Testing Limb Symmetry and Asymmetry after ACL Injury: Four Considerations to Increase its Utility

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Abstract

Anterior cruciate ligament (ACL) injury occurs frequently in sport and surgical reconstruction (ACLR) is often recommended to restore knee joint stability. To guide rehabilitation and determine return to sport readiness, practitioners have used a long-standing practice of calculating the limb symmetry index (LSI) in various functional, biomechanical, and strength tests to compare the injured limb to the non-injured contralateral limb. However, the evidence in support of the LSI calculation to quantify rehabilitation status and return to sport readiness is mixed. We synthesize scientific literature on the LSI calculation and discuss potential reasons for the mixed evidence and limitations. We present four considerations to improve the utility of the LSI calculation including: (1) the importance of establishing the right benchmark of recovery such as the pre-injury contralateral limb or a sport-specific non-injured control benchmark; (2) strategies to manage the high variation in movement asymmetry calculations and the importance of quantifying the intra-subject variability for the component parts of the LSI; (3) the evidence for assessing the movement strategy alongside performance when using the LSI; and (4) how a sport-specific envelope of function can be used to inform post-ACL injury testing that incorporates the LSI.

Key words: asymmetry, return to sport, return to play, strength testing, hop testing, injury prevention

Introduction

A non-contact anterior cruciate ligament (ACL) rupture is among the most severe traumatic knee injuries suffered by athletes, and surgical reconstruction (ACLR) is often recommended to restore knee joint stability followed by an extensive period of rehabilitation (18). Not only must rehabilitation address the neurophysiological injury arising from the ACL rupture itself (35), but also the co-morbidities from the surgical technique (22), the combined injuries to other knee structures such as the articular cartilage and menisci (28), thigh muscle strength loss (22), and the potential fear of reinjury (2). Despite rehabilitation, the risk of a second ACL injury to either the same limb or contralateral limb is high (46,47,54), especially in adolescent and early-adult athletes (40,54), who demonstrate a 30-40x greater risk for ACL injury compared to matched controls without a history of ACL injury (54) Furthermore, athletes have expectations that a return to competitive sport is probable (16). However, a little over 50% of athletes will return to competitive sport (1) and they will likely display reduced sport-specific performance statistics (e.g., points, goals), especially in field and court sports (41).

Given the elevated risk for reinjury and the long-term performance impairments resulting from ACL injury, post-injury neuromuscular testing using a criteria-based approach is recommended to guide rehabilitation and determine return to sport readiness, including tests for muscle strength, power and lower limb function (44). A long standing clinical practice to quantify the functional status of the injured limb in these tests is to calculate a limb symmetry index (LSI) (i.e., LSI (%) = (injured limb/non-injured limb) x 100) or an asymmetry index (AI) (e.g., AI (%) = (non-injured limb – injured limb)/(non-injured limb) x 100); these are ratios that define the function of the injured limb compared to the function of the non-injured contralateral limb (3,10,45). Dating back

40 years (10), the LSIs of non-injured and ACL injured participants during various single leg hop tests and isokinetic dynamometry have been described to establish benchmarks of sufficient rehabilitation after ACLR with a common threshold being an LSI > 85% (3). Others have recommended a more stringent LSI threshold, notably an LSI > 90% (20). However, what defines sufficient rehabilitation after ACL injury as it pertains to reducing ACL reinjury and increasing performance readiness is not well defined, and the scientific evidence in support of the LSI calculation, especially during single leg hop testing is equivocal (30,52).

Nevertheless, neuromuscular testing after ACL injury is recommended to inform training and guide rehabilitation (19). In this manuscript, we present four considerations to improve the utility of the LSI calculation from biomechanical and performance-based testing (including bilateral asymmetry testing) to quantify recovery after ACL injury in athletes. First, we present recent evidence highlighting the potential for contralateral limb detraining after ACL injury, and the need for careful consideration on the benchmark limb when using the LSI calculation. Second, we distinguish between the goal of achieving symmetry in lower limb strength capacity (i.e., having two limbs with symmetrical strength) versus the concept of quantifying movement asymmetries (e.g., change of direction asymmetries), which tend to be variable and task dependent in a healthy control population. Third, we review recent scientific evidence in an ACL injured athlete population showing some of the limitations of the LSI method for predicting ACL reinjury and the importance of quantifying biomechanical measures and movement strategy metrics in change of direction and jumping tasks when determining return to sport readiness. Finally, we introduce a previously published concept known as the 'envelope of function', which describes functional recovery of the ACL and tissue tolerance to load after ACLR (14). We provide suggestions for applying the envelope of function in the context of post-injury strength testing and athlete monitoring, to complement or replace the LSI method when it comes to assessing and monitoring return to sport readiness after ACL injury. While this article examines the use of the LSI calculation in the context of ACL injury, similar considerations may exist for other lower extremity injuries. We also highlight recent evidence that may improve post-ACLR testing in general for practitioners and researchers working with athletes who are at risk for traumatic knee injury.

Consideration 1: How to Best Determine the Benchmark of Recovery?

The conventional use of the LSI calculation assumes that the post-injury contralateral limb is an adequate benchmark of return to sport readiness, yet both the injured limb and the non-injured contralateral limb are at risk for strength loss and functional impairment after ACL injury (17,39,43,53). Consequently, contralateral limb strength loss can contribute to a falsely elevated LSI (e.g., athlete achieves an LSI threshold > 90% due to a weakened contralateral limb), and if missed, could result in an athlete being prematurely cleared to return to sport while they are still exhibiting functional deficits (43,53). The same pitfall has been shown with the hamstring:quadriceps (H:Q) strength ratio where an elevated ratio can be found after ACL injury due to quadriceps strength impairment (smaller denominator in the ratio), not increased hamstring strength (24). This raises an important question as to whether the goal of rehabilitation after ACL injury is to improve symmetry or to increase the functional capacity of both limbs in preparation for a return to sport. Incidentally, this might be one of the factors underpinning the lack of scientific evidence in support of conventional post-ACLR testing methodologies that rely on the LSI calculation (12).

In practice, the goal of rehabilitation after ACLR is not to achieve limb symmetry *per se*, but instead to ensure that an athlete has sufficient strength and functional capacity to meet the sport-specific demands (20,29,30,52). For example, a prospective study examined the relationship between thigh muscle strength, lower limb biomechanics, and contralateral ACL reinjury in 1045 high level athletes and found reduced quadriceps strength LSI (i.e., LSI < 85%) in both groups, but higher absolute strength for the participants who did not sustain ACL reinjury (30). Further, no relationship was found between ACL reinjury and conventional LSI testing in single leg hopping. Taking this one step further, a previous meta-analysis has also shown that passing conventional functional tests that incorporated the LSI (most commonly quadriceps strength testing and single leg hop for distance testing) was associated with a > 200% increased risk for contralateral ACL reinjury (52).

Collectively, these studies highlight the importance of tracking the function of both limbs independently alongside the LSI to ensure an athlete is not prematurely cleared to return to sport with persistent neuromuscular deficits (5). However, it may also be prudent to choose an alternative benchmark to the post-injury contralateral limb that is not prone to injury dependent effects (53) (Figure 1). For example, pre-injury baseline neuromuscular testing obtained from the injured athlete can be used as a benchmark of rehabilitation status, assuming the athlete exhibited acceptable physical capacities to begin with (12,26) (Figure 1B). A recent study also proposed that determining an "estimated pre-injury limb capacity" was a more sensitive benchmark of rehabilitation status and a better predictor of ACL reinjury compared to the post-injury contralateral limb (53). Advantages of determining an estimated pre-injury limb capacity value are that it is insensitive to injury effects, and thus does not require pre-injury baseline testing.

However, in settings where baseline strength testing is routine, an alternative to estimating the strength requirement is to obtain normative biomechanical and strength testing data from a comparative non-injured control group that can be used as a functional benchmark for both the injured limb and non-injured limb after ACLR (25) (Figure 1A). Baseline strength testing before injury, including obtaining pre-injury control data from athletes who eventually go on to suffer ACL injury may provide new insights on better benchmarks that employ the LSI or AI calculations although it should be recognized that this type of data may not be readily available in a clinical or community-based setting. Table 1 highlights these potential benchmarking approaches for ratios aimed at quantifying functional recovery after ACL injury, including providing their respective advantages and disadvantages.

Insert Table 1 Here

Given the importance of assessing return to sport readiness with a criteria-based approach, testing should be multi-faceted and include a variety of maximal strength, explosive strength, and biomechanical assessments (9,26,44).

Insert Figure 1 Here

Consideration 2: Movement Asymmetries are Task Dependent and Variable

The practice of calculating an LSI for performance-based testing (e.g., single leg hops for distance) or strength testing (e.g., isokinetic knee extension strength) aims to measure the limb capacity where a higher ratio or more symmetry (i.e., LSI > 90%) is desired. Conversely, high symmetry is not necessarily observed in normal human biomechanics in more complex multi-joint movements like running, walking, and change of direction maneuvers. Instead, movement asymmetries are often found to be variable, relatively larger, and task dependent over multiple movement cycles in non-injured humans (21). This demonstrates a marked difference from assessing performance-based outcomes using the LSI calculation and necessitates a novel approach for quantifying biomechanical movement asymmetries. One key difference is that movement asymmetries are often quantified using an asymmetry index calculation (AI (%) = (non-injured limb – injured limb)/(non-injured limb) x 100) that maintains the limb directionality of the asymmetry (23). Another major difference between the LSI calculation for strength or performance testing and biomechanical movement asymmetries is that side-to-side movement asymmetries are often measured over multiple movement cycles where the average asymmetry and variation in the resultant asymmetry are both of interest (15,23). Movement variability, for example, has been proposed as a hallmark of normal function while reduced variability has been associated with injury and impairment (42,49). A key aspect of quantifying movement asymmetries is to distinguish potential injury effects from normally occurring fluctuations in asymmetry due to performance- or movement-variability. The relevance of decreasing movement asymmetry to improve sport performance capacity is also unclear (4,8), meaning that unlike the LSI in performance-based testing where more symmetry is desirable, less movement asymmetry may not equate to better sport performance. Additionally, movement asymmetries appear to be task specific and often do not correlate between tests in a non-injured population (6).

Given the complexity of movement asymmetries and their relationship with normal human movement and performance, it becomes evident that different considerations be accounted for when determining return to sport readiness after ACL injury using asymmetry index calculations. After ACL injury, bilateral asymmetries in movements such as jumping may be more prognostic for recovery and performance capacity with time after injury, increasing the relevance for quantifying recovery and return to sport readiness (27,48). Further, statistical relationships are observed between lower limb kinetic asymmetries in the vertical jump, lower limb quadriceps strength asymmetries (37), and lower limb muscle mass asymmetries (23) suggesting a potential underpinning, injury-driven physiological mechanism(s) for increased bilateral asymmetry after ACLR. Nevertheless, while the practice of assessing movement asymmetry (e.g., bilateral vertical jump kinetic and kinematic asymmetries) after ACLR has become more popular (23,48,50), it is important to be aware of the variability and task-specificity of movement asymmetries. Considering these challenges, we propose three key recommendations to enhance the relevance and accuracy of bilateral movement asymmetry testing after ACL injury:

(1) establish the intra-subject reliability of the component parts for the asymmetry calculation – for example, when measuring vertical jump kinetic asymmetries, consider measuring the right and left limb intra-subject reliability for the kinetic measure in question in order to determine when a change of interest has occurred in the composite asymmetry index,

(2) measure movement asymmetries over multiple movement cycles and testing sessions to detect a pattern of high movement asymmetry and account for the higher variation,

(3) use a variety of sport-specific movement tests to better quantify relevant bilateral asymmetries for the context at hand, bearing in mind that asymmetry in one test may not correlate to asymmetry in another test (36) – for example, a practitioner evaluating a soccer player after ACL injury may want to quantify biomechanical change of direction asymmetries during 90° and 180° cuts, along with left and right single leg vertical jump asymmetries to better characterize the sport-specific demands (50).

Finally, as with the practice of pre-season baseline testing or acquiring pre-injury testing data from the injured athlete, measuring movement asymmetries over multiple testing sessions in a longitudinal manner may only be possible in high performance team settings, posing a challenge for clinicians or in community-based settings. Consequently, more research is warranted to address this gap.

Consideration 3: Measure Task Performance and the Movement Strategy

A key limitation reducing the utility of the LSI method to quantify return to sport readiness after ACL injury is that the LSI calculation typically involves a performance-based outcome measure (e.g., the distance jumped in a single leg hop test) and neglects the movement strategy (i.e., how the movement was executed) (55). For example, in a single leg hop for distance test, the forward projection of the body's centre of mass (BCM) permits the relatively stronger hip extensor muscles of an ACL injured athlete to mask deficits of weakened knee extensors allowing them to achieve a symmetrical performance (jump distance) at the expense of an asymmetrical movement strategy (33,51,55). This can be accounted for by incorporating vertical and horizontal jumping in post-injury testing, along with a biomechanical analysis of the movement strategy in jumping and change of direction maneuvers in athletes with ACL injury (34,55). Examples of jump-related movement strategy measures include the downward displacement of the BCM, the ground contact time during drop jumping or the time to takeoff during countermovement jumping, the reactive strength index (RSI = jump height/ground contact time) and lower limb stiffness (lower limb stiffness = Δ force/Δ BCM displacement), which have also been extracted from single leg hop for distance testing (7,11).

The limitations of employing the LSI calculation only with performance outcomes and neglecting the movement strategy highlight the requirement for new approaches to quantify recovery after ACL injury. Emerging research supports this idea and applying these strategies in practice has already begun to yield promising results. A recent study, for example, highlighted that reduced lower limb stiffness, increased ground contact time and a lower RSI obtained from the drop jump predicted ACL reinjury in high level athletes (30). Furthermore, the countermovement jump strategy in the unloading phase (downward descent of the BCM), braking phase (deceleration phase of the BCM) and propulsive phase (upward ascent of the BCM) and the associated bilateral kinetic asymmetries, along with biomechanical movement asymmetries in change of direction maneuvers have been shown to differ between graft type in ACLR athletes (37,38). Additionally, biomechanical asymmetries in jumping and change of direction maneuvers have also been shown to persist after 9-months of rehabilitation, while performance-based asymmetries had minimized in high-level athletes (31,32). To improve the utility of the LSI calculation, therefore, assessments that examine the movement strategy using a progressive criteria based approach is recommended to determine return to sport readiness after ACLR (44). With the limitations of the current methods in mind, we suggest moving towards a more nuanced evaluation such as biomechanical analysis of sport-specific movements informed by a needs analysis of the athlete that can disentangle task performance from the movement strategy and assist with identifying an athlete who is insufficiently prepared to return to sport (31,32). As mentioned in Consideration 2, asymmetries in the movement strategy should also be measured across multiple movement cycles with consideration for the magnitude of the asymmetry, the directionality, and the variation of its component parts.

Consideration 4: Assess Both Limbs Across a Sport-Specific Envelope of Function

The concept of the *envelope of function* was introduced by Dye (1996) to address the biological complexity of post-ACLR recovery and elucidate factors that contribute to a patient's functional recovery (13,14). Importantly, this model is underpinned by the notion that repairing disrupted anatomical structures through surgery to increase joint stability does not equate with restoring the functional capacity of a joint or its tolerance for load. Surgical repair of a ruptured ACL, tissue healing and restoring the knee joint's functional capacity are not the same biological processes (14). The original envelope of function model also depicts time-dependent adaptations in tissue structural tolerance throughout rehabilitation, emphasizing the need for supraphysiological loads to promote adaptation that are above the zone for tissue homeostasis but below the zone for tissue failure (Figure 2A). The envelope of function is a highly useful concept that quantifies joint function with respect to the requisite load capacity defined by what would have been the full pre-injury functional capacity (14), providing a strong alternative to the LSI calculation and the convention of using the post-injury contralateral limb.

Therefore, the envelope of function introduces at least three crucial considerations for practitioners: (1) What was the pre-injury sport-specific functional capacity of the ACL injured athlete across a load continuum? (2) What is the athlete's present functional capacity and load tolerance? (3) What load is required to promote positive tissue adaptation to restore the required envelope of function? We also propose applying this model to both limbs after injury to define the required envelope of strength and function (Figure 2B). Furthermore, in high performance sport settings where athlete monitoring practices are feasible, the envelope of function can be applied to monitoring the work capacity envelope (Figure 2C). Taken together, we propose that the envelope of function approach, especially in the context of expansive lower limb neuromuscular testing and athlete monitoring, provides a more sophisticated benchmarking method for quantifying return to sport readiness and addresses many of the previously discussed limitations of the LSI calculation that incorporate performance-based testing and arbitrary thresholds (e.g., LSI > 90%).

While the envelope of function was first introduced in the scientific literature as a concept related to tissue structural tolerance and adaptation in response to load (Figure 2A), current biomechanical and strength testing methodologies in sport (Figure 2B) along with on-field load tracking (Figure 2C) allow practitioners to define a sport-specific load continuum objectively. This has the potential to increase the utility of the LSI calculation after ACL injury, especially if a functional benchmark is used other than the post-injury contralateral limb (Figure 2). Assessing the functional capacity of an athlete with ACL injury across a load continuum is also consistent with emerging scientific thinking to incorporate broad-based multi-faceted neuromuscular testing after ACL injury to guide rehabilitation and support return to sport decision making (9,44).

As an illustrative example, an offensive lineman in American football who requires high levels of lower limb maximal strength and short-range change of direction maneuverability may have an envelope of function that is defined predominantly by high-force assessments (e.g., isometric squat testing, loaded jumping) and bilateral change of direction tests involving back pedaling and side stepping. In contrast, a female soccer player not only requires maximal strength but also explosive strength, repeat sprint capacity, open field change of direction maneuverability, and muscle endurance to cover large distances at high speeds over the course of a game. Consequently, the envelope of function for a soccer player with an ACL injury might incorporate a range of vertical jump testing, change of direction maneuvers and on-field external load monitoring in addition to lower limb maximal strength testing (50). While the envelope of function uses the pre-injury functional capacity as the target benchmark (13), practitioners should only consider this if the ACL injured athlete displayed sufficient physical capacity before their injury. Alternatively, practitioners can build an envelope of function from a non-injured control group to account for the potential effects of ACL injury on the non-injured contralateral limb. Additionally, as described by Dye et al. (14), the envelope of function incorporates a time-dependent component and the concept of progressive overload both in terms of the loading intensity and volume (Figure 2A). Consequently, the envelope of function must consider a progression from low load/low impact movements with time towards high intensity/high impact demands. Finally, longitudinal monitoring of the LSI across the envelope of function after ACLR may provide a higher time resolution about the progression towards, or regression away from the sport-specific functional requirements (25,26,50).

Insert Figure 2 Here

Conclusion

After ACL injury, functional strength testing is recommended with a preponderance of the scientific and clinical literature recommending the use of the LSI calculation that compares the injured limb to a benchmark, typically the post-injury contralateral limb. Emerging research questions this approach. Therefore, we have provided four recommendations to increase the utility of the LSI calculation (including bilateral movement asymmetry testing) after ACL injury, especially in high performance sport settings where athlete monitoring is readily performed. Recent scientific evidence highlights the importance of choosing the right benchmark for the LSI calculation given the potential for ACL injury to lead to contralateral limb strength deficits and to account for the elevated risk of contralateral ACL injury. We propose a pre-injury benchmark from the injured athlete if it was sufficient in the first place or a non-injured control benchmark from a representative group. It is also clear that achieving limb symmetry on a performance-based strength test should be approached differently than assessing biomechanical movement asymmetries in more complex movements. The fact that movement asymmetries are variable and task dependent suggest differences in terms of how practitioners should approach quantifying limb symmetry in strength capacity vs. movement asymmetries in running, jumping, and changing direction. Even though the LSI calculation for performance-based testing is commonplace, we stress the importance of tracking the performance of each limb independently in addition to the index. In order to quantify biomechanical movement asymmetries, multiple movement cycles and testing sessions may be needed to detect an elevated movement asymmetry and manage the high variation in typical outcome measures used in sport performance and rehabilitation settings. Practitioners should also be mindful that movement asymmetries are task-specific highlighting the need to use a multi-pronged approach to post-injury biomechanical testing aimed at determining return to sport readiness. Finally, given that surgical repair does not equate to restoring functional capacity, the envelope of function concept can assist with developing an understanding of the sport-specific load requirements that can be used to monitor athletes with ACL injury as they transition back to sport and performance. We propose applying the envelope of function concept to the muscular strength envelope and the sport-specific workload envelope.

Future research is needed to support clinicians and practitioners who do not operate in high performance sport settings, especially for the clinic or community sport environment. Pre-injury baseline data, non-injured control benchmarks, and athlete monitoring practices may be highly limited in these sentences. Researchers can address these gaps, including providing a better understanding of the variation in biomechanical movement asymmetries, to assist practitioners in the clinic or community sport environment with return to sport decision making. The current body of scientific evidence that incorporates longitudinal biomechanical testing and loading monitoring practices as it pertains to return to sport testing after ACL injury is also in its infancy. Naturally, this highlights the requirement for researchers to carefully study these relationships to provide evidence-based recommendations to sport stakeholders that are feasible and accurate. Collectively, future research should embrace a holistic testing approach and emphasize knowledge translation to sport stakeholders to promote a safer and more performance-ready return to sport transition after ACL injury.

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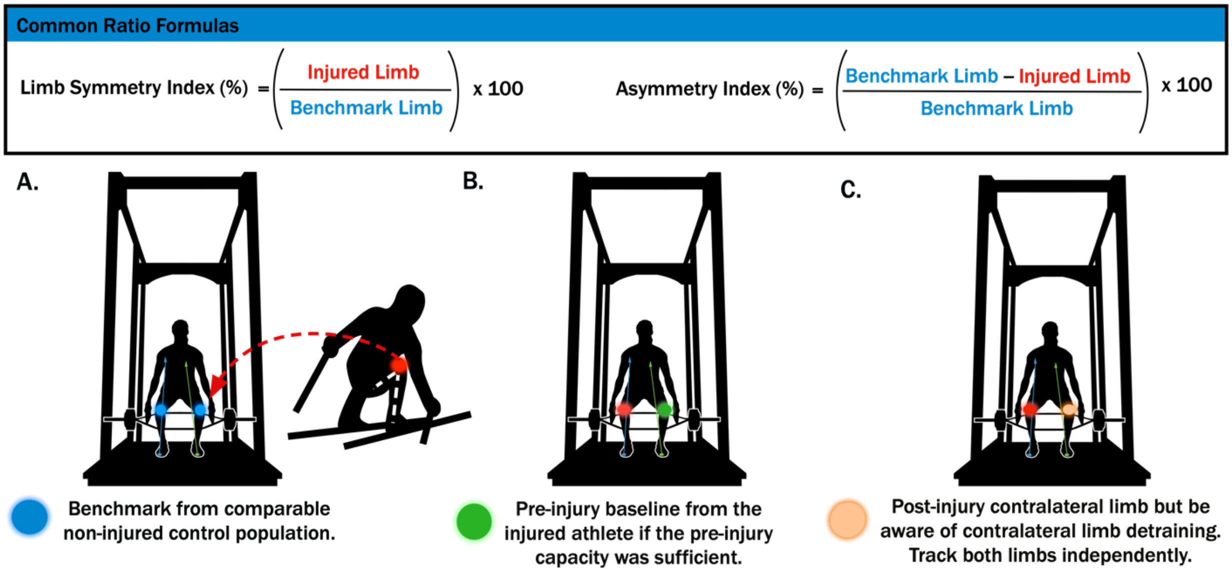

Figure 1. Considerations for choosing a benchmark for the limb symmetry index and asymmetry index calculations. Panel A depicts comparing the injured limb to a benchmark from a non-injured control population or an estimated pre-injury benchmark. Panel B shows a pre-injury benchmark from the injured athlete. Panel C depicts the convention of using the post-injury contralateral limb, but caution is warranted given the effects of anterior cruciate ligament (ACL) injury on the functional capacity of the non-injured contralateral limb.

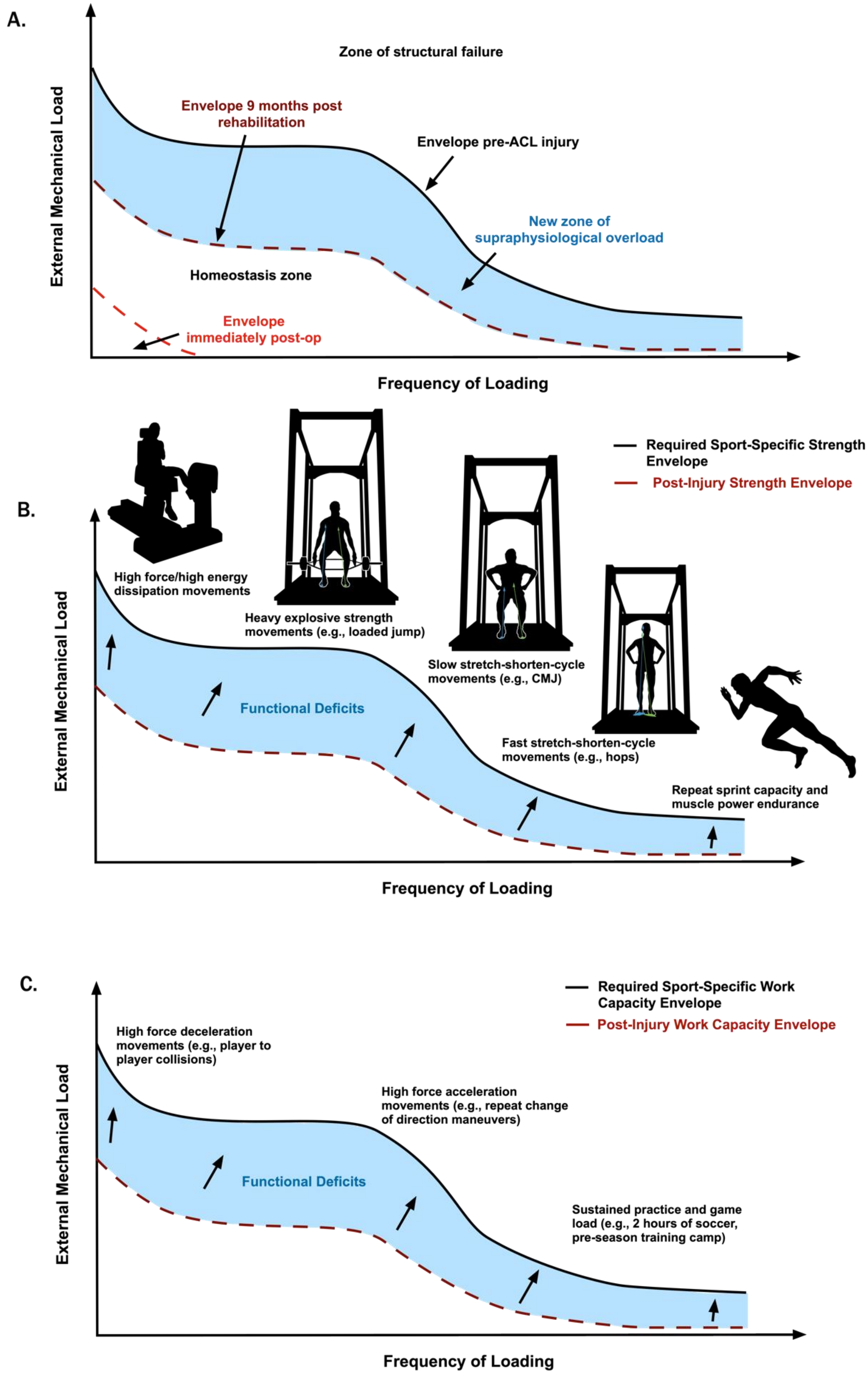
A.
Zone of structural failure
Envelope 9 months post rehabilitation
Envelope pre-ACL injury
New zone of supraphysiological overload
Homeostasis zone
Envelope immediately post-op
External Mechanical Load
Frequency of Loading
B.
Required Sport-Specific Strength Envelope
Post-Injury Strength Envelope
High force/high energy dissipation movements
Heavy explosive strength movements (e.g., loaded jump)
Slow stretch-shorten-cycle movements (e.g., CMJ)
Fast stretch-shorten-cycle movements (e.g., hops)
Repeat sprint capacity and muscle power endurance
Functional Deficits
External Mechanical Load
Frequency of Loading
C.
Required Sport-Specific Work Capacity Envelope
Post-Injury Work Capacity Envelope
High force deceleration movements (e.g., player to player collisions)
High force acceleration movements (e.g., repeat change of direction maneuvers)
Sustained practice and game load (e.g., 2 hours of soccer, pre-season training camp)
Functional Deficits
External Mechanical Load
Frequency of Loading

Figure 2. Panel A provides an overview of the envelope of function concept adapted from Dye et al. (14) and depicts the post-operative (post-op) envelope, the envelope at 9 months post-surgery and the required functional envelope. The zones of tissue homeostasis and tissue failure are shown. Panel B shows the concept of the envelope of function for muscle strength testing and external load monitoring in Panel C. The envelope of function incorporates an objective baseline and can be applied to both limbs after injury to ensure sufficient recovery and preparedness for a return to sport *Note: CMJ = countermovement jump ACL = anterior cruciate ligament.*

Table 1: Advantages and disadvantages of common benchmark methods after injury.

Method	Advantages	Disadvantages	Setting
Estimated pre-injury benchmark	Insensitive to the injury and does not require baseline testing	Estimation of the functional or strength requirement	Clinical or community setting
Non-injured control benchmark	Insensitive to the injury and sport-specific	Requires baseline testing from a non-injured population	High performance sport environment or collegiate sport
Pre-injury benchmark from the injured athlete	Insensitive to the injury and athlete-specific	May underestimate functional requirements if athlete was not sufficiently prepared to begin with	High performance sport environment or collegiate sport
Post-injury non-injured contralateral limb	Readily obtained in the post-injury testing environment	Post-injury contralateral limb is sensitive to detraining effects and there is a high risk of contralateral limb injury	Clinical or community setting