

IS IT TIME TO CHANGE HOW WE ASSESS FUNCTIONAL PERFORMANCE FOLLOWING ACL RECONSTRUCTION?

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INTRODUCTION

Optimal criteria to guide successful rehabilitation and return to sport (RTS) following ACL reconstruction (ACLR) remain unclear. While a minimum time-period post operatively is required to allow for sufficient biological recovery¹, there has been a progressive shift towards a criterion-based approach². Most common criteria for RTS following ACLR include various combinations of isokinetic strength or ratios of the quadriceps and hamstrings, or a series of single leg hops to ‘discharge’ athletes for RTS.

There is some evidence that indicates passing a battery of assessments for RTS, including strength and hop tests, reduces the risk of re-injury^{3,4}. However, recently the validity of these protocols has been

questioned^{5,6} with hop tests in particular shown to have low sensitivity for the identification of compensatory movement patterns⁷. More comprehensive appraisals of functional performance and movement strategies used by athletes following ACLR during physical performance tasks are warranted. This article provides a brief overview of the current practice and proposes some potential limitations that could be addressed to enhance the efficacy of assessment protocols and optimize decision making for athlete readiness to RTS safely following ACLR.

Where did the current tests come from?

Hop testing was first cited in the early 1980’s with a number of papers espousing their use to evaluate closed chain performance in

athletes with ACL injury^{8,9}. A limb symmetry index (LSI) ratio (sum of the involved leg / uninjured leg x 100) was proposed to assess the likelihood of a ‘functional abnormality’ in the ACL reconstructed knee. These early studies have helped to shape current guidelines, providing an objective measure for use in evaluating performance during RTS testing.

The adoption of these tests is likely due to their practical utility and ease of administration. Objective decision ‘regarding restoration of function’ could be made by directly comparing the reconstructed and un-involved leg, with LSI scores greater than 90% suggested as a clinical criterion to ‘pass’ and subsequently complete rehabilitation^{10,11}. However, several concerns have recently been raised

regarding the efficacy of isolated strength or hop protocols used in current RTS assessments following ACLR. While no test is without limitations, the following section outlines some pertinent considerations that can help ensure that clinicians interpret data, particularly limb to limb symmetry outcomes with the appropriate level of caution.

How valid is a limb symmetry index?

To calculate limb symmetry, the un-injured limb is used as an index or reference benchmark during rehabilitation. Most often the contralateral uninjured limb is subject to progressive detraining and load exposure that will underlie significant strength and function loss that parallels, albeit to a lesser extent the reconstructed limb. In addition, fear or lack of motivation can also be apparent, raising concerns that athletes, consciously or subconsciously may be able to manipulate test performance on their contralateral reference limb to mask residual deficits on the reconstructed limb, expediting their progression to RTS. Thus, we are correct to question if the non-injured limb provides the ideal reference measure of the athlete's true functional capacity. For example, reduced absolute hop distance deficits have been shown on both the involved and uninvolved limb following ACLR in comparison to healthy matched controls or preoperative values^{12,13} for up to 24 months' post-surgery¹⁴. Similarly, limb symmetry can be achieved by hopping shorter distances on the un-involved leg compared to asymmetric patients, and healthy matched controls¹³. Thus, we also need to consider the absolute performance and not just symmetry between-limbs. This poses a hypothetical question – would you prefer a symmetrical 'weak' athlete or an asymmetrical 'strong athlete'? While speculative, stronger athletes may be better able to tolerate the demands of training and competition and while increasing symmetry is likely important, this should not be achieved at the detriment of overall physical development.

A practical strategy (in the absence of pre-injury data) is to measure the contralateral limb preoperatively, with the aim of achieving their pre injury capacity. Using this approach, only 29% of patients met hop distance criteria (90% LSI) at the point of RTS when using preoperative distance as the comparative measurement, versus



Figure 1: Standard battery of 4 hop tests used to assess readiness to return to sport after ACL injury and reconstruction.

57% when using the non-injured limb post-operative performance as the index measurement¹⁵. When pre-operative data are not available, normative values from related populations may also be beneficial to guide absolute functional capacity. In addition, it is advised to report symmetry and relative hop distance performance trajectory on each limb through the later stages of rehabilitation to give the clinician a more accurate benchmark and estimation of the athlete's state of readiness for RTS. The absence of maintained trajectory of absolute performance towards contralateral pre-surgery measures or population specific normative value would highlight a potential marker for a clinician to refocus late stage rehabilitation.

Do we need numerous tests that measure similar things?

The primary 4 hop tests used as part of a RTS test battery require horizontal propulsion and displacement of the centre of mass, with ¾ including a rebound component (figure 1). Individually, the hop tests show poor sensitivity in their ability to identify limb to limb deficits.^{16,17} However, using all 4 tests as a 'battery' appears to be no greater than using just 2¹⁷. Additionally, there appears to be no 2 hop tests that when performed together, showed greater sensitivity

compared to any other test combination. Overall, the evidence suggests that using all 4 tests simultaneously is likely not necessary to detect abnormality. The inclusion of more tests that measure similar constructs increases the inherent error associated with execution which comes from many sources (athlete fatigue, motivation, tester error etc.). Reducing the volume of these tests also provides additional time to examine other important constructs which can guide the clinician regarding the function of their athlete. Further investigation is warranted to determine if an optimal combination of tests exists that provides the clinician with the most insight into the athlete's state of readiness for safe RTS.

Vertical vs. horizontal hops

Unilateral vertical jumps demonstrate lower LSI scores than horizontal hops at a range of time points post ACLR¹⁸. Vertical and horizontal hops could therefore be considered distinctly different tasks by virtue of their moderate relationships with each other¹⁹. Differences in performance between vertical and horizontal hopping may in part be due to alterations in lower extremity joint contributions. Specifically, the greatest relative total positive work occurs at the knee during vertical jumps²⁰ with lower contributions from the knee in horizontal

vs. vertical jump tasks respectively²¹. While both vertical and horizontal jumping tasks have their respective merits, it could be suggested that a task requiring vertical acceleration of the body is determined more heavily by function of the knee extensors. Due to the residual deficits in quadriceps strength in athletic populations following ACLR²² we speculate that vertical jumps provide an accurate representation of knee joint function and could be used either as an alternative (in cases where time is limited) or addition to more traditional horizontal hopping protocols.

The task and variable dependent nature of asymmetry

Asymmetries are task, variable and physical quality specific; therefore, practitioners should not expect to see the same between-limb differences across different screening tests^{23,24}. Variability in asymmetry scores between different modes of strength and jump tests have also been shown previously^{25,26} and for a range of variables measured within the same task^{23,24}. An example of this can be seen in figure 2 with data recorded during the performance of a triple hop for distance as part of a RTS test battery following ACLR. In this case the athlete 'passed' with an LSI hop distance score of 94%; however, measurement of other variables during the test via an optoelectrical system displayed pronounced compensation strategies and these varied

across the different hops within the test that are not readily evident to the clinician's visual perspective.

While reduced between-limb deficits are likely a desirable outcome, applying a single, and somewhat arbitrary criterion value for a 'safe' RTS (e.g. > 90% LSI) for every variable to determine adequate symmetry is limited. Before clinical recommendations can be provided to determine what an acceptable threshold is, a clearer understanding of task specific 'normal' asymmetry is required. Test scores should be examined separately and may require values that are population, task and metric specific to more accurately determine 'abnormal' asymmetry. Establishing better guidelines aligned with specific testing metrics will assist practitioners in making more effective and evidence-based decisions to determine readiness to RTS.

Distance is not enough – the importance of assessing movement quality

Measurement of horizontal hop distance and vertical jump height are common when assessing readiness to RTS⁶. These variables alone are likely insufficient to observe alterations in the movement strategy and lack sensitivity to identify deficits in knee function^{7,13}. For example, LSI single hop scores of > 90% were achieved in patients after ACLR; however, reductions in peak knee flexion were evident on the involved limb, indicating a compensatory strategy.²⁷

Assessing performance during the test (attempting to maximize hop distance) is important, but other factors relating to neuromuscular control should also be examined and form part of the RTS decision making process. In addition, distance/time measures of performance that do not consider movement quality also are void of primary ACL injury risk factors that contributed to the primary ACL injury.

Integrating biomechanical assessment and movement quality evaluations into rehabilitation has not been commonplace, likely due to expensive equipment and labor-intensive analysis procedures. Recent improvements in wearable technology provide more feasible options for clinicians which allow them to make more informed and objective decisions. For example, inertial sensors can easily attach to the thigh and shank to measure knee joint kinematics and have been shown to provide accurate and reliable measures of angular velocity associated with deficits in knee power in ACL injured athletes²⁸. In addition, force platforms are now frequently used as an affordable and time-efficient method, whereby data can be collected without the need for time-consuming set-up and analysis procedures. Vertical ground reaction forces (VGRF) are associated with knee joint moments, indicating their viability as a surrogate for assessing compensation strategies in knee kinetics²⁹. Cumulatively, measurement of the movement strategy as well as performance outcomes must be considered a non-negotiable component of RTS assessment moving forward as the research consistently shows that whilst a comprehensive rehabilitation program may have been adhered to, pronounced inter-limb asymmetries persist in kinetic and kinematic characteristics that are associated with increased risk of future injury.

There is more to life than peak torque!

Quadriceps strength deficits are a known outcome following ACLR²². Isokinetic dynamometry provides an objective measure of muscle strength and is considered the 'gold standard'. Somewhat surprisingly, the most common isokinetic output variable is not a strength profile, but merely a single peak torque value for each tested joint rotation velocity³⁰. However, the torque production and results are affected by

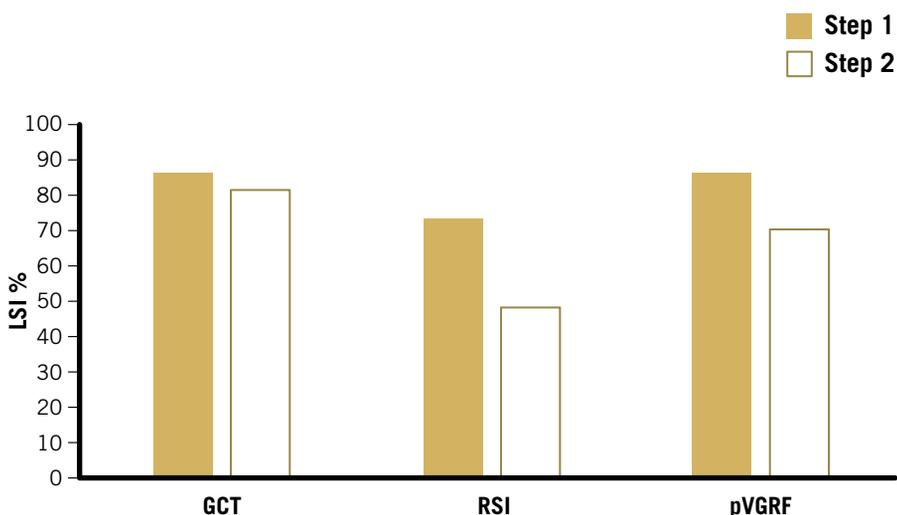


Figure 2: Limb symmetry scores for strategy variables during the triple hop for distance across the different hops within the test. Note: this patient 'passed' the test with a hop distance LSI score of 94%. GCT=ground contact time; RSI=reactive strength index; pVGRF=peak vertical ground reaction force.



Measurement of the movement strategy must be considered a non-negotiable component of assessment. Thus, practically viable solutions for on-pitch/court measurement are needed to allow coaches to ‘bridge the gap’ between the laboratory and sports environment to facilitate a more informed decision-making process.



the modes of contraction, angular velocity, range of motion, number of repetitions and gravity correction, with wide variation seen and no standardization of testing protocols within the literature³⁰.

An important limitation with a data reductionist approach (i.e. just looking at peak torque) is that it discards angle-specific moment generating capacity throughout the range of joint motion. This has increased importance following ACLR as knee ligament injury can introduce angle-specific deficits, which may well remain undetected without evaluation of the entire angle-moment profile³¹. Specifically, between-limb quadriceps muscle strength deficits are most significant at 40° of flexion in patients following ACLR and exceed those measured at the angle of peak torque^{31,32}. While it should be considered that predicting uncertain outcomes such as a future injury remains challenging, the poor sensitivity of commonly used metrics could in part be due to a lack of critical analysis, whereby, factors which more closely relate to the mechanism of injury and characteristics required for sports performance are not being assessed. For example, ACL injuries occur with the knee in a position close to full extension and sporting tasks are undertaken with the trunk in a relatively upright position. Thus, further research is warranted to determine the effect of joint angle and test position on muscle strength deficits to provide a more comprehensive profile of athletes who wish to return to competitive sport.

It's not just about the strength of the injured site - we need to also consider the global 'system'

While testing knee extension/flexion strength is undoubtedly important following ACLR³, low correlations have been reported between these tests and functional performance measures^{33,34}. Consequently, in addition to the assessment of isolated, single joint protocols (including those of the ankle, knee and hip), more sports relevant and detailed strength assessments have been indicated for ACL patients following surgical reconstruction.

There is now a cumulative body of evidence to describe the utility of strength assessments using an isometric mid-thigh pull or squat within the available literature³⁵⁻³⁸. Importantly, these tests are easy to administer, reliable and strongly correlated to both dynamic and maximal strength assessments and the ability to effectively change direction³⁸. In ACL patients who are returning to sports such as soccer, the ability to rapidly decelerate and re-orientate their limbs is a fundamental component of safe and effective performance; thus, surrogate assessments that can be conducted in a clinical setting prior to clearance for sports specific training allow for a safer and more informed decision as to the patient's level of 'readiness'.

Currently, limited data are available to quantify the level of strength of an individual in functional tasks at the time of discharge from rehabilitation with

prospective monitoring of injuries to examine if strength, force production asymmetry and rate of force development are pertinent risk factors for re-rupture. Strength deficits present on discharge are a plausible explanation for the high rates of early re-rupture due to the known relationships between the ability to produce force and reactive strength³⁹, speed⁴⁰, jump performance⁴⁰, aerobic endurance⁴¹, changing direction³⁸ and recovery following sporting match play⁴². Isometric testing to examine force-diagnostics are now readily available to clinicians and sports scientists alike. With their time efficiency and cost-effectiveness, these approaches may warrant further consideration in the future.

The importance of rate of force development

Diminished physical capacities should also be considered when interpreting the high rates of re-rupture shown following RTS. In sports, the ability to produce a high force quickly is important for both sports' performance and injury protection. Rate of force development (RFD) is a key physical quality due to the short time-frame (< 50 ms) associated with ACL injury mechanisms following ground contact; thus, the time for muscles to activate and reduce joint loading is brief.

RFD is defined as the ability of the neuromuscular system to produce a high rate of rise in muscle force per unit of time during the initial phase following contraction onset, calculated as



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$\Delta\text{Force}/\Delta\text{Time}$. Angelozzi et al.⁴³ showed significant deficits in RFD 6 months post-ACLR in professional soccer players who had completed a typical standardized rehabilitation program and achieved nearly full recovery in subjective ratings of knee function and maximal voluntary isometric contraction; all commonly used to guide return to sports decision-making. Similarly, Kline et al.⁴⁴ demonstrated reduced quadriceps RFD in subjects at 6 months post-ACLR with patellar tendon autograft. Thus, assessments that target key physical capacities which may be deficient following injury and rehabilitation should be included as these deficits are sensitive to change following focused periods of training⁴³.

We also need to assess change of direction

Change of direction (CoD) has been recognized as a mechanism of non-contact ACL injury⁴⁵; however, there is a distinct lack of research pertaining to performance as a component of RTS testing and the utility of these assessments to identify associations with secondary injuries or a return to pre-injury levels of competition and performance. Due to the importance of effective CoD abilities for athletes following ACLR, accurate tests which isolate

and measure this physical quality are warranted.

Field-based testing protocols commonly used to assess CoD performance include the shuttle run, carioca, t-test, Illinois agility and 5-0-5⁴⁶. These tasks do not isolate an athlete's ability to change direction⁴⁷, are highly correlated and may not measure different constructs, instead they provide a generic assessment of an individual's ability to change direction⁴⁸. For example, acceleration is also examined, and as the duration of the test increases, there is a greater emphasis on anaerobic capacity and linear sprinting⁴⁷. This is confounded by data which show that only 31% of the time spent performing a 5-0-5 test (involving a 180° action) is used to execute the change of direction component⁴⁹.

Using total time solely to measure CoD is also not adequate to identify important qualitative information (e.g. trunk position, foot placement, centre of mass height, knee angles, arm actions and visual focus) presented by an athlete while executing the movement. Recently, King et al.⁵⁰ examined the performance and biomechanics of athletes who were 9 months' post ACLR during a 90° cutting task. Differences in biomechanics were observed between the

involved and un-involved limbs despite no differences in performance time. As CoD is affected by a range of factors such as entry speed, the distribution of braking force between the penultimate and plant step, and the kinematics; improving our understanding of how athletes change direction will allow us to more clearly examine an athlete's task completion strategy and design individualized training programs⁴⁶. To do this, practically viable solutions for on-pitch/court measurement are now needed to allow coaches to 'bridge the gap' between the laboratory and the sports environment. This approach may facilitate a more informed decision-making process with the end goal being, a 'return to performance' with a lower risk of re-injury.

Patient and athlete follow-up to determine successful outcomes

In order to assess the outcomes of surgery and rehabilitation, performance indicators need to be established and assessed. On a basic level, this should include return to play at the same level of competition, and re-injury / re-rupture rates. In addition to this, it is proposed that (where possible) training load and key performance indicators should be monitored on the athletes RTS

to further document exposure, tolerance to training and competition demands and if the athletes achieve previous levels of performance.

While this is a considerable challenge, it is encouraged that the development of a system allowing clinicians to capture the level of sport participation, injury surveillance, training load and competition monitoring, clinical assessment, fitness testing, movement screening assessments and psychosocial evaluation should become part of routine practice to describe the 'return to sport journey'. Furthermore, this allows the exploration of factors associated with successful clinical outcomes and performance on RTS.

A final point of consideration is that ALL injuries should be monitored and recorded for a minimum period of 12 months following RTS but more appropriately over the 24 months. Secondary injuries such as significant muscle strains occurring early following RTS could be considered errors in loading and, may be due to potential deconditioning. Thus, global preparation of the whole athlete needs to become a key consideration. This involves a thorough needs analysis of the sport and should act as a precursor to the design and implementation of any effective re-conditioning program, including:

- The biomechanical characteristics of the movements involved
- The physiological demands
- Normative data to establish physical performance standards
- The reported injury epidemiology

A system-based approach, such as "performance modeling" can also be applied⁵. This concept promotes the design of training programs which use a clear system of analysis, testing, and exercise prescription. Speculatively, transfer of training is enhanced with a greater impact on sports performance. For further information, readers are encouraged to view our previous work in this area⁵.

We need increased methodological rigor in the use of return to sport testing!

Our observation of the methods currently used within the available research to ascertain RTS pass status has indicated there is pronounced variation. For example, differences in test order, warm-up activities, familiarization, number of practice and recorded trials, control of hand position,

point of measurement (heel/toe), limb order and rest periods, all of which can affect the test outcome. Often these details are not adhered to in the scientific literature. Thus, there is a need for greater transparency and quality in the reporting of methodological procedures in RTS tests following ACLR. For RTS tests to be valid and generalized across clinical settings, standardized outcome measures are required with specific procedures for administration, scoring, and interpretation. Similarly, we believe that the heterogeneity in how these data are collected and subsequently reported could at least in part, account for the equivocal results found within the synthesized literature⁶. Without an adequate description of the methodological processes adhered to during RTS testing, it is difficult for a clinician to interpret and confidently translate the findings.

SUMMARY

Criteria to determine successful rehabilitation and RTS remain unclear. In this article, we have outlined that while some evidence indicates passing a battery of assessments including strength and hop tests, reduces the risk of re-injury, the cumulative body of evidence is equivocal. Limitations have been discussed which if addressed, may enhance the efficacy of assessment protocols and more accurately guide readiness to RTS following ACLR. While some are open for debate, it appears that measurement of the movement strategy, as well as performance outcomes must be considered a non-negotiable component as the research is consistently showing that whilst a comprehensive rehabilitation program may have been adhered to, pronounced inter-limb asymmetries persist which may increase risk of future injury. Practically viable solutions for on-pitch/court measurement are now needed to allow coaches to 'bridge the gap' between the laboratory and the sports environment. This approach may facilitate a more informed decision-making process with the end goal being, a 'return to performance' with a lower risk of re-injury.

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