EXPLOSIVE STRENGTH AND STRETCH-SHORTENING-CYCLE CAPACITY DURING ACL REHABILITATION

MECHANICAL BIOMARKERS FOR RETURN TO SPORT AND PERFORMANCE READINESS

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INTRODUCTION

Human skeletal muscles are biological motors that drive movement and function, in turn, causing functional capacity to be highly dependent on our muscles' strength capacity. Consequently, muscle strength impairments after anterior cruciate ligament (ACL) injury contribute to persistent functional losses and an increased risk for ACL reinjury[1,2]. However, muscle strength should be considered as an umbrella term that encapsulates several distinct physiological and biomechanical muscle force parameters[3]. For example, maximal muscle strength is typically measured as the peak force or torque generated in a maximum voluntary contraction (MVC), and it can be measured in eccentric, isometric or concentric muscle actions. Maximal muscle strength is determined, in part, by the physiological cross-sectional area of the target muscles and the magnitude of neural drive from the central nervous system, notably motor unit recruitment discharge rate modulation[3-5]. Moreover, maximal functional muscle strength capacity is influenced by the contractile properties of skeletal muscle dictated to a great extent by the force-velocity and force-length relationships[6].

Explosive strength, on the other hand, describes the rapid force generating capacity of the neuromuscular system[7]. It is typically measured as the rate of rise in muscle force or torque during isometric MVCs that are executed "fast and hard" or during "burst-like" isometric contractions[8] (Figure 1). In addition to average slope analysis of the recorded torque-time

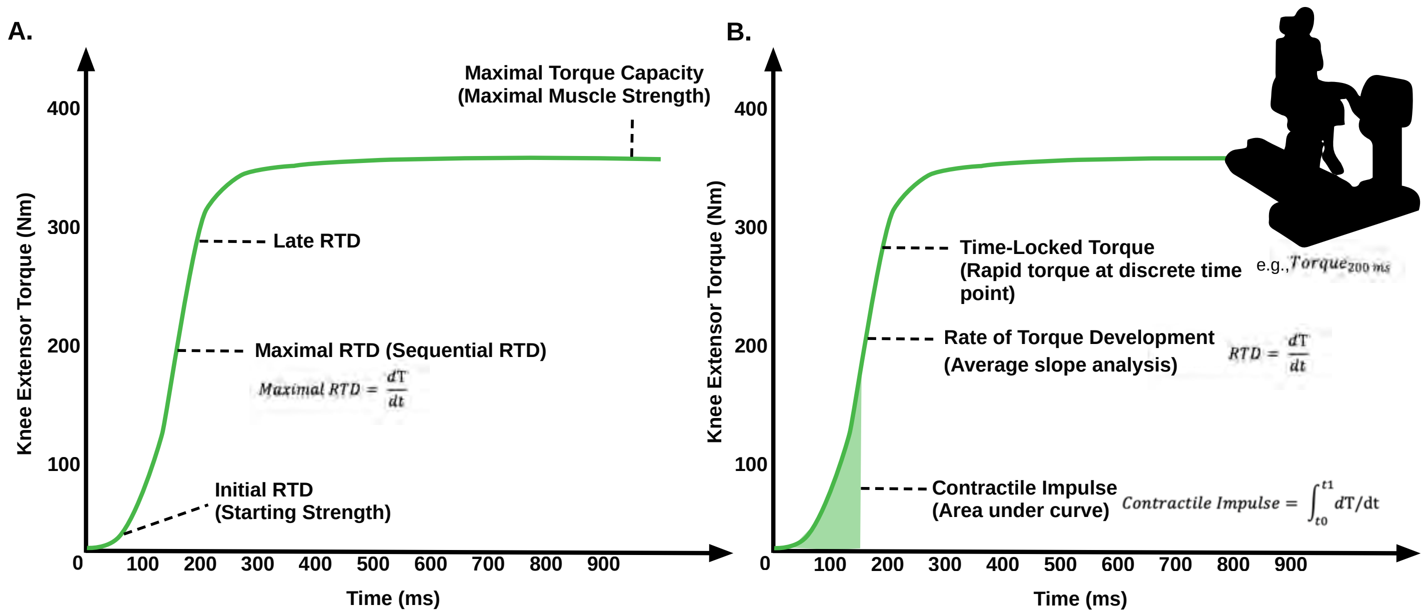

Figure 1: Panel A differentiates sub-capacities of explosive strength that have been measured during isometric maximum voluntary contractions (MVCs). The initial rate of torque development (RTD) is typically measured over intervals < 100 ms while late RTD development extends from 100-200 ms. Sequential RTD analysis obtained from an already activated muscle (e.g., maximal RTD) can be obtained by the derivative of the torque-time curve. Panel B shows common approaches for quantifying explosive strength capacity during isometric testing. RTD=rate of torque development; T=torque; t=time

curve (i.e., rate of torque development – RTD) or force-time curve (i.e., rate of force development – RFD)[9], explosive strength can also be measured as time-specific force or torque sometimes referred to as time-locked force (e.g., force at 50 ms)[10,11], and as the contractile impulse (time integral of the force- or torque-time curve over a specific time period)[7] (Figure 1).

While the neuromuscular determinants of explosive strength share some commonality with those of maximal muscle strength capacity, especially in the late phase of a fast isometric contraction (i.e., > 100 ms), the early rise in force at the onset of an MVC is associated with distinct neuromuscular properties including the muscle fibre type distribution, increased motor unit discharge rates, and motor unit recruitment, along with factors outside the contractile elements of a muscle such as series elastic and tendon stiffness[9,10,12-18]. Sometimes referred to as starting strength[3] or initial RTD capacity[9], the rapid rise in force or torque at the onset of a muscle contraction is distinct from maximal muscle strength not only in terms of its neuromuscular determinants but also with respect to the strength training methods that are needed to elicit an adaptation[7,19-22]. Rapid hamstring versus quadriceps torque production over time intervals that approximate an ACL injury event (i.e., 40-100 ms) is thought to be important for ACL injury prevention[23-25], and increasing RFD capacity throughout ACL rehabilitation has been recommended to better prepare athletes for a return-to-sport than solely focusing on maximal muscle strength and heavy strength training[26].

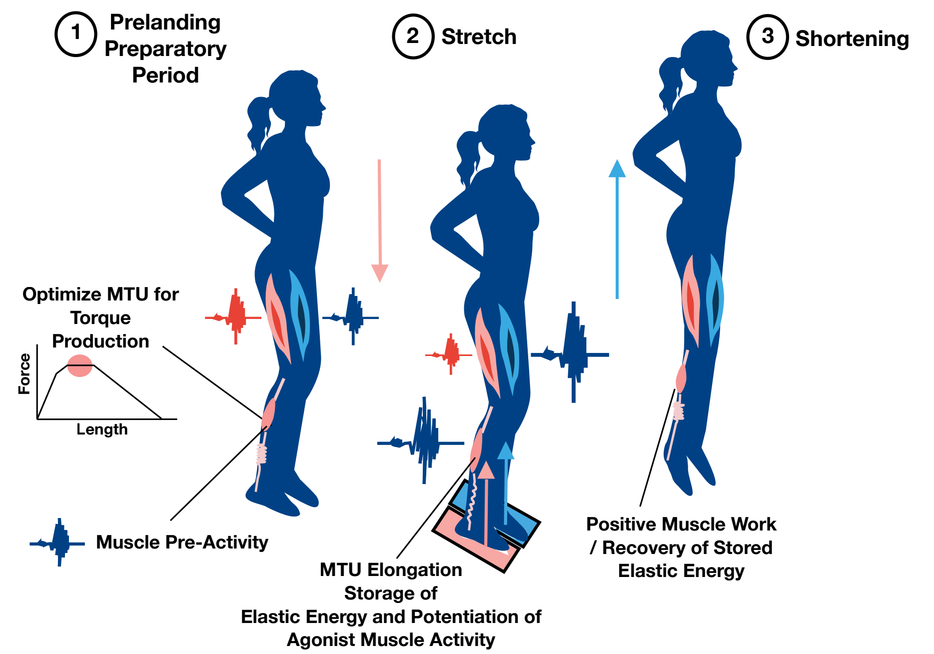

Figure 2: Illustration of the stretch-shortening-cycle (SSC) and the contribution to neuromuscular performance in hopping and vertical jumping. MTU=musculotendon unit.

Explosive strength capacity is strongly correlated with other fast human activities that arise in sport, including stretch-shortening-cycle (SSC) movements that occur in hopping, jumping, and sprinting activities[7,27-29]. SSC movements in sports typically involve fast coupled eccentric-concentric muscle actions that increase muscle power and RFD through the involvement of the stretch reflex response, increased passive series elastic stiffness of the muscle tendon unit (MTU), along with optimized intermuscular coordination and

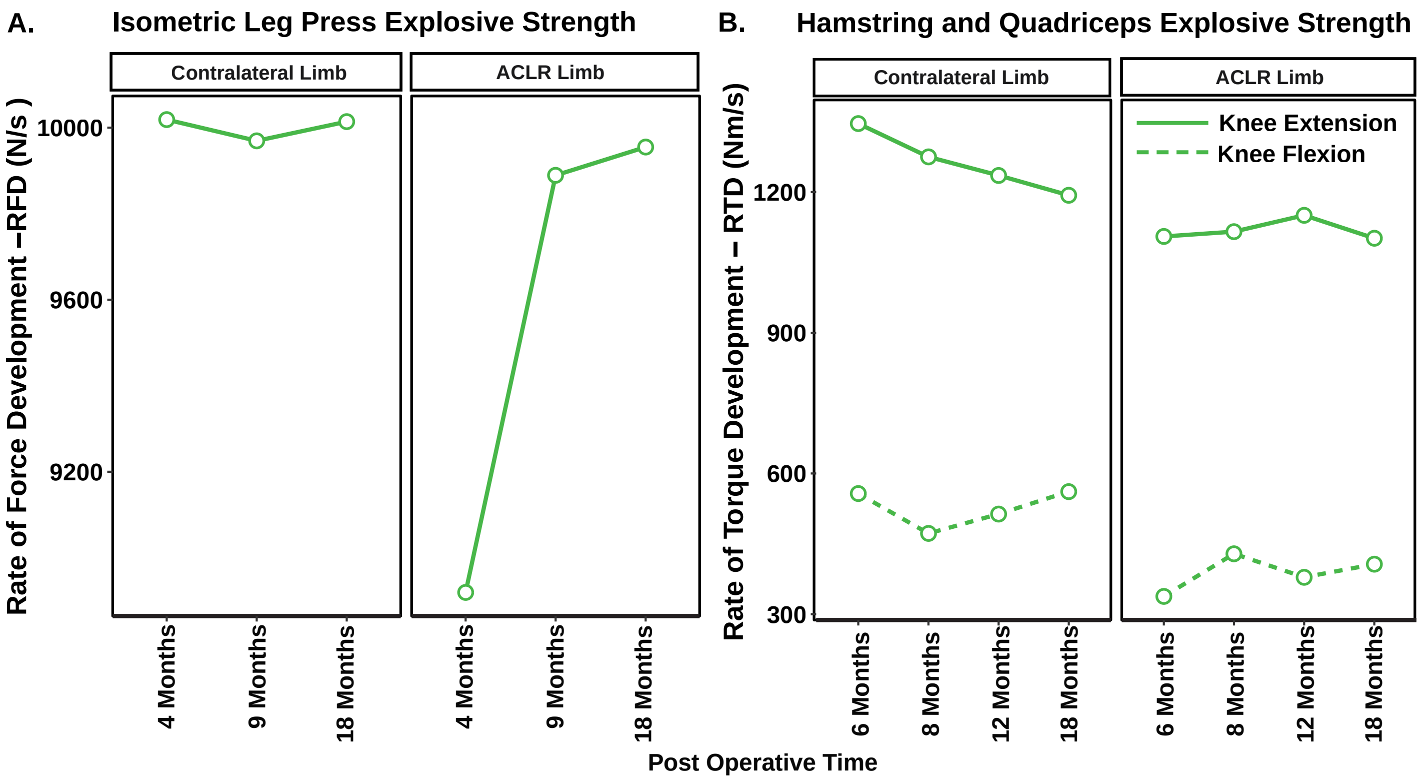

Figure 3: Recovery in isometric leg press, knee extension, and knee flexion explosive strength after anterior cruciate ligament (ACL) surgery (ACLR) with a semitendinosus autograft. Knee extension and knee flexion explosive strength remained impaired up until 18 months post-surgery with evidence of contralateral limb detraining.

muscle pre-activity that modulate active joint and MTU stiffness[30] (Figure 2).

Following ACL injury and ACL reconstruction surgery (ACLR), restoring quadriceps maximal muscle strength must be a focus in the rehabilitation setting to reduce the risk of ACL reinjury[1,31]. However, restoring an athlete's explosive strength capacity including muscle function during SSC movements is also critical for preventing ACL reinjury in competitive athletes[32], while also addressing common comorbidities that occur with ACLR such as those arising from the bone patellar tendon bone (BPTB) and semitendinosus tendon (ST) autografts[24,25,33,34]. These surgical procedures compromise the structural and neural elements that contribute to both active and passive MTU stiffness, thereby contributing to diminished explosive strength capacity. Therefore, the goal of this article is to provide practitioners and clinicians with an overview of the relevance of explosive strength and SSC testing for the ACL injured athlete, and present evidence supporting of mechanical biomarkers as a part of a comprehensive return-to-sport and return-to-performance test battery.

WHY MEASURE EXPLOSIVE STRENGTH AND STRETCH-SHORTENING-CYCLE CAPACITY AFTER ACL INJURY?

An ACL injury affects every level of the neuromuscular system including the CNS[35], skeletal muscle morphology and function[36], and muscle tendons[33,34]. Consequently, rehabilitation is a long, progressive process that must remedy a host of neuromuscular impairments rather than targeting just the single ACL rupture per se[26]. ACL injury and subsequent ACLR impair many neuromuscular determinants of explosive strength and SSC capacity, in turn leading to reduced neural drive, decreased MTU series elastic stiffness, along with alterations in muscle architecture and marked shifts in the torque-joint angle relationship[25,37-39].

While it may not surprise that knee extensor and knee flexor explosive strength deficits exist after ACL injury, what might be unexpected is the degree to which they persist even after maximal muscle strength capacity has recovered including beyond 12 months post-surgery[24,40]. This result suggests that practitioners and clinicians must pay closer attention to restoring explosive strength deficits through targeted strength and plyometric training[26], especially given the strong association between explosive strength capacity and attributes of sport performance such as sprinting speed[27-29,41].

SSC function after ACL injury is typically assessed using standardized jumping and hopping movements[42-45], and just like explosive strength, long-term SSC deficits appear to persist in athletes after ACL injury[46,47]. Additionally, clinic-based functional tests (e.g., single leg hop for distance or a single leg triple hop for distance) that centre on jump performance outcomes without accounting for the movement strategy may fail to predict athletes who are at risk for ACL reinjury[48]. However, biomechanical analysis of SSC strategy during plyometric movements such as the drop jump may be more prognostic for ACL reinjury[2]. Notably, reduced lower limb stiffness, increased ground contact time (instant of touchdown to the instant of toe-off), lower jump height, and a decreased reactive strength index (RSI = jump height/ground contact time) were found to predict athletes who were at risk for ACL reinjury whilst no associations were found with single leg hop for distance testing and measurements of the quadriceps muscle strength limb symmetry index (LSI)[2,32]. Additionally, it seems single leg hop testing protocols after ACL injury can be improved by accounting for the jump strategy (e.g., measuring the jump contraction time) alongside jump performance for interlimb asymmetry testing[49].

Taken together, complementary tests of explosive strength and SSC biomechanics and performance can provide practitioners and clinicians with specific information on the neuromuscular capacities of an ACL injured athlete, including insights into neuromuscular function that are distinct from those associated with maximal muscle strength. Assessing and training the ability of the neuromuscular system to express force or torque rapidly and produce high power and impulse during SSC movements may complement return-to-sport and return-to-performance testing by providing a more holistic evaluation of an athlete's neuromuscular capacities across an envelope of function and muscle strength[50-52].

MEASURING EXPLOSIVE STRENGTH AFTER ACL INJURY

In the scientific literature, explosive strength capacity of athletes and patients with ACL injury has been investigated extensively during multi-joint leg extension, isolated knee extension and knee flexion test maneuvers[24,25,33,34,40,53-56], including in case study analyses in which explosive strength testing were used to monitor the recovery in neuromuscular function in elite athletes[57] (Figure 3). As a case example and evidence of the potential for long-term explosive strength deficits to persist in elite athletes long after ACLR, Figure 3 shows that even at 18-months post-ACLR, knee extensor and flexor maximal RTD remained unchanged from the first test at 6-months post-surgery, and that the explosive strength capacity of the non-injured contralateral limb knee extensors remained substantially reduced at 18-months post-surgery too.

Consistent across several studies, the degree of interlimb asymmetry in isometric knee extension torque capacity can vary considerably during a fast and hard MVC (Figure 4). Figure 4 shows the time locked knee extensor torque asymmetries in an ACL injured athlete for early phase torque (~100 ms), late phase torque (~ 200 ms and 400 ms), and MVC torque with an interlimb asymmetry index that ranges from 14-20% for measures of explosive strength versus only 3% for MVC torque. In addition to flagging a potentially divergent post-ACLR response in the recovery of explosive strength compared to maximal muscle strength, explosive strength assessments have also been used to monitor acute neuromuscular fatigue in athletes, which presents a promising avenue for testing athletes exposed or disposed to ACL injury[58].

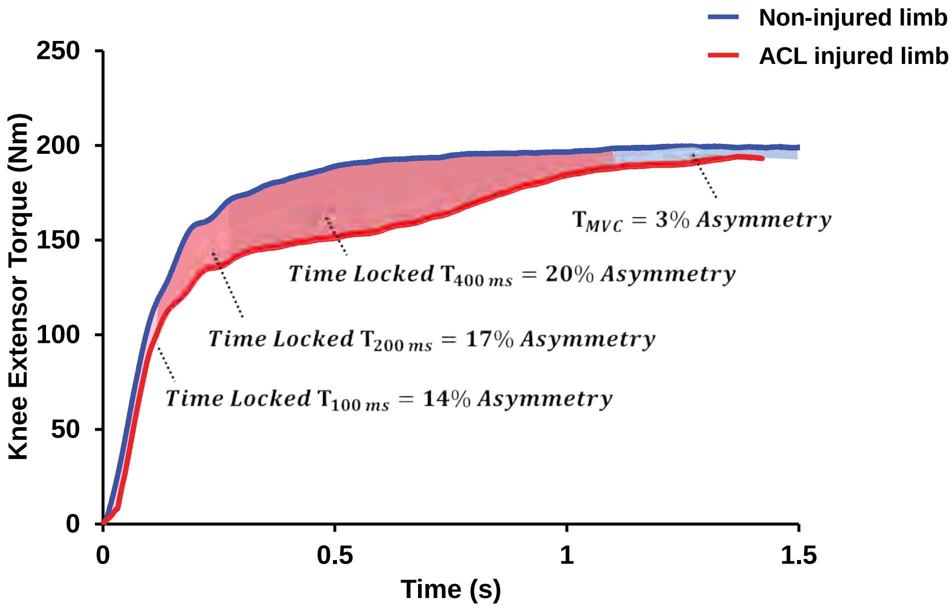

Figure 4: Torque-time curve for an anterior cruciate ligament (ACL) injured athlete showing interlimb asymmetries in time-locked torque during a "fast and hard" maximum voluntary contraction (MVC) of isometric knee extension. T=torque; MVC=maximum voluntary contraction.

The reliability of explosive strength testing after ACL injury especially in the context of routine athlete monitoring, is highly dependent on the methodological approach[8,59]. As reviewed elsewhere, there are several considerations that can be used to help increase the reliability of explosive strength testing[8]. Key points include:

1. Ensuring that athletes are instructed to develop torque "fast and hard" during burst contractions (i.e., fast rapid explosive isometric contractions)[10,59];
2. Completing a minimum of three repetitions for MVC testing and ~ 10 repetitions when using the burst contraction method;
3. Use a mean value of 3-5 attempts to quantify explosive strength; and
4. As values for the average slope may be hampered by poor reliability especially for assessments of early phase RTD, consider using a time-locked analysis (i.e., measure torque at discrete time points)[10].

Lastly, the explosive strength isometric testing rig should be designed to minimize compliance in the system, and force should be sampled at a minimum frequency of 1000 Hz with appropriate signal processing methods to reduce motion artefacts and to accurately determine the onset of contraction[8].

MEASURING STRETCH SHORTEN CYCLE CAPACITY AFTER ACL INJURY

Biomechanical analyses of jumping variations (countermovement jump – CMJ testing; squat jump -SJ testing; drop jump testing; repeat hop testing; and horizontal jump testing) using force plate methodology have become increasingly common in sport performance settings due to the high reliability of the test outcome measures, the ease-of-use, and the sensitivity for detecting deficits in athletes with ACL injury[45,47,60-62]. Vertical jump testing, such as the CMJ, SJ and drop jump, appear to be particularly powerful in helping to identify knee extensor strength deficits in athletes with

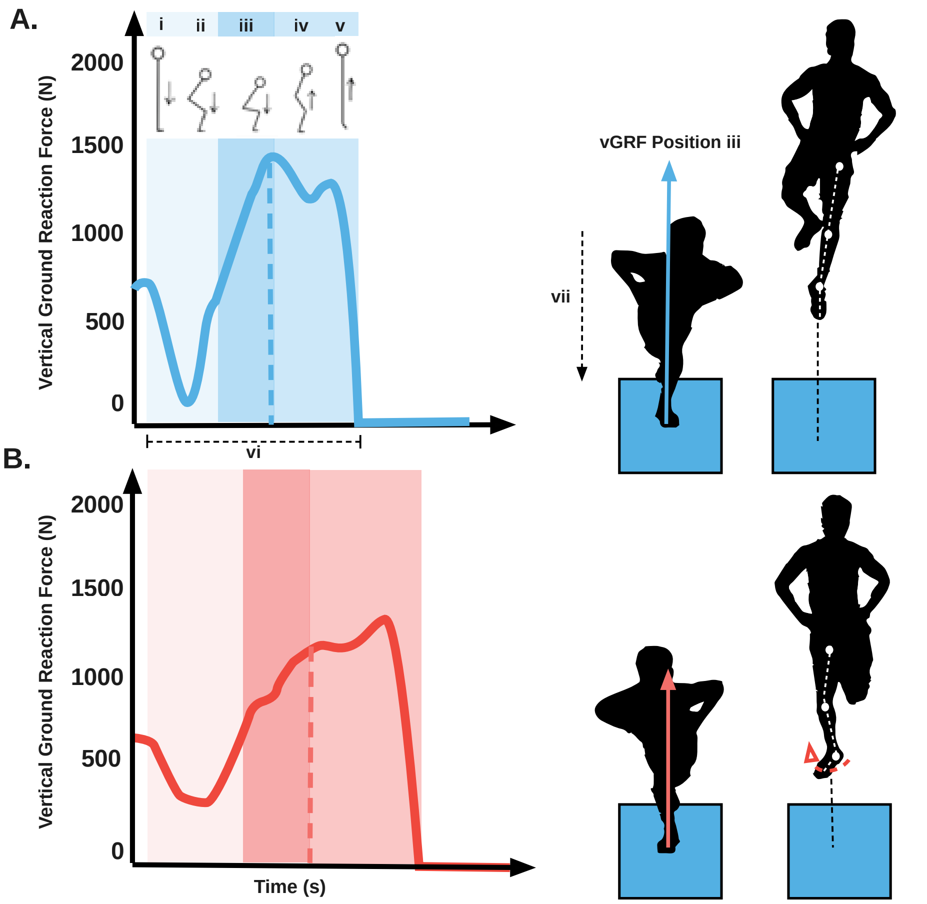

Figure 5: Case study example of the left vs. right force-time curves for an anterior cruciate ligament (ACL) injured athlete ~ 12 months post-surgery (Panel A: left non-injured limb – blue; Panel B: right ACL injured limb – red). The dark regions of the force-time curve show the eccentric deceleration phase with a reduced rate of force development on the injured side. Silhouettes show a reduced vertical ground reaction force (vGRF) at the end of the eccentric deceleration phase for the ACL injured limb (lowest position of the body centre of mass) compared to the left non-injured limb. Reduced knee extension angle, increased tibial external rotation angle and decreased jump height on the ACL injured limb compared to the left non-injured limb after takeoff are also shown. i=jump initiation; ii – downward descent; iii=eccentric deceleration phase; iv=propulsion phase; v=takeoff; vi=jump contraction time; vii=downward displacement of body centre of mass.

Table 1

Test	*Protocol*	*Common Outcome Measures*
Bilateral CMJ	*3-5 repetitions of a two-legged jump separated by 5-10 s. Ensure a stationary baseline force reading (i.e., minimum 1 s preferably 3-5 s) before each jump and at the start of the test*	*Vertical jump height; right and left concentric impulse; right and left eccentric deceleration impulse; jump contraction time; modified RSI (jump height/jump contraction time)*
Unilateral CMJ	*3-5 repetitions of a one-legged jump separated by 5-10 s. Ensure a stationary baseline force reading (i.e., minimum 1 s preferably 3-5 s) before each jump and at the start of the test*	*Vertical jump height; right and left concentric impulse; right and left eccentric deceleration impulse; jump contraction time; modified RSI (jump height/jump contraction time)*
Unilateral Drop Jump	*3-5 repetitions of a fast vertical jump preceded by a drop off a box of a standardized height; typically performed to minimize ground contact time and maximize vertical jump height*	*Vertical jump height; ground contact time; RSI (jump height/ground contact time); impulse; peak force; lower limb stiffness*
Unilateral Repeat Hop Test	*10-15 repetitions or 15 s timed hop test; typically performed to minimize ground contact time and maximize vertical jump height; a 5-jump mean value typically obtained from hops performed in the middle of the recording*	*Vertical jump height; ground contact time; RSI (jump height/ground contact time); impulse; peak force; lower limb stiffness*

Table 1: Common vertical jump force-time test protocols after anterior cruciate ligament (ACL) injury. CMJ=countermovement jump; RSI=reactive strength index.

ACL injury compared to horizontal jump testing[63,64]. Using a phase-specific analysis of the vertical ground reaction force (vGRF), as described in detail elsewhere[45], it appears that CMJ force-time asymmetries are graft-type specific[65,66], sensitive to severe traumatic knee injuries[62,66], and demonstrate a time-dependent pattern of recovery[46]. Reduced plyometric capacity, assessed using unilateral drop jump testing, has also been found to predict ACL reinjury in male high-performance athletes[32].

SSC function can be evaluated using various bilateral or unilateral vertical jump tests. In addition to quantifying performance outcome measures such as the vertical jump height, a kinetic analysis of unilateral and bilateral jumping permits an assessment of jump strategy, which has been shown to vary between non-injured and ACL injured athletes[45,62,67]. Figure 5 shows the unilateral CMJ force-time curves for an ACL injured athlete (~ 12 months post-surgery), which implicate deficits in specific and trainable neuromuscular capacities. Noticeable differences can be seen in the force-time curve of the injured side including a blunted eccentric deceleration RFD that

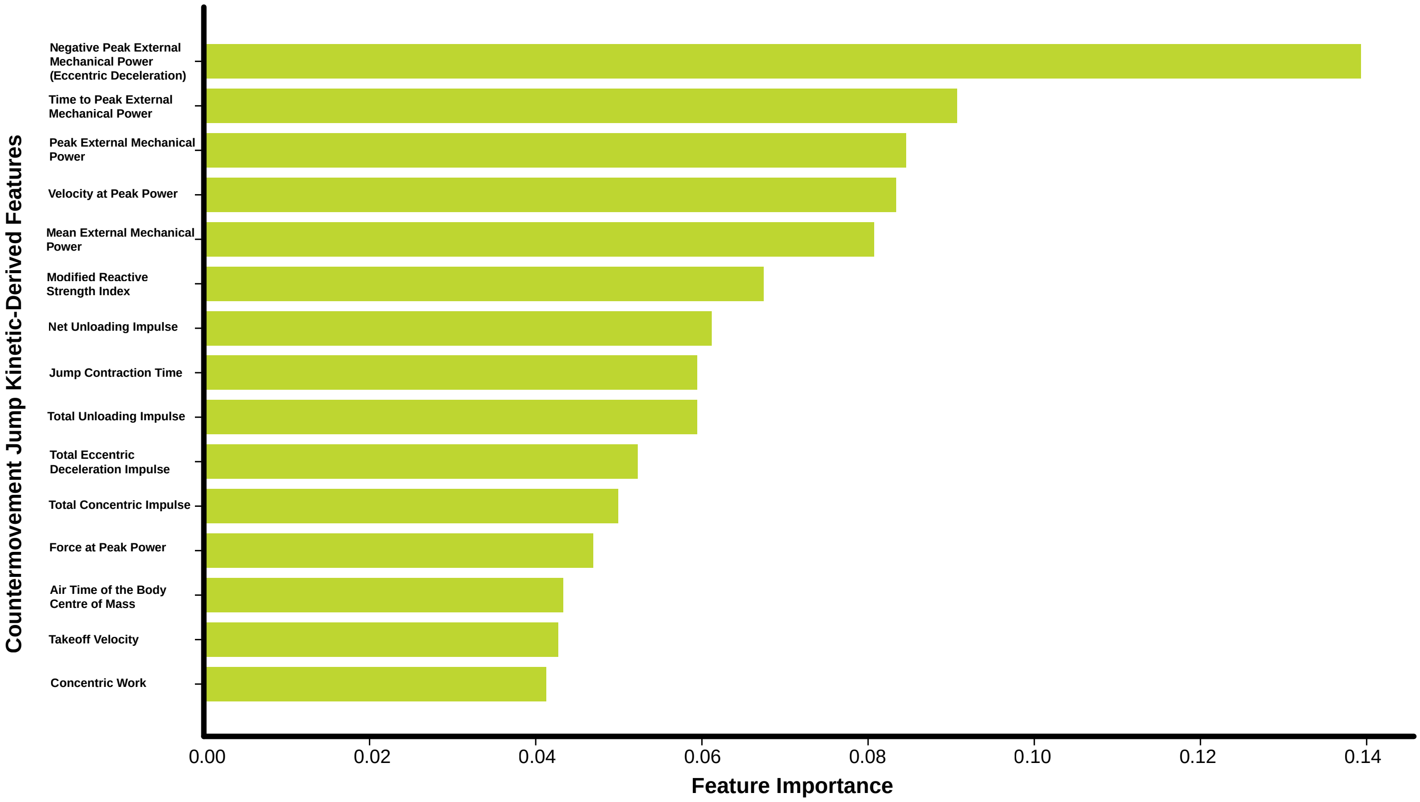

Figure 6: Random forest classification analysis showing feature importance for classifying athletes with and without a previous history of anterior cruciate ligament (ACL) injury. The random forest classification model identified athletes with a previous history of ACL injury with 97% accuracy (F1 score = 0.94).

corresponds with reduced knee flexion in the bottom position. This kinetic profile depicts an adopted movement strategy that may characterize a reduced contribution of the knee joint to the total mechanical work performed during the jump. Additionally, at the point of takeoff, a reduced knee extensor involvement leads to visible compensation strategies that are reflected in the CMJ force-time curve.

This case example, and recommendations available in the scientific literature[61,67], highlight the importance of using a phase-specific approach for evaluating jump strategy and jump performance in athletes with ACL injury. A phase-specific kinetic analysis is typically obtained by portioning the jump using the velocity of the body centre of mass (BCM) to identify the unloading phase (initiation of the downward displacement), the eccentric deceleration phase (termination of the downward displacement phase), and the concentric or propulsive phase[45,58,61,67] (Figure 5). In addition to quantifying the force-time characteristics over these phases using mechanical measures, such as the impulse obtained by time integration of the vGRF, the individual phase durations and total jump contraction time may also be important indicators of neuromuscular recovery after ACL injury. Table 1 provides an overview of common vertical jump testing protocols and outcome measures.

Selecting kinetic measures from CMJ testing that incorporate force plate methodology can be a daunting task post ACLR testing due to the sheer number of potential outcome measures[61,67]. To address this gap, a recent article highlighted three kinetic-derived measures (the downward displacement of the BCM, jump contraction time, vertical jump height) and two kinetic-derived ratios (lower limb stiffness = Δ vGRF/Δ BCM displacement – calculated over the eccentric deceleration phase; modified RSI = jump height/jump contraction time) for their utility in post-ACLR testing[67].

Machine learning, including feature analysis and classification methods, is a promising approach to streamline post-ACLR testing[68] and to assist with metric selection from vertical jump testing[69]. As an example of potential avenues to improve the selection of tests and metrics for ACL injured athletes, we performed a preliminary machine learning analysis of 600 bilateral CMJ testing sessions and 600 unilateral CMJ testing sessions from an associated longitudinal study examining ACL return to sport testing in athletes who were on average ~ 6 months post ACLR (University of Calgary Research Ethics Board: REB15-1094, REB14-2270). In alignment with previous published research[69], a random forest classification model was generated to predict athletes with a previous history of ACL injury from a cohort of non-injured university athletes (n = 256). Fifty-two commonly derived kinetic measures were used as inputs into the model, and it predicted with a 97% accuracy the athletes with a previous history of ACL injury (F1 score = 0.94) (Figure 6). The random forest classifier training protocol included, scaling the features, conducting a principle component analysis for dimensionality reduction, oversampling the ACLR class, and fitting the random forest classifier. A feature analysis (Figure 6) shows the highest ranked kinetic measures.

We identified kinetic-derived measures in addition to the recommendations provided by Bishop et al. (2022), including

Image: Illustration.

the negative peak external mechanical power (peak mechanical power in the eccentric deceleration phase), the time to peak external mechanical power in the propulsive phase, and the velocity at peak power (Figure 6). In agreement with Bishop et al. (2022), we also found that the jump contraction time, jump height, modified RSI, unloading impulse, eccentric deceleration impulse and concentric impulse ranked highly in the analysis (Figure 6). It must be mentioned that this was an exploratory analysis that is not without limitations. However, it may inform promising methodologies that can help practitioners and clinicians to streamline post-ACLR testing for monitoring explosive strength and SSC capacity. Longitudinal research, using a prospective design and more frequent testing (i.e., an athlete monitoring approach), is certainly needed to better understand the relationship between kinetic-derived jump measures, explosive strength capacity, ACL injury, ACL reinjury and return-to-sport readiness.

TRAINING EXPLOSIVE STRENGTH AND STRETCH-SHORTENING-CYCLE CAPACITY AFTER ACL INJURY

Understanding the physiological determinants of explosive strength and SSC capacity can assist in developing training progressions to restore neuromuscular function after ACL injury. In general, a progressive criteria-based approach is recommended, which can be used as well for addressing explosive strength and SSC capacity after ACL injury[50]. To address the comorbidities of ACL injury including reduced anabolic response of knee extensor muscle along with the potential for impaired MTU function, increasing muscle hypertrophy and tendon strength/stiffness should be a top priority. In addition to conventional hypertrophy loading parameters, low load (30-60% of 1 repetition maximum – RM), high repetition (15-30 RM) strength training augmented with blood flow restriction may be beneficial[70]. Heavy strength training (>70% of 1 RM) is beneficial for tendon stiffness[71], which is important for increasing explosive strength. Heavy strength training (< 6 RM) causes increased motor unit discharge rate and motor neuron excitability, which in turn also supports the retraining of explosive strength[7,72,73]. Mid- to late-stage strength training should prioritize fast force production using methods such as ballistic training, burst-like isometrics and plyometrics, which evoke robust improvements in RFD and SSC function[22,74]. Table 2 provides a strength training progression to target explosive strength and SSC capacity after ACL injury.

CONCLUSION

In conclusion, the aim of this paper was to highlight the importance of assessing the explosive strength capacity of the lower limb muscles along with SSC function in the vertical jump in athletes who are recovering from ACL injury. It was demonstrated that there are unique neuromuscular determinants of explosive muscle strength and SSC function, and that recovery of these physiological capacities differs from the results of assessing just

TABLE 2

Target Adaptation	*Example Training Methods*	*Example Training Parameters (S – Sets, R – Repetitions)*	*Stage Post-Op*
Muscle Hypertrophy	*Low Load (Momentary Failure)* *Hypertrophy Loading*	*S: 2-4 R: 15-30 @30-60% 1RM* *S: 3-4 R: 5-12 @ 70-85% 1RM*	*Early (0-3 months)*
Maximal Strength / Tendon Stiffness	*Heavy Strength Training*	*S: 3-5 R:1-6 @ 85-100% 1RM*	
Maximal Muscle Power	*Strength-Speed*	*S: 4-6 R:5-8 @20-60% 1RM*	*Mid (3-5 months)*
Explosive Strength	*Ballistic Training* *Burst-Like Isometrics* *Fast Eccentrics*	*S: 3-6 R: 3-6:10-50% of 1RM* *S: 3-6 R: 5-10: @ 70-100% MVC* *S: 3-6 R: 3-6 @ 0-25% 1RM*	
SSC Capacity	*Long GCT Plyometrics (>250 ms)* *Short GCT Plyometrics (<250 ms)*	*S: 3-6 R: 6-20 @ Bodyweight* *S: 3-6 R: 3-6 @ Bodyweight*	*Late (> 6 months)*

Table 2: Strength training progression and loading parameters to address explosive strength and stretch-shortening-cycle (SSC) capacity deficits after ACL injury. GCT=ground contact time.

maximal muscle strength after ACL injury and ACLR in isolation. Practitioners and clinicians can use explosive strength and SSC assessments to identify lagging neuromuscular function(s) in athletes with ACL injury with the goal of prescribing targeted strength training protocols to reduce deficits and to identify athletes who might be at increased risk for ACL reinjury. Taken together, explosive strength and SSC testing may be used to provide sensitive mechanical biomarkers of post-ACL injury recovery that can complement existing return-to-sport and return-to-performance testing practices that include measures of maximal muscle strength, psychological readiness, and sport-specific movement biomechanics.

References
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