been proposed as a complement to PBT.[3 9] Exercise intensity is controlled by tracking the velocity of each repetition.[9] This method involves monitoring the concentric phase velocity of each repetition in order to control the real intensity of the training.[30] Interest in lifting velocity is not new,[31] but research over the last decade has provided solid evidence of its importance.[9 30] First, there is a high linear relationship between mean movement velocity and relative load expressed as a percentage of 1-RM in various resistance training exercises.[32] Second, percentage velocity-loss (%VL) threshold is a metric that helps determine the optimal exercise dose to elicit optimal strength adaptations and quantify the level of effort incurred during exercise.[14 27 33 34] The %VL is determined on the basis of the fastest repetition (usually first) and is generally between 0% and 40%.[33] The greater the VL, the closer the individual is to muscular failure.[33] Several authors have demonstrated that determining the set volume using a low percentage of VL (between 5% and 10%) enhances athletic performance, such as sprinting or vertical jumping, more effectively than a set volume with a high percentage of VL.[27] It has also been demonstrated that a low-to-medium %VL yields similar 1-RM improvements as a 40% VL, despite requiring only half the exercise volume.[35] These observations confirm that it is not necessary to reach muscular failure to achieve significant neuromuscular improvements.[5 35] The magnitude of VL and changes in blood concentrations of metabolic markers such as lactate or ammonium ions, which are direct indicators of metabolic stress,[5] or the decline in the maximum pre- and postexercise height during a counter-movement jump are intimately linked.[23] However, Rodríguez-Rosell *et al.* have revealed that it is also possible to accurately determine this fatigue by monitoring the velocity of movement.[23] Third, it is possible to predict the daily 1-RM using submaximal loads by establishing LVR.[36] The use of individual LVR is preferred over using a general LVR.[36] Determination of individual LVR consists of applied multiple-point method by evaluating the velocity outputs of multiple submaximal loads.[36] The resulting profile is individual, specific to the exercise and dependent on the testing conditions (eg, using a Smith machine or free weights for the squat exercise). Finally, real-time monitoring of the velocity of each repetition provides extrinsic feedback to maintain motivation levels.[9]

Table 1 Comparison of VBT devices: features, practical advantages and considerations[9 38 65]

Device type	Key features	Practical advantages	Considerations
Linear position transducer	Measures velocity through cable movement. High-accuracy, low-error margin (±1%–2%).	Accurate and reliable for barbell exercises. Provides real-time feedback.	Requires proper setup and attachment to the barbell. Slightly expensive.
Wearable inertial sensors (eg, accelerometers)	Tracks movement using acceleration data. Compact and portable.	Lightweight, versatile for various exercises, including free weights.	Less accurate than linear position transducer for some lifts. Requires proper calibration.
Laser-based devices	Uses lasers to track barbell movement and velocity.	Non-contact, easy setup and highly accurate.	More expensive than other options. Limited to barbell exercises.
Smartphone apps with video analysis	Estimates velocity using video recording and frame analysis.	Cost-effective, accessible for home or gym use. No additional hardware required.	Lower accuracy, dependent on camera quality and manual input.
Force plate systems	Measures ground reaction forces to derive velocity metrics.	Provides detailed data on force, velocity and power. Useful for advanced diagnostics.	High cost, primarily used in research or elite performance settings.
Barbell encoders	Measures rotational velocity of a barbell.	Accurate for barbell movements, robust design.	Limited to barbell training. Moderate cost.

VBT, velocity-based training.

Various technological tools are used to measure velocity, but a position transducer is the gold standard.[37] This device converts a mechanical signal (variation in cable length) into an electrical signal, making it possible to obtain the displacement of the centre of mass and its velocity and acceleration.[37] The position transducer demonstrates a very low measurement error, typically within a margin of ±1%–2%, ensuring high precision in velocity-based measurements. Furthermore, its absolute reliability (eg, SE of measurement) and relative reliability (eg, intraclass correlation coefficients (ICCs)) are generally within acceptable ranges, often reported as ICC values above 0.90, indicating consistent performance across repeated measures and users. These metrics confirm the device's suitability for VBT applications in both research and practical settings.[38] Other devices include self-magnetising accelerometers[39] and motion capture smartphone applications enhanced by artificial intelligence (table 1).[40]

The type of velocity to be measured depends on the type of exercise (ballistic or not) and the type of load to be moved (light or heavy).[9] Weakley *et al*. recommend using the mean concentric velocity for non-ballistic exercises performed with heavy loads (> 70% 1-RM) and peak force for ballistic exercises.[9] There are three options for assessing 1-RM and prescribing loads (figure 1):

1. universal velocity zones, where each velocity range is associated with a specific 1-RM percentage and a corresponding physical quality (eg, velocities between 0.75 and 1.0 m/s correspond to 50%–60% of 1-RM and to the development of strength–velocity qualities)[39];
2. general LVRs, which are determined on the basis of incremental load tests for a given exercise, carried out by a large population;
3. individualised LVRs, which can be determined using direct 1-RM evaluation methods such as incremental loads, indirect or methods such as the two-point

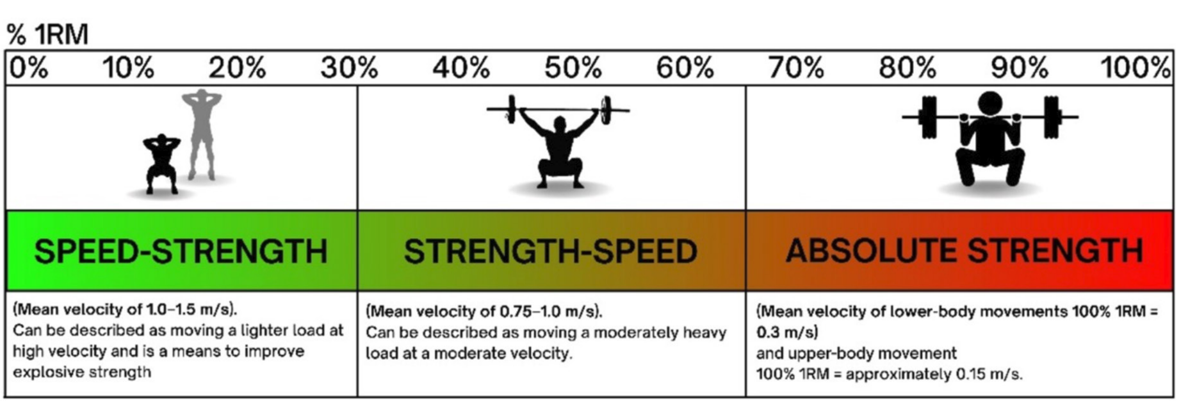

Figure 1 Relationship between %1-RM and velocity ranges for different types of muscular strength.[14] RM, repetition maximum.

method and regression models such as second-order polynomial regression.[36]

Strategic integration of VBT during mid- and late-stage ACLR rehabilitation

The presence of muscle function deficits after ACLR, notably amyotrophy and reduced force production in the quadriceps and hamstrings, necessitates careful management by practitioners to ensure successful rehabilitation. The recovery from these muscle function disorders is crucial as it decreases the risk of a new ACL injury. Recent research indicates that each 10% reduction in the ratio of knee flexor to extensor strength is associated with a 10.6% increased risk of ACL reinjury.[41 42]

Buckthorpe and Della Villa have divided the rehabilitation after ACLR into five phases: preop stage, early stage, midstage, late-stage and return-to-sport phase.[43] Each phase builds on the previous one, with the ultimate aim of achieving maximum performance on returning to field. The early stage aims to reduce pain and restore the overall functionality of the lower limb.[44] Then, during the midstage, the aim will be to restore strength, muscle hypertrophy and neuromuscular function. Finally, the final two phases will prepare the patient for a return to sport, focusing on developing the physical, physiological and athletic qualities needed for a safe return to sporting activity.[45]

Throughout this process, restoring levels of muscle strength has a legitimate and essential place.[45] Monitoring mean concentric velocity during specific exercises provides a practical tool for enhancing muscular performance and optimising training loads while minimising fatigue. The main objectives of the early stage are to restore correct knee function, in particular, preventing the onset of arthrogenic muscle inhibition or its consequences.[46] As the patient already has a few objectives to achieve, we think that it makes more sense to incorporate the VBT method from the second part of midstage rehabilitation. Criteria for progression from the mid to late stage of ACLR rehabilitation include effective pain management, control of oedema and achievement of sufficient range of motion of the knee joint, usually full knee extension and knee flexion of at least 120°.[43] Recovery of muscle strength, particularly in the quadriceps, must be over 80% of that of the non-injured limb, and the ability to perform functional tasks with a minimum of compensation is essential.[43] Besides, it is essential to consider the non-involved limb during rehabilitation, which also experiences deficits in strength, neuromuscular control and overall function.[47 48] These deficits are likely due to compensatory movement patterns, neural adaptations and reduced bilateral activity during the recovery process.[47 48] From the early stages of rehabilitation, addressing the non-involved side is crucial to prevent functional imbalances and ensure symmetrical recovery.

Proposed application of VBT in mid and late stage in ACLR rehabilitation

Enhancing the midstage phase: path to maximum strength and muscle volume

The objectives of midstage rehabilitation are to restore maximal muscle strength, improve movement quality and recondition physical fitness.[43] These goals include resolving muscle strength and joint stability imbalances, recovering strength in closed kinetic chain movements and basic motor relearning.[43 44] Concerning muscle strength, the main goals are to restore trophicity and improve maximal force production and absorption capacity.[43] To achieve these objectives, improving the size of type 2 muscle fibres is crucial for promoting the expression of an explosive muscular phenotype.[49] The conventional approach to achieve this involves a series of exercises until the muscles are unable to perform any further or 'training to failure'.[3] However, recent research like the systematic review with meta-analysis by Refalo *et al.* (they studied the influence of the proximity of resistance training to failure on muscular hypertrophy) highlights the potential non-linearity of the relationship between proximity to failure and muscular hypertrophy.[5 43] These results support the conclusions of previous studies, which show that training to failure is likely leading the athlete to perform repetitions which do not bring any benefits in terms of adaptations in strength and muscle volume.[50] Furthermore, this excess effort generates significant fatigue, which can hinder neuromuscular freshness in the following session,[51] if the athlete participates in two or three rehabilitation sessions per week as recommended.[43] In addition, some authors recommend applying a training intensity of between 8 and 12 RM or a relative load of between 70% and 80% of 1-RM.[43] However, they do not recommend 1-RM assessment methods applicable to the individual who has suffered an ACLR. Traditional methods for calculating 1-RM include direct assessment, which involves lifting maximum loads, and indirect assessment, which uses submaximal loads along with estimation tables to predict 1-RM (figure 1).[14 52] However, these methods are often unsuitable for an injured knee, as they either require maximum effort or induce muscle failure from submaximal loads, both of which may not be well tolerated during rehabilitation.[53] Daily variations in 1-RM require daily measurement of 1-RM, which is utopian in the rehabilitation context.[17] This makes it difficult to provide an appropriate training stimulus. To solve this problem, Sanchez-Medina and González-Badillo recommend monitoring proximity to failure by tracking VL relative to the velocity of the first repetition,[33] provided that each repetition is performed with the intention of reaching maximum velocity.[30] Several authors have studied the impact of determined VL thresholds, measured as a %VL, on the extent of gains in muscle volume and strength.[27 33 34 50] Their conclusion is unanimous: the higher the VL threshold, the more neuromuscular adaptations are directed towards the development of muscle trophicity. This is in line with traditional hypertrophic training recommendations, which are in favour of high training volumes to increase the total time the muscle is under tension.[54]

Recommendations for implementing VBT methods

Familiarisation period

Being able to maintain maximum velocity intent in every repetition requires maximum concentration and commitment.[23] Thus, we suggest implementing a familiarisation period to ensure that the patient is familiar with the instruction: 'push as fast and hard as possible' from the onset of each repetition. The aim is to incorporate velocity feedback in usual training at a determined load that provides a sufficient volume of repetitions to induce hypertrophy adaptations (eg, 60%–70% RM) and use velocity feedback to ensure that the patient maintains the intention of maximum velocity,[39] taking care to monitor the appearance of pain or joint effusion.

Determination of individual load–velocity profile

1-RM is the key performance indicator for establishing exercise intensity. However, as explained earlier, traditional methods of determining 1-RM have limitations that prevent their safe use until functional recovery of the knee and muscle strength levels are sufficient.[9] To overcome these limitations, it is advisable to use LVR equations to predict the daily 1-RM with a good level of accuracy by using submaximal loads.[36] An individual load–velocity profile can be established between each relative load (%1-RM) and an average concentric velocity.[30] This profile has the advantage of being stable over time, despite the daily fluctuations of the 1-RM.[30] We recommend using the two-point method instead of the multiple-point methods for its simplicity and quick use.[55] The two-point method is a streamlined approach for assessing an individual's load–velocity profile by measuring movement velocity at just two distinct loads. This method leverages the approximately linear relationship between load and velocity observed in various resistance exercises, allowing for the accurate estimations of key performance metrics with minimal testing.[56–58] In resistance training, as the load increases, the velocity at which an individual can move that load typically decreases in a linear fashion. By measuring the velocity at two different loads—preferably one light and one heavy—practitioners can plot these points on a graph and draw a straight line to represent the LVR.[56 57] This line can then be used to predict performance outcomes, such as the 1-RM without the need for exhaustive testing across multiple loads. Consider an athlete performing the barbell squat exercise. Using the two-point method, the athlete might perform one set with a light load (eg, 40% of estimated 1-RM) and another with a heavier load (eg, 80% of estimated 1-RM), recording the velocity of each lift. By plotting these two velocity measurements against their corresponding loads, a linear relationship can be established. This linear model can then be extrapolated to estimate the athlete's 1-RM or to determine the optimal load for power development.[58]

Compared with multiple-point methods, the two-point method does not generate detrimental neuromuscular fatigue that could disrupt the exercise session.[55] For the lower limbs, research on individual load–velocity profiling by using the two-point method has primarily focused on squat exercise. Garcia-Ramos *et al.* recommended using two distant loads corresponding to approximately 45% and 85% of 1-RM lifted with maximal effort intention.[56 57]

Application of VL method

In the second part of midstage rehabilitation, the targeted muscular objectives are to develop muscle hypertrophy and increase strength levels until achieving a limb symmetry index of 80% for quadriceps strength and a 1-RM equal to 1.25 times body weight for the squat exercise.[43] These cut-offs of muscular strength establish the foundation necessary to begin late-stage rehabilitation.[43] VL is a method that allows for limiting exercise volume while maximising the targeted neuromuscular adaptations without resorting to muscular failure (figure 2).[33] If we consider squat exercise variations,[32] research shows that the optimal VL range for achieving significant hypertrophy gains is 25%–40%, with an initial velocity range corresponding to an intensity of 60%–70% 1-RM,[5 27 34] while the optimal VL range for improving strength gains is 15%–30% with an initial velocity range corresponding to an intensity of 70%–80% 1-RM.[59] However, when prescribing VL ranges to improve hypertrophy, consider that 30%–40% VL at an intensity of 60%–70% 1-RM causes greater neuromuscular fatigue, which takes 72 hours to recover. The limitation of recovery, which can sometimes take up to 72 hours due to fatigue, should be considered when integrating VBT into rehabilitation. Studies suggest that managing VL thresholds (eg, limiting sets to 10%–20% VL) can help optimise adaptation while preventing excessive neuromuscular fatigue.[10] Additionally, session planning should integrate recovery-based periodisation strategies, alternating high-intensity VBT sessions with traditional strength-based rehabilitation to ensure appropriate muscle recovery and reduce injury risks. When compared with the 20%–25% VL range, there is no statistically different improvement in hypertrophy.[26] While VBT has been integrated into rehabilitation, a structured approach to session planning remains underexplored. A practical example of a mixed programme could involve the following.

- *Day 1*: Traditional resistance training focusing on maximal strength (eg, squat and leg press at 80%–90% 1-RM, 3–4 sets, 4–6 reps and 3–4 min rest).
- *Day 2*: VBT session focusing on explosive power (eg, jump squats or loaded jumps with 40%–60% 1-RM, using a VL threshold of 10%–20% to minimise fatigue).
- *Day 3*: Active recovery or mobility-based session.

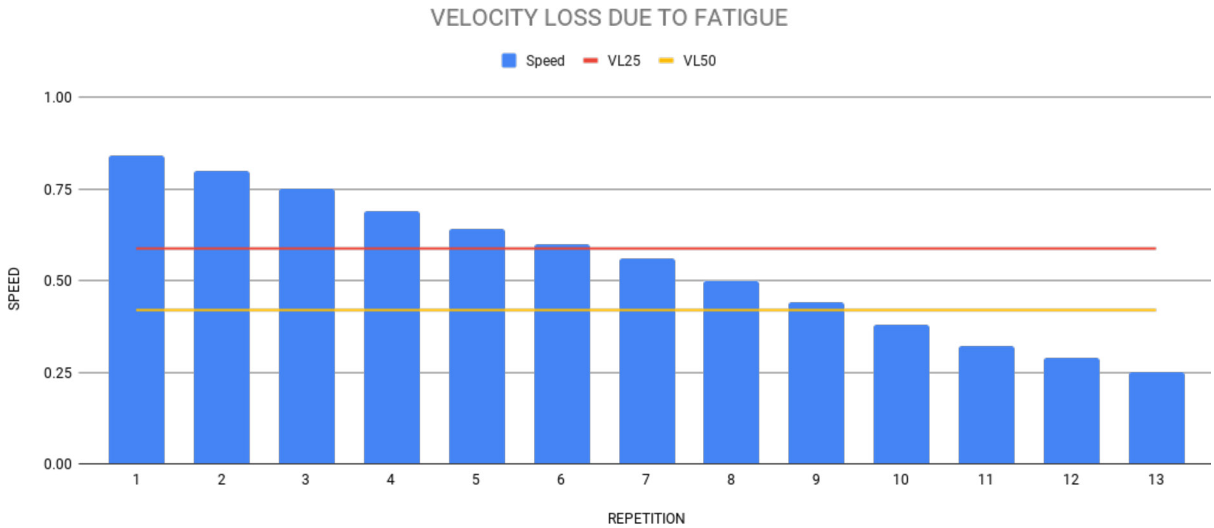

Figure 2 Example of how to use VL. In VL25, you would stop your set after repetition 7 because velocity dropped more than 25%. In VL50, you would stop your set after repetition 10 because velocity dropped more than 50%. In both cases, you would be able to do more repetitions, but stop nevertheless (www.molab.me). VL, velocity loss.

- *Day 4*: Hybrid session combining traditional strength work with VBT monitoring to regulate intensity dynamically.

This structure allows for neuromuscular adaptations while respecting recovery needs, preventing overtraining and ensuring progressive strength and power development in ACLR rehabilitation.[10]

Few studies have focused on periodisation with VBT, but Zhang *et al*. have shown that muscle strength gains are favoured by the following configuration: using an intensity between 70% and 80% of 1-RM, performing 3–5 sets with 2–4 min of interset recovery, at a frequency of 2–3 times per week (table 2).[59] In this midstage, we can include the VBT in classic strengthening exercises, such as squat variations, leg extension, deadlift variations, lunge variations or while using the leg press.[43] The aim is to perform these exercises with the optimal load, intensity and volume while incorporating feedback from the VBT.

Table 2 Example of VBT programme using squat exercise for midstage ACLR rehabilitation

	D1	D2	D3
Intensity (%RM)	70% RM	80% RM	70% RM
VL threshold	30%	15%	30%
Volume (sets)	5 sets	4 sets	5 sets
Rest interval	3 min	4 min	3 min

ACLR, anterior cruciate ligament reconstruction; D, day; RM, repetition maximum; VBT, velocity-based training; VL, velocity loss.

Transition to the late-stage: emphasizing explosive strength and power capacities

The late-stage acts as a bridge between the off-field and the on-field rehabilitation.[45] The objectives of this phase include multidirectional coordination, development of muscle strength and explosive power, improvement of sport-specific skills, recovery of general fitness and preparation for the return to sporting activities with specific training and simulations under match conditions.[45] Gym training involves the whole body, but the intensity of exercises involving the lower body and based on traditional training methods is high (5 RM), using heavy loads for machine-based strengthening exercises like knee extension and moderate (8–12 RM) for functional exercises such as the squat (table 3).[45] Special attention is given to the improvement of strength and explosive power, which is an essential physical trait for sports performance.[45] The time allocated to explosive sports tasks that are crucial during gameplay (eg, during sprinting or vertical jumping) is too short to allow for the expression of maximal force, nor the time required to actively stabilise a joint.[60] For example, the ground contact time during the stance phase of sprinting is generally between 80 and 120 ms, while an ACL rupture typically occurs within 50 ms after the foot strikes the ground.[61] Consequently, the ability to quickly produce the force required for these decisive actions is probably more important than reaching the maximum force itself.[4] This capacity is based on the production of explosive force, which is largely dependent on the RFD, represented by the slope of the force–time curve over a given period.[61] It reflects the ability to exert force rapidly, which is crucial in explosive movements such as jumping or sprinting. RFD is typically calculated by dividing the change in force by the change in time.[61] The interval analysed is usually within the initial milliseconds (eg, 0–50 ms or 0–200 ms) after the onset of

Table 3 Rehabilitation and exercise prescriptions in ACLR rehabilitation[6]

	Training aim	Exercise prescription
Work capacity emphasis	To increase strength endurance of the quadriceps	► Unilateral leg extension (three sets with manageable load until failure) ► SL squat (three sets until failure)
Strength emphasis	To increase quadriceps muscle strength	► Front squat (3–4 × 70%–90% 1-RM @10%–20% VL threshold) ► Split squat (3–4 × 70%–90% 1-RM @10%–20% VL threshold) ► Romanian deadlift (3–4 × 70%–90% 1-RM @10%–20% VL threshold)
Power and RFD emphasis	To increase power output and RFD	► Split squat (3×3 RM each leg) ► Squat jumps (3×4) ► CMJ (3×4) ► SL hop (3×4 each leg)
Peak power and RFD emphasis	To increase peak power, RFD and enhanced stiffness	► Front squat (2–3 × 80%–90% 1-RM @5%–15% VL threshold) ► Drop jumps (2–3 × 80%–90% 1-RM @5%–15% VL threshold) ► Repeated hurdle jumps (2–3 × 80%–90% 1-RM @5%–15% VL threshold) ► SLCMJ (2–3 × 80%–90% 1-RM @5%–15% VL threshold)

ACLR, anterior cruciate ligament reconstruction; CMJ, counter-movement jump; RFD, rate of force development; RM, repetition maximum; SL, single leg; VL, velocity loss.

contraction, as this period is most relevant for explosive strength. High RFD values are associated with greater performance in dynamic- and power-oriented sports. Early RFD (ie, <100 ms from the onset of force) is strongly determined by neural factors and is highly correlated with athletic performance.[62] However, conventional rehabilitation programmes often fail to restore RFD despite improvements in maximal strength. The values for the RFD remained deficient 6 months after surgery and only returned to their preinjury level after 12 months with a well-conducted rehabilitation programme focusing on the development of muscular power.[60] This observation indicates an inadequacy in the rehabilitation content regarding the development of explosive force production capacities. For this reason, improving the RFD before return to sport must be given just as much attention as improving the capacity to produce maximum force.[45] Enhancing RFD requires a multifaceted approach that includes high-speed resistance training, exercises with the intent for rapid force production, fast velocity eccentric training and movement pattern-specific training.[6] We believe that incorporating VBT methods is a good strategy to enhance the RFD. The training recommendations for early RFD are to use heavy loads with few repetitions and sufficient recovery time to allow the nervous system to maintain its freshness.[63] The range of VL threshold that corresponds to these objectives is low. It is recommended to use heavy loads, allowing the bar to be moved at an initial load corresponding to 80%–90% 1-RM while using a VL threshold of 10%–15% (table 4).[59]

In this late stage, we can include the VBT in on-field exercises, such as acceleration, deceleration, sprint work and jumps, in addition to the strengthening work already mentioned in the previous stage.[45] We can incorporate sprint-specific training into our sessions, such as sled-resisted sprinting or uphill sprinting.[64] In jumping work, such as counter-movement jump, drop jump with or without additional weight using VBT has already proved its worth.[65] Resistance sled sprint training is a training method that can improve sprint performance.[64] Furthermore, some results show that athletes' sprinting ability can be further improved by adding incremental resistance against the runner's displacement to increase the ability to produce anteroposterior force.[64] Sled training significantly improves 505-agility test and counter-movement

Table 4 Example of VBT programme using squat exercise for late-stage ACLR rehabilitation

	D1	D2	D3
Intensity (%RM)	80%–90% RM	80%–90% RM	80%–90% RM
VL threshold	10%	10%	10%
Volume (sets)	4 sets	4 sets	4 sets
Rest interval	4 min	4 min	4 min

ACLR, anterior cruciate ligament reconstruction; D, day; RM, repetition maximum; VBT, velocity-based training; VL, velocity loss.

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jump performance compared with traditional unresisted sprint.[66] With this training method, we can simply add the use of the VBT to get feedback on the sprint performance. This will enable us to develop velocity for late-stage ACLR patients.

Limits and perspectives

Although the VBT methodology offers numerous advantages that warrant wider application in ACLR rehabilitation, it does have certain limitations. Most studies focus on trained populations, with no data available on injured populations and limited information about female populations. Therefore, this article aims to propose practical guidelines for practitioners. Additionally, there is a lack of data on open-chain, single-joint exercises, such as leg extensions, which are essential for muscle strength recovery after ACLR. As we saw earlier, sprint work using VBT and resistance sled sprint has proved its worth on healthy athletes while there is a lack of proof on injured athletes. Besides, current technology cannot assess the eccentric phase of movement, which is crucial in ACLR rehabilitation and testing. However, this remains one of the future perspectives in late-stage ACLR rehabilitation. VBT may be proven efficient in redeveloping sprint skills following ACLR and enabling a safer return to sport for our athletes.

However, certain challenges must be considered. First, the implementation of VBT requires specialised equipment, which is often expensive and may limit its accessibility in some rehabilitation settings.[40] Additionally, both therapists and patients must acquire the necessary skills to properly use the equipment and effectively interpret the data, presenting a learning curve.[9] Over-reliance on technology can also pose a problem, as equipment malfunctions or improper use may disrupt the rehabilitation process.[40]

Furthermore, focusing primarily on movement velocity could compromise the proper technical execution of exercises, thereby increasing the risk of injury. It is, therefore, essential for physiotherapists to ensure that patients maintain correct posture and alignment while striving to improve their execution speed.[40]

Future research has to focus on the application of VBT in the early ACLR rehabilitation phase. It could be a way to address the unwanted neuroplasticity, caused by solely providing task-oriented exercises with mainly internal focus. VBT provides augmented feedback and drives external focus. Research describing the constrained action hypothesis indicates that this can restore automatic control processes, improve coordination and movement efficiency.[67–69] It should be investigated if this could address neurophysiological changes more effectively.

CONCLUSION

VBT offers a dynamic method to regulate training loads, enhance power and strength and improve athletic performance while minimising unnecessary knee joint stress. This innovative approach has established itself as an addition within resistance training during ACLR rehabilitation. By focusing on the velocity of movement execution, VBT is proving to be a valuable tool for developing neuromuscular qualities, particularly the RFD. VBT represents a significant advance in the field of rehabilitation and sports training. By incorporating this method in ACLR rehabilitation protocols, healthcare professionals cannot only improve functional outcomes for patients but also promote a more modern, evidence-based approach. It is likely that our improved clinical outcomes will push them to move from a tradition-based paradigm to an evidence-based paradigm, thus possibly paving the way for more effective and personalised rehabilitation strategies.

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