VELOCITY-BASED REHABILITATION AFTER ACL RECONSTRUCTION

TESTING AND TRAINING

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ANTERIOR CRUCIATE LIGAMENT INJURY AND RETURN TO SPORT

Anterior cruciate ligament (ACL) ruptures are frequent in sport. As only two thirds of athletes return to the same level of play and the rate of reinjury could reach 20%[1], their burden is high. One possible explanation of these poor results is the loss of muscle function associated with long term (> 6 months) reduced activity following ACL reconstruction (ACLR). An inability to recover muscle force or power, especially in the lower limb, could lead to an increased risk of reinjury as well as reduced possibility of return to sport (RTS) at the same level of play. Objective criteria are necessary to prevent reinjuries[2] and optimize chances of successful RTS. Mounting evidence suggests that RTS decision-making process should include objective assessments rather than purely time-based criteria[3]. Several evaluations exist to help clinicians make valid decision for RTS following ALCR such as patient reported outcome measures, clinical measures, isokinetic evaluations and various hop tests.

FORCE PRODUCTION CAPACITIES AND RETURN TO SPORT AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

Among the different evaluations of lower limb functional abilities, some of them are a complex combination of different properties as force, motor control, or proprioceptive integration (e.g. hop tests, Star Excursion Balance Test) while others focus only on force production capacities (e.g. maximal isokinetic force of knee extensors or maximal vertical jump tests). We will focus on the latter – force production tests – here. It is important to consider the effect of contraction velocity on maximal force production: while peak force is typically considered an important metric, there is not only one maximal force value! From isolated muscle to single joint or multi-joint movements, the maximal force decreases when velocity increases. There is one maximal force per velocity: this is the well-known force-velocity (FV) relationship[4]. For now, let's consider only lower limb extensors. If the general shape of this relationship is the same for everybody (linear for lower limb extension, rather curvilinear for knee extension), its overall level and its inclination changes across individuals from different sport activities, levels of practice, ages and even codes within the same sport[5]. Instead of comparing force at each velocity, the FV relationship can be summarised by its two extremums: the theoretical maximal force at null velocity (Fo, representing force production capacities at low velocity) and the theoretical maximal velocity until which some force can be produced (Vo, corresponding to force production capacities at high velocity, (Figure 1). The maximal power (Pmax), apex of the power-velocity relationship, presents the advantage to integrate both Fo and Vo in only one index, but without the possibility to distinguish them. And what is interesting with Fo and Vo is that they are independent: being strong at low velocity is different from being strong at high velocity. So, different force-velocity profiles exist. Two athletes can present the same Pmax (or even the same vertical jump height) with two different FV profiles (Figure 1).

While producing high power output is very important in many sport activities in which force needs to be developed during high intensity actions, the importance of force capacities at high or low velocity differ between sport activities, playing position, and level of practice. Beyond optimizing performance, producing high force is also required to prevent injury (e.g. ACL injury) during key movements where a joint is subject to abrupt forces outside the capacity of the passive constraints. For example, the knee may be subject to such forces during a change of direction in team sports or during a ski turn with a trajectory mistake. In these specific cases, being able to produce high force quickly and at high contraction velocity could be decisive to prevent damage to ligament and other passive tissue, as these often occur in very short time intervals. In addition to observing very different FV profiles across individuals, the adaptations or alterations of force production capacities are velocity dependent. Indeed, since the structural and neuromuscular mechanisms underlying force production at high and low velocities are different, F0 and V0 do not change in the same manner following strength training[6] or fatiguing exercises[7], the changes being specific to the training or exercise modalities. This may be the same for the reductions in force production capacities induced by an injury, be they directly associated to tissue damages specific to the injury or to the unavoidable immobilization, as recently shown after ACLR[8, 9].

On one side, the different objective assessments performed after an ACLR, notably force production capacities testing, aim at helping the clinicians in the RTS decision. On the other side, some rehabilitation training programs are set to improve force production capacities so that objective criteria (if any) can be reached. However, both assessment and rehabilitation training rarely consider the large differences in FV profiles between individuals and the velocity effects on the injury-induced alterations or training-induced adaptations of force capacities. So, it seems interesting to distinguish force production capacities at high and low velocities during both testing and rehabilitation strength training, and to adapt the latter to the results of the former[10]. The interest of such a velocity-based approach of rehabilitation has been supported and proposed for hamstring injuries. First, force production capacities at low velocity during sprinting (F0) have been shown to be still altered at the RTS in soccer players after a hamstring injury, without any alteration in force at high velocity[11]. Then, some rehabilitation training modalities specific to target maximal horizontal force production during sprinting (F0) have been proposed and included in a multifactorial, individualized, criteria-based progressive algorithm for hamstring injury treatment[12, 13]. The aim of this article is to present the main lines of a velocity-based approach during rehabilitation after an ACL injury for both clinical assessment and training of force production capacities.

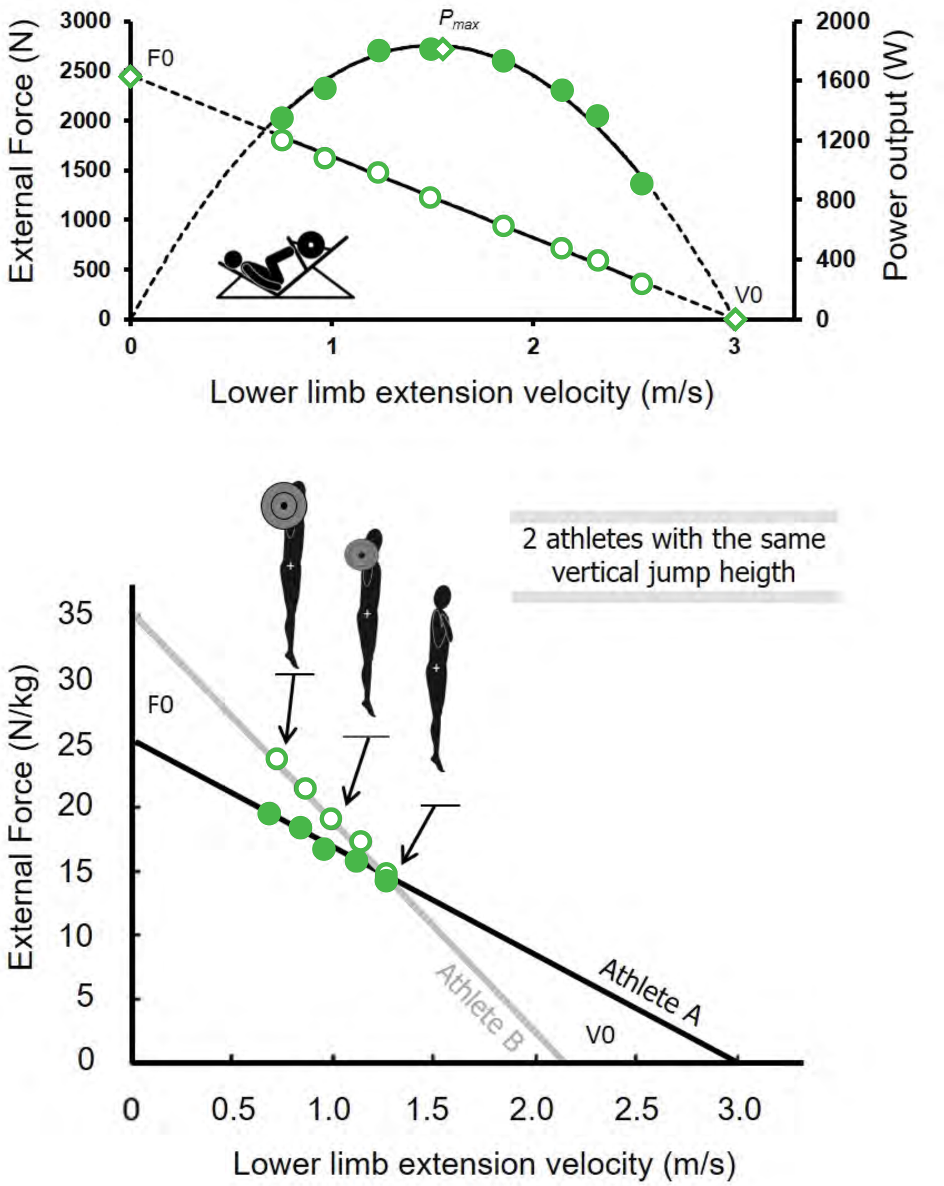

Figure 1: Upper panel: Force-Velocity (white symbols) and Power-Velocity (black symbols) relationship for a typical athlete obtained from lower limb extensions on a leg-press. Lower panel: Illustrative Force-Velocity relationships of two athletes (grey and black lines and symbols) presenting the same jump height without additional load. Each symbol represents force and velocity values measured during one lower limb extension.

VELOCITY-BASED APPROACH FOR TESTING IN REHABILITATION

When testing force production capacities, the output metrics are specific to the configuration of the body, the contraction mode, and the muscle groups involved in the task considered. For example, measuring the strength of the lower limb extensors (i.e. the extensors of the hip, knee, and ankle) during a squat movement gives different values from measurements in a seated position on a horizontal press, during pedalling sprints, or during an isokinetic test of the knee extensors. The task must therefore be chosen according to what the evaluation targets, the level of recovery during rehabilitation and the balance between analytical (e.g. isokinetic strength of the knee extensors) and functional (e.g. single leg jump or sprint running) information. Even if the metrics (not the values) are the same (e.g. maximal isometric force, 1 repetition maximal – 1RM-, F0, V0, Pmax) and more or less correlated between the different tasks, each task (or level of analysis) each gives different insights regarding lower limb strength.

Force-velocity profile

The individual FV relationship offers an entire view of the dynamic force production capacities of the neuromuscular system. Force and velocity must then be obtained during different (3 to 5) conditions of velocities (e.g. different loads or resistance) of a same task over a same range of motion (e.g. knee extension or vertical jump) performed with maximal intensity[14]. The range of velocities covered should be as high as possible. The advantage of FV relationship is to obtain metrics (F0, V0, Pmax) that are independent of the choice of the conditions tested (e.g. loads or velocities), in contrast to strength testing performed at a given (relative or absolute) resistance or velocity. Several lab methods exist to measure force and velocity during different lower limb tasks using force sensors, linear encoder or motion capture[10]. Other field methods were proposed and validated to estimate force and velocity from simple measurements out of laboratories, directly in the field, but only in some very specific movements (jumping or sprinting[15, 16]). Some validated smartphone apps can be used to measure the basics inputs and do the computations (e.g. MyJump® or MySprint® Apps[17, 18]). Note that since hamstrings are key contributors of horizontal force production capacities during sprinting[11], the FV profile in sprinting would be likely altered following ACLR, especially if the hamstring were harvested for the surgical technique. So, FV profile in sprinting can be also considered as a macroscopic functional assessment of lower limb strength in the late phase of the RTS.

Indirect assessments of Force-Velocity capacities

If clinical daily constraints make difficult the determination of complete FV relationship, other testing processes can give useful information, albeit less accurate or complete, regarding force production capacities at both high and low velocities. These can be appraised through two tests at two different loading or velocity conditions, provided the two conditions are sufficiently different from each other. It is then important to standardize the loading or velocity conditions since the metrics will be very sensitive to this choice. For example, this can be done by measuring the maximal force at two velocities (e.g. 30°/s and 180°/s) during knee extensor isokinetic testing, on a leg press via the maximal isometric force (or 1RM) and the maximal velocity in a condition without additional load (considered here as a proxy of force at high velocity), or through measuring jump heights with and without additional loads. Even if it is possible, accurate, and reliable to draw a FV relationship from only two conditions in some specific cases[19], the interpretation of the data obtained from two tests performed at two different velocities can also be done without determination of FV curves, but just by separately analysing the performance obtained in the two conditions as indirect metrics of force at low and high velocities[8]. This kind of approach was proposed by Carmelo Bosco in the 1990's to compare athletes' FV profiles through the ratio between jump heights reached with (75 or 100% of body mass) and without an

Image: Illustration.

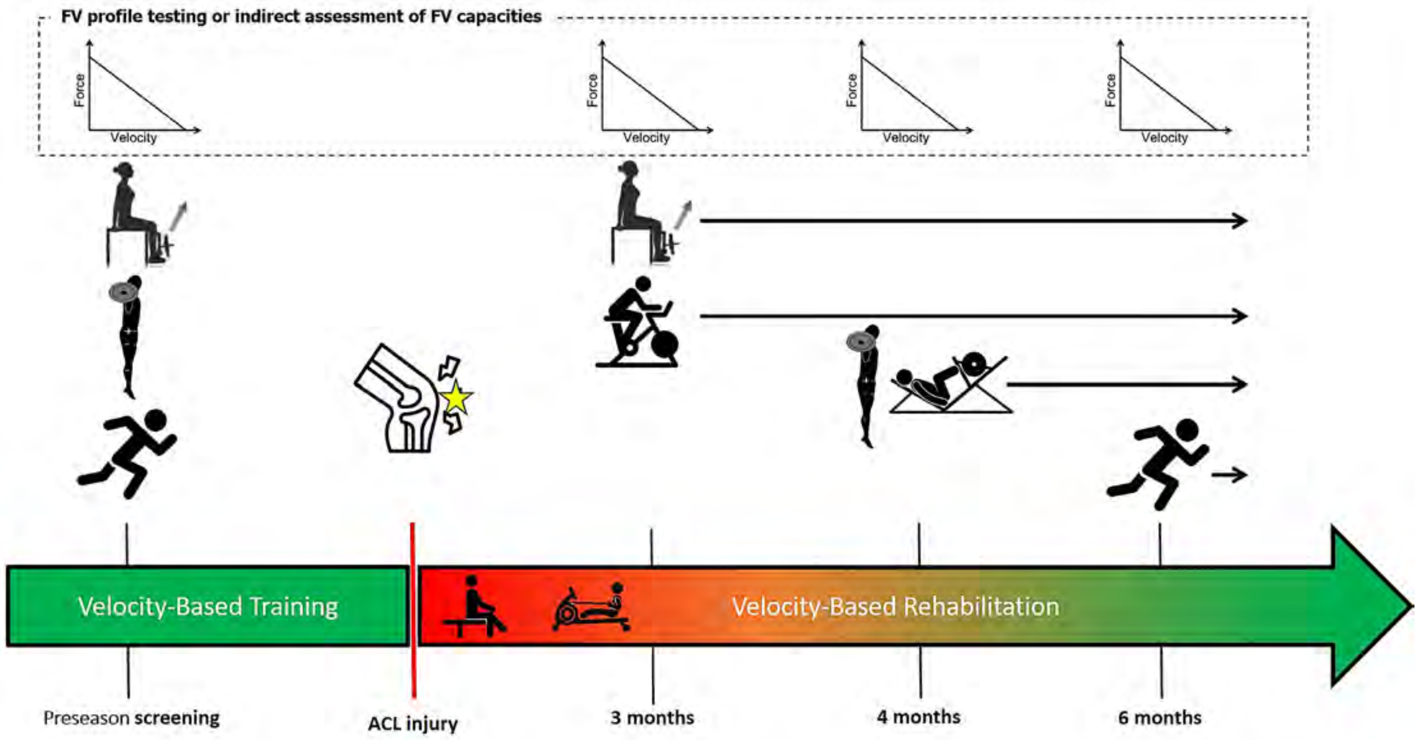

Figure 2: Schematic illustration of an "ideal" time-line model for a velocity-based approach during rehabilitation with a gradual "analytical-to-functional" approach. Nowadays, thanks to the widespread use of these tools in the field of strength and conditioning (notably in sprint or vertical jumping during pre-season tests), clinicians can access pre-injury data obtained in the context of screening tests in high-level athletes. From ~3 months after the injury, the patient can normally perform an intensive effort in very standardized conditions, as during knee extension or pedalling, which can be used to orient rehabilitation program. Later, vertical jumps or leg press exercises with or without resistance can be used in bilateral and then single-leg conditions. Finally, at the time of return to sport, sprint testing can be useful to test strength in the context of locomotion. The selection and timing of tests and rehabilitation exercises must be based on objective criteria related to individual specific strength deficits.

additional load[20]. The higher this index, the higher the force capacities at low compared to high velocities.

Methodological considerations

Whatever the task used for testing, bilateral or single-leg modalities can be used. For rehabilitation purposes after ACL injury, the single leg condition remains more relevant since it allows examination of only the injured side, to compare values to the non-injured side and to compute asymmetry indexes[21]. If for some very standardized tasks (e.g. knee extension or leg press lower limb extension), single-leg testing does not present any methodological challenges, this requires some additional caution for other functional testing, as for jump tests. For instance for vertical jump tests, the body mass (without any additional load) represents an important load preventing from reaching high contraction velocities, the lower perception of safety may alter the implication of the athlete, the landing phase can be done on both legs to enhance safety, but the free-leg's motion should be minimized to avoid any overestimation of lower limb force capacities[22]. It is worth noting that vertical jumping is a very practical, easy-to-use, and inexpensive way to assess lower limb force production capacities after ACLR, as well supported by the work of Jordan and colleagues[21,23]. Moreover, other strength indices can be assessed during vertical jumping, such as reactive strength index which has been shown to bring additional insights about strength deficits compared to maximal force only[24]. In the same way, explosive strength, assessed through rate of force development during maximal isometric contraction, was reported to be important to monitor throughout rehabilitation and RTS after ACLR[25]. While basically different, lower limb external force production capacities at high velocity, reactive strength indices and rates of force development are interconnected (through some similar underlying neuromechanical mechanisms) and may present some similar recovery kinetics over the RTS[24, 26]. Recently, clinical guidelines from ASPETAR recommended performing countermovement and drop jumps to evaluate both limb symmetry and reactive strength index (LSI and RSI)[3].

Ideally, pre-season data could be used as benchmarks and reference values to be achieved at the end of rehabilitation. Clinicians should therefore look for a significant deficit in strength indices (notably force capacities at low and high velocities) compared to the values obtained prior to the injury. During single-leg assessments, the uninjured limb could also serve as a reference for clinicians. Testing does not only aim at obtaining some scores for comparison to RTS criteria, but could also serve as a goal-oriented assessment to tailor the rehabilitation in order to recover from strength deficits[10]. So, testing may start relatively early following the injury. An idealised time-line model for a velocity-based testing is presented in Figure 2, presenting a gradual "analytical-to-functional" approach.

VELOCITY BASED APPROACH FOR TRAINING IN REHABILITATION

Velocity-Based Training

Once the force production capacities have been characterized and the needs of each athlete identified, the rehabilitation training process requires exercise modalities to target the desired adaptations. These exercise modalities are very often prescribed on the basis of loads to be mobilized (or force to be developed) relative to the maximum capacities of the athlete if known, (e.g. 1RM load) or through a progressive increase in absolute resistance. An alternative method appeared nearly 20 years ago in strength and conditioning literature and proposed to characterize the intensity and specificity of an exercise on the basis of the velocity of execution during maximal efforts (Velocity Based Training[27]). Exercises can thus be considered according to the velocity zones of the FV relationship the athletes can reach and the velocity zones targeted for the improvement of force production capacities. The resistance, loads or assistance, applied during the movement are adjusted to set the velocity during a movement performed with maximal effort intention. This can be done using velocity feedback during the exercise to control the velocity zone or knowing the load-velocity relationship specific to each movement and each individual. Beyond strictly applying the principles and guidelines of Velocity Based Training in rehabilitation, having a just a global velocity-based approach during rehabilitation training can be helpful. This requires at least considering that training force production capacities at high or low velocities are very different and associated with different underlying neuromuscular or structural factors[28]. One way to stimulate these mechanisms is to train within the velocity zone in which strength gain is expected. A polarized approach can also be applied and corresponds to using exercise modalities that target the stimulation of the underlying factors (often through training at the extremes of the FV relationship) rather than the specific velocity zone of the strength gain per se. For instance, to improve force capacities at intermediate velocities (close to optimal velocity maximizing power), training force at both high and low velocities can also contribute to develop some underlying mechanisms of strength in the middle of the FV relationship.

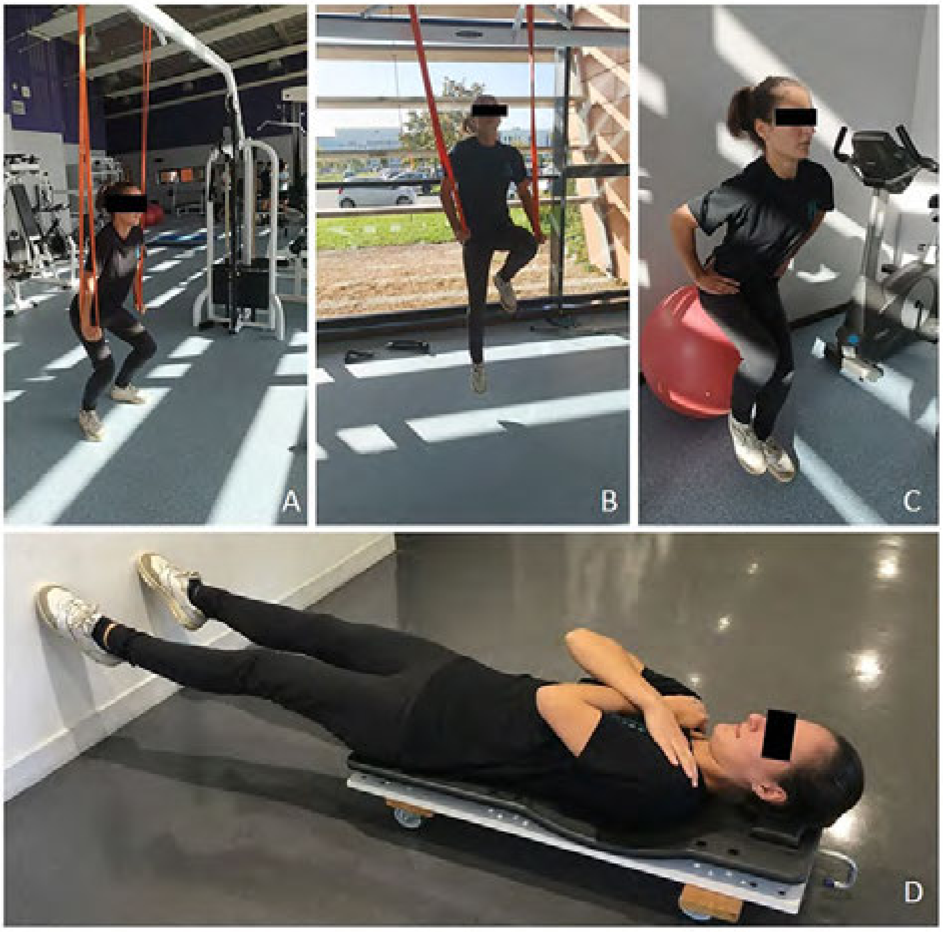

Figure 3: Pictures illustrating four exercise modalities allowing athletes to reach high lower limb extension velocities: Elastic-band assisted bilateral (A) and single-leg (B) vertical jumps, Swiss-ball assisted single-leg vertical jump (C), bilateral horizontal jump (D).

Application in rehabilitation

In the context of ACLR rehabilitation[29], most muscle strengthening protocols aimed to target force capacities, but rarely at high velocities (e.g. leg extension, Nordic-hamstring, bench press, squat). If the exercise modalities specific to improve the 'force' side of the FV relationship have been well documented[30], training force capacities at high velocity is less well-described. However, such training modalities can be helpful in rehabilitation where injured athletes may display a larger force impairment at high than at low velocities. For this kind of training, the objective is to reach high movement or contraction velocity during the exercise, therefore using low loads or resistance. When focusing on the lower limb in the context of rehabilitation after ACLR, this can be a challenge since the body mass (associated to inertia) and the body weight (associated to resistance during a vertical movement) correspond to high mechanical constraints, thus often limiting the movement velocity too much to reach high velocity zone. Note that a bilateral vertical jump without additional load is associated with force and velocity outputs in the middle of the entire FV spectrum. This is even more pronounced during single-leg exercises. To overcome this, several modalities have been proposed: exercises with low/no load and without movement of the body mass (e.g. leg press), exercises with assistance (negative loads or elastic band[31]), exercises with low pneumatic resistance[32], or exercises performed in the horizontal direction (horizontal squat[33]). Whatever the task, notably with low load, maximal effort removing deceleration phase at the end of the movement allow the athlete to reach higher velocities while producing some force throughout the movement (with bar throw or jump[34]). If some of these modalities require some very specific equipment, not always available for clinician in daily practice, other modalities can be easily set up: jump with elastic band or Swiss ball to

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unload body weight, or horizontal jump while being supine on a rolling device (e.g. long sliding board) and pushing with the feet onto a wall (Figure 3). The latter modalities, shown to target similar velocities as during a vertical jump with an assistance of ~30% of body mass[33], offer the possibility to do bi-or uni-lateral push-offs, to use rubber bands to add resistance or assistance, to remove the high-constraint landing phase and to perform lower limb extension safely and very early in the rehabilitation process (Figure 3).

CONCLUSION

ACL injuries are frequent in sports and practitioners need to optimize the rehabilitation process in order to improve RTS at the same level of play and decrease the rate of reinjury. When focusing on force production capacities (one piece of the complex RTS puzzle), a velocity-based rehabilitation approach could help to have an entire view of the alteration and recovery of the lower limb strength from low to high velocities and to monitor and individualize training modalities regarding the athlete's needs and the sport activity demands in terms of performance or injury prevention. Force-velocity profile testing and velocity-based training can contribute to this kind of approach and may be applied in practice by clinicians using simple and easy-to-use methods. Further studies should establish some normative values in terms of deficits in force capacities at both high and low velocities and test the effectiveness of such a velocity-based rehabilitation to help the practitioner in the decision-making process.

References
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