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INTERVIEW

OUSMANE DEMBÉLÉ

Barcelona's rising star

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TARGETED TOPIC Return to Performance After ACL Reconstruction

THE EDITORIAL TEAM

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FROM OUR EDITOR

Nebojsa Popovic MD PhD
Editor-in-Chief

This issue sees us highlighting the modern approach for assessing and reconditioning athletes, as they aim to return to the high demands of modern sport following ACL surgical reconstruction.

I have therefore asked the well-respected Sport Scientist at Aspetar, Paul Read PhD, to guest edit this issue. As the lead investigator on the research project on ACL Return to Play study here at Aspetar, he is perfectly placed to take on this challenging topic.

He has done a great job both with this issue, and with his research in general.

I would like to thank all the contributors, but especially Paul, for his generous contribution and effort which makes this possible.


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OPTIMIZING THE 'RETURN TO SPORT JOURNEY'

A 21ST CENTURY APPROACH TO TESTING, REHABILITATION AND RECONDITIONING!

Paul Read PhD
Clinical research Scientist
Aspetar – Orthopedic and Sports Medicine Hospital

Albert Einstein famously once said that "the definition of insanity is doing the same thing over and over again and expecting a different result." Controversially, this same thinking could be applied to the ACL return to sport literature. In the last 40 years, the world has evolved and advancements in technology have been astronomical. However, we are still today predominantly using testing protocols that were developed in the 1980's (originally to identify functional abnormalities) as our method to determine readiness to return to sport.

Considering the current evidence, it appears that at best, our ability to determine successful outcomes following ACL reconstruction is equivocal. Furthermore, re-rupture / injury rates remain high; thus, we need to question if current recommendations are suitable to prepare athletes to 'return to performance'. Now is the time to change as we are still a long way from understanding pertinent factors associated with successful patient outcomes. To do this we need to think more critically and develop strategies to effectively 'bridge the gap' between rehabilitation and return to performance.

As a start point, we need to more fully appreciate that return to sport is a journey and should not be defined by a single or selected group of tests. Specifically, optimal reconditioning after such a serious and traumatic injury requires learning/re-learning of skills, physical capacity development, exposure and re-integration of cognitive function by progressing from control to chaos, graded progression and gradual accumulation of both enough load (volume and intensity) and representative load (considering physical and cognitive sport demands), while integrating regular and precise monitoring of adaptation. That is the focus of this special edition, with novel and outstanding content provided from each one of our invited experts in their respective fields.

The athletes journey begins on day 1, and while initially this may mean training around the injury, we must not forget that an athlete should always remain an athlete. We of course should respect the principles of protection, repair and appropriate joint loading, but we should also encourage and promote a variety of means to develop / maintain athleticism. Our approach needs to be sensible, diligent and methodical. However, we shouldn't be scared, over-cautious, afraid to load or wait too long before applying an appropriate stimulus. Remember we are aiming to return an athlete to a state in which they are ready to re-perform and not just focusing on an injury. While important, it is not just about the knee; we also need to consider global athlete preparation. Thus, we could consider a paradigm shift, in which 9 months (or whatever the required timeframe is for return to sport) is seen as an opportunity to grow and develop.

Finally, it is important to recognize the significance of a multidisciplinary team in the planning and implementation of effective return to sport conditioning. Not to underplay the importance of the medical team, but sports science should also be an integral part of the return to sport puzzle, whereby a collective range of skill sets are utilized to most effectively design and deliver a high-performance reconditioning plan for our athletic populations. We hope this special edition provides some unique insights into a modern approach for assessing and reconditioning athletes as they aim to return to performance following ACL injury and surgical reconstruction.

ASSESSMENT STRATEGIES

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

– Written by Paul Read, Darren Paul, Philip Graham-Smith and Sean McAuliffe, Qatar, Will Davies, United Kingdom, Joao Marques, Qatar, Mat Wilson, United Kingdom, and Greg Myer, USA

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 recovery[1], there has been a progressive shift towards a criterion-based approach[2]. 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 patterns[7]. 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 / uninvolved 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-surgery[14]. Similarly, limb symmetry can be achieved by hopping shorter distances on the un-involved leg compared to asymmetric patients, and healthy matched controls[13]. 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 57% when using the non-injured limb post-operative performance as the index measurement[15]. 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.

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

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 2[17]. 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 ACLR[18]. Vertical and horizontal hops could therefore be considered distinctly different tasks by virtue of their moderate relationships with each other[19]. 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 jumps[20] with lower contributions from the knee in horizontal vs. vertical jump tasks respectively[21]. 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 ACLR[22] 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 RTS[6]. 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]

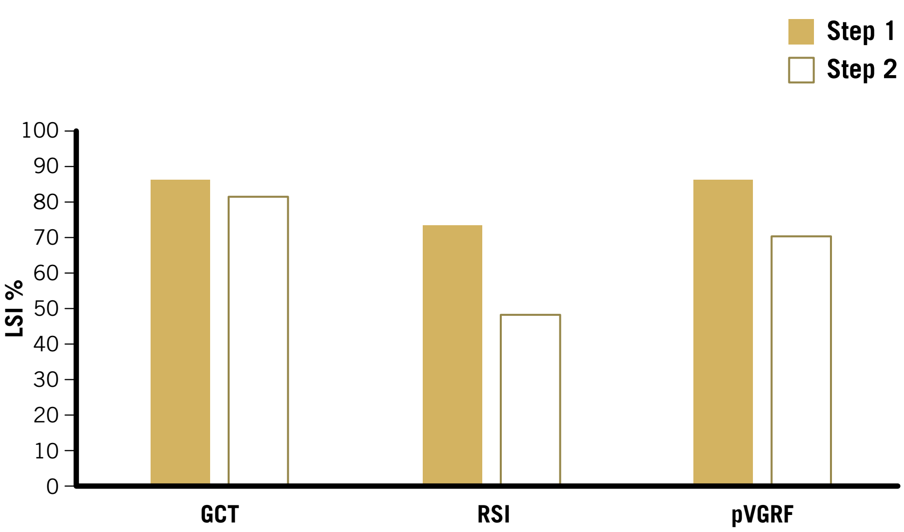

Figure 2: Limb symmetry scores for strategy variables during the triple hop for distance across the different hops within the test. Note: this patient 'passed' the test with a hop distance LSI score of 94%. GCT=ground contact time; RSI=reactive strength index; pVGRF=peak vertical ground reaction force.

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 athletes[28]. 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 kinetics[29]. 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 ACLR[22]. 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 velocity[30]. However, the torque production and results are affected by

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 literature[30].

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 profile[31]. 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 ACLR[3], 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 literature[35-38]. Importantly, these tests are easy to administer, reliable and strongly correlated to both dynamic and maximal strength assessments and the ability to effectively change direction[38]. 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 strength[39], speed[40], jump performance[40], aerobic endurance[41], changing direction[38] and recovery following sporting match play[42]. 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

ΔForce/ΔTime. 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 training[43].

We also need to assess change of direction

Change of direction (CoD) has been recognized as a mechanism of non-contact ACL injury[45]; 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 5-0-5[46]. These tasks do not isolate an athlete's ability to change direction[47], are highly correlated and may not measure different constructs, instead they provide a generic assessment of an individual's ability to change direction[48]. For example, acceleration is also examined, and as the duration of the test increases, there is a greater emphasis on anaerobic capacity and linear sprinting[47]. 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 component[49].

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 programs[46]. 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 applied[51]. 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 area[51].

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 literature[6]. 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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INTER-LIMB ASYMMETRY DURING REHABILITATION

UNDERSTANDING FORMULAS AND MONITORING THE "MAGNITUDE" AND "DIRECTION"

– *Written by Chris Bishop and Anthony Turner, United Kingdom, Oliver Gonzalo-Skok, Spain and Paul Read, Qatar*

INTRODUCTION

Monitoring and reporting inter-limb asymmetry during rehabilitation has been a common line of investigation[2,15,22,28,29,31]. Between-limb deficits in strength have been reported[11,18,22,32] and the use of horizontal hop tests have been a popular choice to detect residual side-to-side differences in functional performance[2,15,20,22,28,31]. With strength and power typically seen as two of the most important physical qualities for athletic performance,[16,35,36] it is not surprising that asymmetries in these two physical qualities are frequently tested during injury rehabilitation to determine an individual's state of readiness to return to sport[2,18,22,28].

A key focal point of returning an athlete to their chosen sport is often to reduce and potentially minimize inter-limb asymmetry during rehabilitation. Given that often an obvious between-limb deficit exists when an athlete is injured, progressively enhancing the capacity of the injured limb can be seen as a "window of opportunity" for physical training and conditioning[19,26]. In addition, with such an obvious between-limb difference present, the direction of asymmetry is likely to be consistent. That is to say, the uninjured limb is likely to most frequently produce the best score compared to the injured side. However, recent findings (albeit in healthy populations) have suggested that both the magnitude and direction of asymmetry are both highly variable and task-specific[4,6,12,25]. Monitoring the magnitude of asymmetry alone may hinder a practitioners' ability to use this information as part of the ongoing monitoring process, especially when athletes are nearing return to participation, and once they have returned to full competitive activities. Thus, considering both the magnitude and direction of asymmetry may provide a clearer understanding of which deficits are consistent or natural fluctuations in performance variability due to training load adaptations and normal movement variability.

Choosing the most appropriate formula to calculate inter-limb asymmetry is also an important consideration. Previous literature has highlighted that multiple formulas exist to calculate inter-limb differences[5,7], which poses challenges for practitioners given that the reason why one formula should be chosen over another is often not obvious. From an injury perspective, limb symmetry

Table 1

Asymmetry Name	Formula	Asymmetry (%)	Reference
Limb Symmetry Index 1	*(Inv/un-Inv)*100*	*87.5*	*Logerstedt et al*[24]
Limb Symmetry Index 2	*(1–Inv/un-Inv)*100*	*12.5*	*Schiltz et al*[33]
Limb Symmetry Index 3	*(R–L)/0.5(R+L)*100*	*13.3*	*Bell et al*[3]
Bilateral Strength Asymmetry	*(Strong–Weak)/Strong*100*	*12.5*	*Impellizzeri et al*[19]
Bilateral Asymmetry Index 1	*(D–ND)/(D+ND)*100*	*6.7*	*Kobayashi et al*[21]
Bilateral Asymmetry Index 2	*(2*(D–ND)/(D+ND))*100*	*13.3*	*Wong et al*[38]
Asymmetry Index	*(D–ND)/(D+ND/2)*100*	*13.3*	*Robinson et al*[30]
Symmetry Index	*(High–Low)/Total*100*	*6.7*	*Shorter et al*[34]
Symmetry Angle	*(45–arctan(L/R))/90*100*	*4.2*	*Zifchock et al*[39]
Standard Percentage Difference	*100/(Max)*(Min)*-1+100*	*12.5*	*Bishop et al*[7]

Inv = involved; un-Inv = un-involved; R = right; L = left; D = dominant; ND = non-dominant.

Table 1: Inter-limb asymmetry formulas and values using a hypothetical example of peak force during a CMJ. N.B: 800 N=un-involved, right, strong, high and dominant limb; 700 N=involved, left, weak, low and non-dominant limb.

index (LSI) formulas have often been used to quantify existing between-limb deficits throughout the rehabilitation process. Intuitively, this makes sense given that the injured limb is likely to produce a lower score. However, when an athlete is nearing return to play (RTP), it is possible that the injured limb may actually display heightened performance relative to the uninjured limb, which can compromise calculating the magnitude of asymmetry and where complications in the formulas arise (discussed later). This further highlights the need for a consistent approach to calculating between-limb differences, considering both the magnitude and direction of asymmetry regardless of what stage of rehabilitation the athlete is at.

The aims of this article are to first highlight key considerations regarding the formulas selected for calculating the magnitude of asymmetry during injury rehabilitation and secondly, propose an evidence-based justification for monitoring both the magnitude and direction of asymmetry during the rehabilitation process.

MONITORING THE MAGNITUDE OF ASYMMETRY AND DIFFERENTIATING BETWEEN TEST METHODS

Choosing an appropriate formula

Using Table 1, we propose a hypothetical example whereby peak force asymmetry is measured during a countermovement jump (CMJ). In this example, the reader is asked to assume that 800 N corresponds to the uninjured, dominant, right and stronger limb. There is of course no guarantee that this will always be the case, but should be assumed purely for the purpose of illustrating this point. Before deciding which formula to use, first we must consider the notion of how standard percentage differences are calculated. To do this, understanding how fractions of 100 are computed is important, noting that traditional mathematics only teaches this one way (i.e., in relation to the maximum value) and that difference then gets expressed as a percentage of 100. Thus, with standard percentage differences quantifying between-limb deficits relative to the maximum value, Table 1 highlights three formulas which calculate our hypothetical peak force asymmetry value in such a way: Bilateral Strength Asymmetry, Symmetry Index and the Standard Percentage Difference method. The Bilateral Strength Asymmetry and Standard Percentage Difference equations are set up to always calculate the percentage difference the same way, noting that the equations themselves do not change, just the raw data that goes into them. In addition, the reader should note that these formulas do not consider the total value generated by both limbs; therefore, these can only be considered when calculating inter-limb asymmetry from unilateral test methods.

Table 1 also shows that many different approaches have been adopted when calculating inter-limb differences. Injury based research typically uses terms such as 'involved' and 'un-involved' when reporting limb differences; thus, the LSI-1 and LSI-2 formulas are commonly used to quantify between-limb deficits. In addition, the reader could look at Table 1 and think that the LSI-2 formula could be used to calculate asymmetry from unilateral test protocols, noting that the percentage value is the same as the Bilateral Strength

Asymmetry and Standard Percentage Difference equations. However, it is likely that this is only consistent when an athlete is injured, because an obvious reason exists for the between-limb asymmetry (i.e., one limb is injured). For athletes that have been rehabilitated post-injury, trained consistently over an extended period of time and successfully returned to competition; the reason for existing side-to-side differences becomes less apparent. In fact, it is plausible that a previously injured limb may perform superiorly over time, in which case, complications in the formulas can arise. To prove this point, if we swap the peak force values around in that second equation from Table 1 so that the un-involved limb now scores 700 N instead of 800 N, the asymmetry value becomes -14.3%. The negative sign tries to tell us that the involved limb produced greater peak force; however, it has compromised the magnitude of asymmetry (12.5%), which was previously determined from our standard percentage difference. In addition, given the absolute force difference measured between limbs has not changed (i.e., 100 N), the percentage difference should not be altered. Thus, not all equations may be robust enough to withstand every scenario that are presented to practitioners when collecting data. Therefore, when calculating asymmetry from unilateral tests, the formulas proposed by Impellizzeri et al.[19] or Bishop et al.[7] are the suggested options.

During a bilateral CMJ, if practitioners wish to quantify between-limb differences in peak force, it is suggested that the imbalance must be expressed relative to the sum total of force production given that both limbs are interacting together. The key point here being that if each limb is not acting independently, the quantification of imbalances should not be treated as separate entities. In contrast, during a unilateral CMJ there is no ground contact contribution from the other limb; thus, quantifying any existing side-to-side differences can be done without considering the opposing limb's involvement (noting that it has none). The formulas proposed by Kobayashi et al.[21] or Shorter et al.[34] calculate between-limb differences relative to the total value, remembering that this is suggested because both limbs are interacting together. Whilst other formulas also do this in Table 1 (e.g., Bell et al.[3], Wong et al.[38] and Robinson et al.[30]), there is no evidence to suggest that

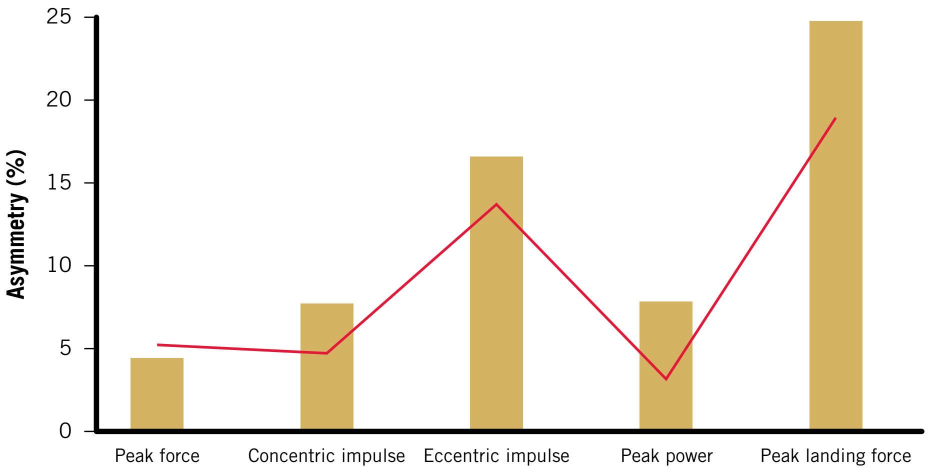

Figure 1: Hypothetical example showing the metric-specific nature of asymmetry (gold bars) during a countermovement jump in relation to the coefficient of variation (red line).

the asymmetry outcome should be altered anywhere in the formula by either dividing by 0.5, multiplying by 2 or dividing by 2 respectively. Thus, the proposed formulas for calculating inter-limb differences during bilateral tests are either the Symmetry Index or Bilateral Asymmetry Index 1.

Now that proposed formulas have been suggested for the quantification of asymmetries, it is important to realise that practitioners are merely left with a percentage value, known as the magnitude of asymmetry. Previous literature has suggested that magnitudes of 10-15% may increase the risk of an athlete getting injured and should be used as a minimum target for an athlete to 'pass' return to sport testing[2,22,28,31]. However, with an abundance of evidence to show that asymmetries are task and metric-specific[4,6,8,9,12,17,23,25], this notion appears rather superficial given that any magnitude could only be applied relative to the chosen test, metric or population in question. Thus, when left with the magnitude of asymmetry, it poses the question of how to interpret the data.

Interpreting the magnitude of asymmetry

An often overlooked component of asymmetry data interpretation is to examine and interpret the differences in the context of the typical error associated with the test. We must acknowledge that there is inherent error present in any test that we administer which can come from many sources. Thus, we need to be able to determine what is a 'real' asymmetry. Previously, Exell et al.[13] highlighted the need to consider intra-limb variability in conjunction with the inter-limb difference value. In short, it was inferred that an asymmetry may only be considered real if it was greater than the variability in the test. Practically this can be measured in the form of the coefficient of variation (CV) which is determined by looking at the standard deviation relative to the mean, and then expressed as a percentage by multiplying by 100[37]. Previous literature has suggested that values < 10%[10] or 5%[1] can be considered as acceptable variability. However, practitioners are encouraged to determine these for their own groups of athletes due to variations in movement skill and training age (see Turner et al.[37]) for an example of how to do this). Despite any disagreement on a proposed threshold, it is accepted that the lower the CV value, the more reliable the test or metric[10,37].

Where asymmetry is concerned, reporting any existing side-to-side differences in conjunction with test variability (i.e., the CV) may help to differentiate between 'the signal and the noise'. Furthermore, both values are reported in percentages providing practitioners with an easy comparison between the two. When an athlete is injured, especially if the injury is severe, it is likely that between-limb differences will be much greater than the CV when testing protocols resume. As rehabilitation and functional performance progresses, the imbalance should reduce and practitioners may wish to use the CV value as a target to aim for as a threshold for inter-limb asymmetry. In essence, this helps provide an individualised threshold for each athlete during the rehabilitation process

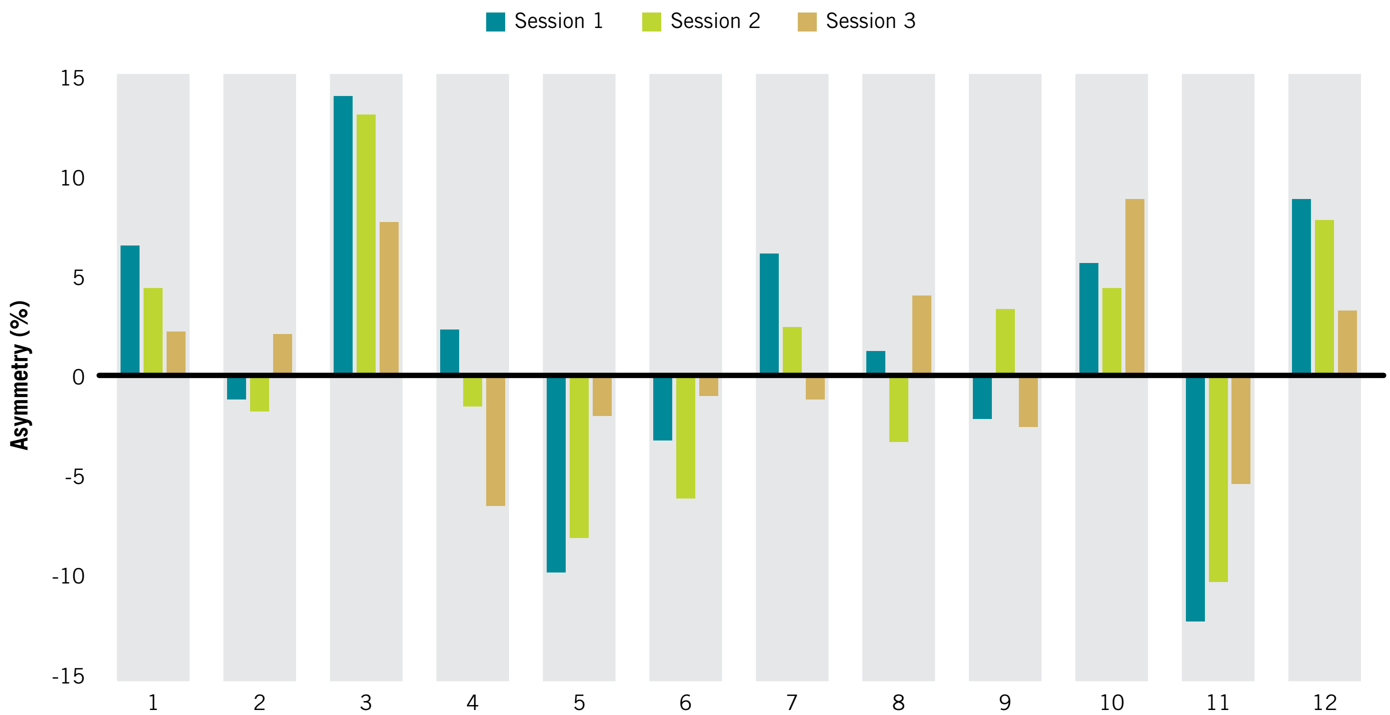

Figure 2: Hypothetical peak force asymmetry data for 12 athletes during a countermovement jump over three test sessions. Above 0 = asymmetry favours the dominant limb; below 0 = asymmetry favours the non-dominant limb.

and can be used for different metrics within the same test.

Figure 1 shows hypothetical asymmetry data (gold bars) for five metrics in a CMJ test, with the CV mapped on as a red line. Peak force is the only metric exhibiting asymmetry smaller than the CV; however, in this instance, not all metrics may be usable. Eccentric impulse and peak landing force are exhibiting inter-limb asymmetries of 16.6 and 24.8% respectively, both of which are greater than the CV. However, with CV's of 13.7 and 18.9%, the reliability of these metrics could be questioned[1,10,37]. Thus, although it has been suggested that the CV can be used to aid interpretation of asymmetry and as a potential target when reducing imbalances during rehabilitation, it is imperative to appreciate that if the CV is high (i.e., > 10%), practitioners may wish to be mindful of using such data to help inform the decision-making process due to the pronounced variability in the way the task is being executed by the injured athlete.

ADDING "DIRECTION" TO ASYMMETRY

Recent literature has highlighted the importance of the direction of asymmetry[26], which refers to the consistency of asymmetry favouring one side (i.e., right vs. left or dominant vs. non-dominant). As previously mentioned, when an athlete is injured, an obvious between-limb deficit is present; thus, the direction of asymmetry is likely to always favour the uninjured limb. However, when athletes are healthy or nearing RTP, the consistency of asymmetry may be lower and using the magnitude alone may be missing a piece of the puzzle when reporting an athlete's between-limb deficits.

This notion is supported in recent research by Bishop et al.[4,6] who showed the direction of asymmetry (i.e. the same limb being recognised as the highest performer) to be just as variable as the magnitude in healthy athletes. Specifically, peak vertical ground reaction force displayed low agreement across different strength and jumping tests used (again indicating the task dependent nature of asymmetry)[4]. In addition, analysis of the consistency of asymmetry favouring the same 'dominant' limb between separate test sessions in a unilateral isometric squat, CMJ and drop jump (DJ) tests often indicated only fair to moderate levels of agreement[6]. This has led to recent suggestions that the interpretation of inter-limb asymmetry should be done on an individual basis, rather than using the group mean value as a guide[4,6]. Figure 2 shows an example of hypothetical data for peak force asymmetry during a CMJ being recorded over three test sessions for 12 participants. Values above 0 favour the dominant limb and below 0 favour the non-dominant limb, providing a clear distinction in the direction of asymmetry (Figure 2).

Therefore, and remembering that some equations provide the direction of asymmetry (by creating a negative value) but also compromise the magnitude, practitioners need a formula which is consistent to calculate both the magnitude and direction of asymmetry throughout the entire 'rehabilitation journey'. This can be done by adding an 'IF function' to the end of the relevant formula in Microsoft Excel: *IF(D<ND,1,-1). Simply put, this tells the asymmetry value to become negative if the non-dominant limb is the larger value without changing the magnitude. Therefore, when aiming to monitor the direction of asymmetry, the following equations are suggested for bilateral and unilateral tests respectively:

- Bilateral tests:
  ((D–ND)/Total*100)*IF(D<ND,1,-1)
- Unilateral tests:
  ((D–ND)/D*100)*IF(D<ND,1,-1)

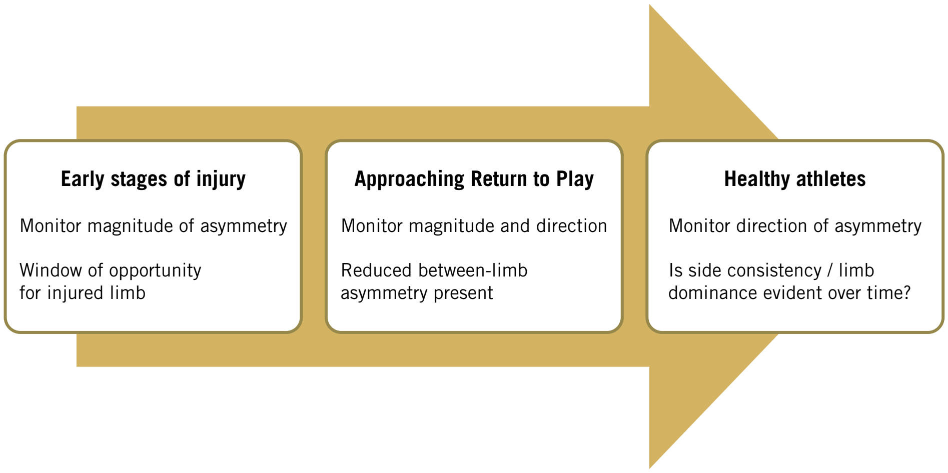

Figure 3: Suggested approach for monitoring asymmetry during the rehabilitation process and once the athlete has returned to sport.

It is important to note that the above formulas are defining limbs via dominance which is a common method of differentiating performance between limbs[12,14,19,27]. However, practitioners can define limbs differently if desired (e.g., left vs. right or involved vs. un-involved) depending on which scenario suits their needs. From an injury perspective, replacing the dominant limb with 'un-involved' and the non-dominant limb with 'involved' would ensure that the magnitude of asymmetry is always computed relative to the maximum value when an obvious between-limb difference exists. In addition, the IF function will ensure that practitioners become aware if and when the involved limb surpasses the un-involved limb, providing a notable change in the direction of asymmetry. Thus, the process for monitoring both the magnitude and direction of asymmetry is suggested in Figure 3.

CONCLUSION

Calculating inter-limb asymmetries is perhaps more complex than we might think. The selection of an appropriate equation may depend on the nature of the test selected (e.g., bilateral or unilateral); however, it is essential that practitioners always keep in mind the needs of the athlete when selecting the most appropriate test. Owing to asymmetry being a variable concept, there is a need to be able to distinguish between the signal and the noise, which is why practitioners may wish to consider the CV to be useful when interpreting asymmetry scores. In addition, the use of a single asymmetry threshold (i.e. 10%) is likely not possible due to the task-specific and variable nature of measured between-limb deficits. Finally, the use of an IF function in Microsoft Excel can enable the direction of asymmetry to be monitored without altering the magnitude, and should be considered as an additional tool in understanding the both the relevance and consistency of asymmetry throughout the rehabilitation journey, especially as athletes are nearing RTP.

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ASSESSING VERTICAL JUMP FORCE-TIME ASYMMETRIES IN ATHLETES WITH ANTERIOR CRUCIATE LIGAMENT INJURY

– *Written by Matthew J. Jordan, Graeme Challis, Nathaniel Morris, Mike Lane, Jeremiah Barnert and Walter Herzog, Canada*

INTRODUCTION

An anterior cruciate ligament (ACL) rupture is a devastating injury for an athlete. ACL injuries occur frequently in field sports[1–5] and winter slope sports, such as alpine ski racing and snowboarding[6–9]. After suffering an ACL rupture, reconstruction surgery (ACLR) is often recommended for athletes to restore knee joint stability, but functional deficits are likely to persist after surgery[10]. While a high fraction of winter slope sport athletes have been shown to return to their preinjury performance level after ACLR[11], less than 65% of field sport athletes return to the same level of competitive performance[12–14]. The risk of ACL injury in athletes with a previous history of ACLR is substantially greater compared to athletes with no history of ACL injury[15], and ACL reinjuries, especially on the contralateral limb, are prevalent in winter slope sports[16] and field sports[1,4,15] alike. Despite an elevated risk for reinjury, elite athletes with ACLR often return to sport with pronounced functional deficits, such as elevated between-limb (interlimb) asymmetries in muscle strength and power[17–22], and sport science/sport medicine practitioners have been shown to rely only on subjective assessments and time-since-surgery as determinants of return to sport readiness[23].

To account for the high risk of ACL reinjury, objective testing that uses a functional milestone based approach is recommended prior to return to sport clearance[24] alongside ensuring adequate time for tissue healing[25]. However, the efficacy of functional return to sport testing batteries has been questioned recently due to the high fraction of athletes who pass criteria while masking deficits that are associated with ACL reinjury (e.g. achieving a limb symmetry index > 90% in a single leg hop test for distance but failing to achieve a quadriceps strength limb symmetry index > 90%)[18,26]. It is likely that individuals with a history of ACLR compensate during performance-based functional testing by altering their movement strategies. For example, they may rely on a hip dominant jump or squat movement pattern to account

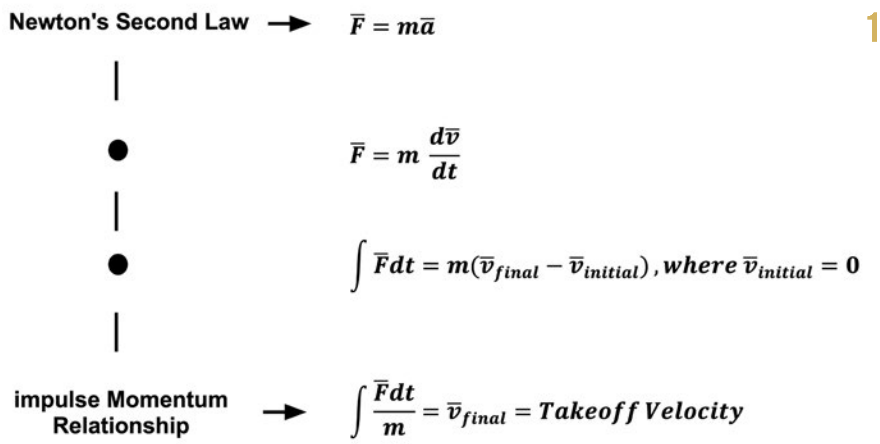

Figure 1: Determining the takeoff velocity in the vertical jump using the impulse momentum relationship.

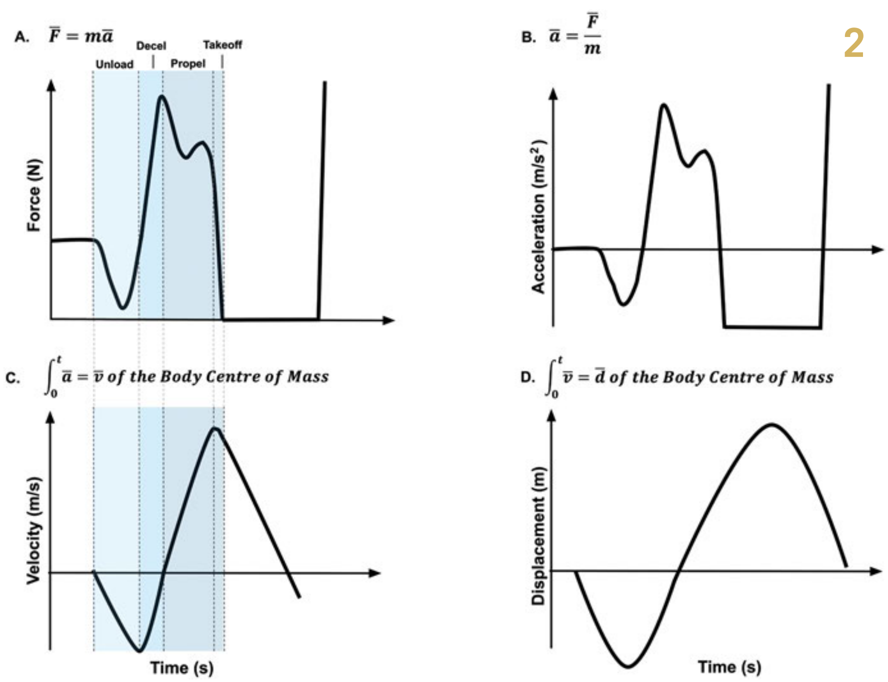

Figure 2: Sequence of equations for using time integration of the vertical ground reaction force – $\bar{F}$ (A) to determine the acceleration – $\bar{a}$ (B), velocity – $\bar{v}$ (C) and displacement – $\bar{d}$ (D) of the body centre of mass.

for persistent neuromuscular deficits such as knee extensor strength loss[27].

The requirement for practical and sensitive assessments that can be used in a high-performance sport environment to detect deficits in athletes following ACLR has spurred practitioners to incorporate field-based assessments of vertical jump interlimb force-time asymmetries measured with a dual force plate system[19,20,22,28–33]. While there are currently no studies providing evidence of a statistical relationship between elevated lower limb vertical jump force-time asymmetries and an increased risk ACL reinjury, assessing vertical jump asymmetries is becoming increasingly popular. The aim of this short review is to provide a practitioner's perspective on assessing lower limb force-time asymmetries in the vertical jump using a dual force plate system. We will focus on strategies to enhance data quality, force-time analysis techniques, normative values for vertical jump force-time asymmetries, considerations for employing asymmetry testing with athletes following ACLR, and future perspectives.

THE BASICS OF FORCE-TIME ANALYSIS

Newton's second law of motion tells us that the acceleration of an object with a constant mass in any given direction is proportional to the net forces that are applied to the object in that same direction. This equation also connects the application of force in a given time frame (i.e. impulse) to an object's change in velocity. These equations are shown below to determine the takeoff velocity in a vertical jump (Figure 1). The relevance of these equations is that the application of force during human movements like the vertical jump dictates how fast we move.

The vertical velocity of the body centre of mass can also be determined by time integration of the vertical component of the ground reaction force, Fz[37], and double integration of the acceleration vs. time tracing allows us to determine the displacement of the body centre of mass (Figure 2). The derivation of these equations is shown in Figure 2 and they are helpful when assessing vertical jump asymmetries in ACLR athletes. Whereas lower limb strength asymmetries are often assessed using discrete time point analysis (e.g. the instant of peak force or peak torque in a maximum voluntary contraction), vertical jump force-time asymmetries are best assessed over movement phases of interest and multiple movement cycles[38]. Movement phases can be defined using the velocity of the body centre of mass show in Figure 2A and 2C[20–22,28,30,32]. In addition to the method described here whereby the movement phases of interest in the vertical jump are defined using the velocity of the body centre of mass, other statistical methods, such as functional data analysis[28] and statistical parametric mapping, can be used to quantify interlimb asymmetries across the vertical jump force-time waveform.

It is important to evaluate interlimb asymmetries over the entire vertical jump force-time curve. Figure 3 shows the countermovement jump (CMJ) and squat jump (SJ) force-time asymmetries for an athlete with a history of ACLR. Limb dominance indicating greater force production on the reconstructed limb is shown with the light shaded blue region and non-injured limb dominance is shown with a dark blue shade. Visual inspection of Figure 3 shows that the directionality of the interlimb asymmetry changes over the propulsive and landing phases of the CMJ and SJ, with the ACLR limb generating a higher impulse in the CMJ eccentric deceleration phase and the early phase of the SJ. While this may appear counterintuitive, greater loading of the ACLR limb in the vertical jump has been reported elsewhere[20,21]. Conversely, the non-injured limb is dominant in the concentric (propulsive) phase of the CMJ and the late takeoff phase of the SJ.

The *movement asymmetry* shown in Figure 3 differs from strength or power interlimb asymmetries measured using dynamometry. In fact, humans display considerably more variability when it comes to movement asymmetries[39], and interlimb differences appear to be task dependent[40]. In the ACLR athlete factors such as the graft type can affect the directionality of vertical jump interlimb asymmetries[32] alongside propulsive versus energy absorptive movements[21]. For example, patients undergoing a semitendinosus autograft have been shown to demonstrate lower CMJ eccentric deceleration phase and concentric phase asymmetry compared to patients with a bone patellar tendon bone autograft[32].

In summary, we can improve our detection of vertical jump force-time interlimb asymmetries in athletes with ACLR using the following steps:

- Apply the physics of motion when assessing vertical jump force-time asymmetries.
- Assess vertical jump interlimb asymmetries over the entire force-time tracing and phases of movement.
- Assess vertical jump interlimb asymmetries over multiple movement cycles. Avoid discrete time point analysis such as the instant of the peak vertical ground reaction force.
- Remember that interlimb asymmetries are often variable and specific to the task in which they are measured.
- The directionality of the interlimb asymmetry may change in the recovering ACLR athlete; thus, both the magnitude and direction of between-limb differences should be considered
- Interlimb asymmetries in ACLR athletes are also affected by factors like the surgical procedure.

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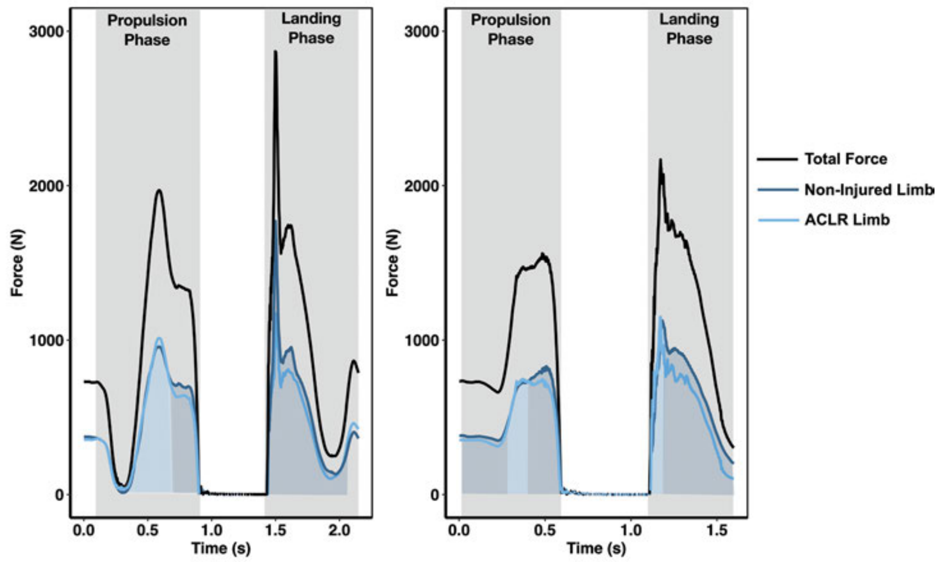

Figure 3: Vertical jump force-time interlimb asymmetries for an athlete with anterior cruciate ligament reconstruction (ACLR) during a countermovement jump (A) and squat jump (B). The light blue shading shows ACLR limb dominance and the dark blue shading shows non-injured limb dominance.

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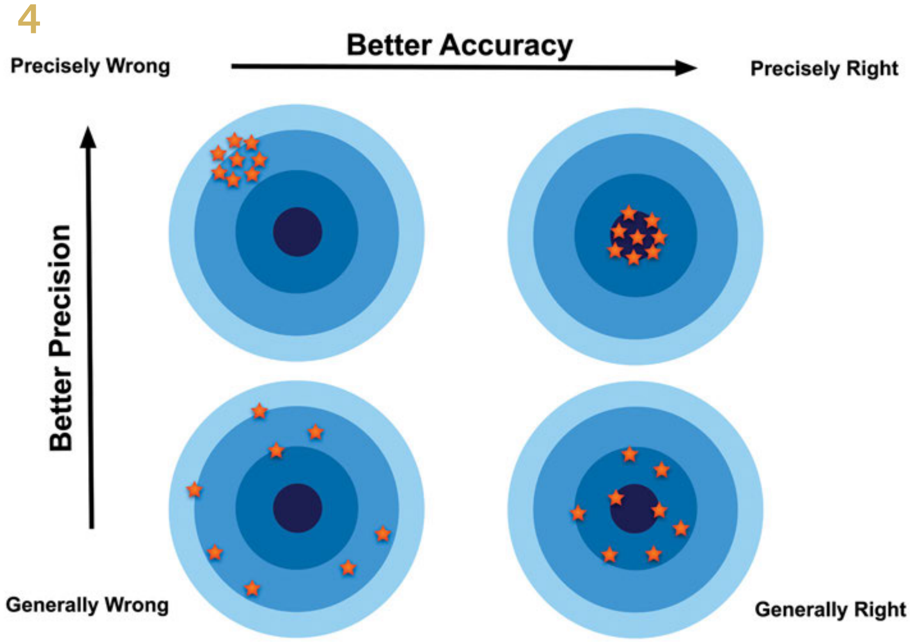

Figure 4: An analogy for accuracy and precision.

GETTING QUALITY DATA

Some degree of error is present in any measurement system. A dual force plate system doubles the measurement error and a faulty force plate (or two) can be problematic. For example, imagine we are assessing an athlete recovering from a right limb ACLR whose true interlimb asymmetry index is 20%. If the right force plate increases the vertical ground reaction force (Fz) and the left force plate decreases Fz, we may observe an asymmetry index of 9% and underestimate the true imbalance. We would erroneously conclude the athlete is sufficiently prepared for a return to sport. This example highlights the importance of ensuring data quality, especially given the impact on athlete health and safety. To

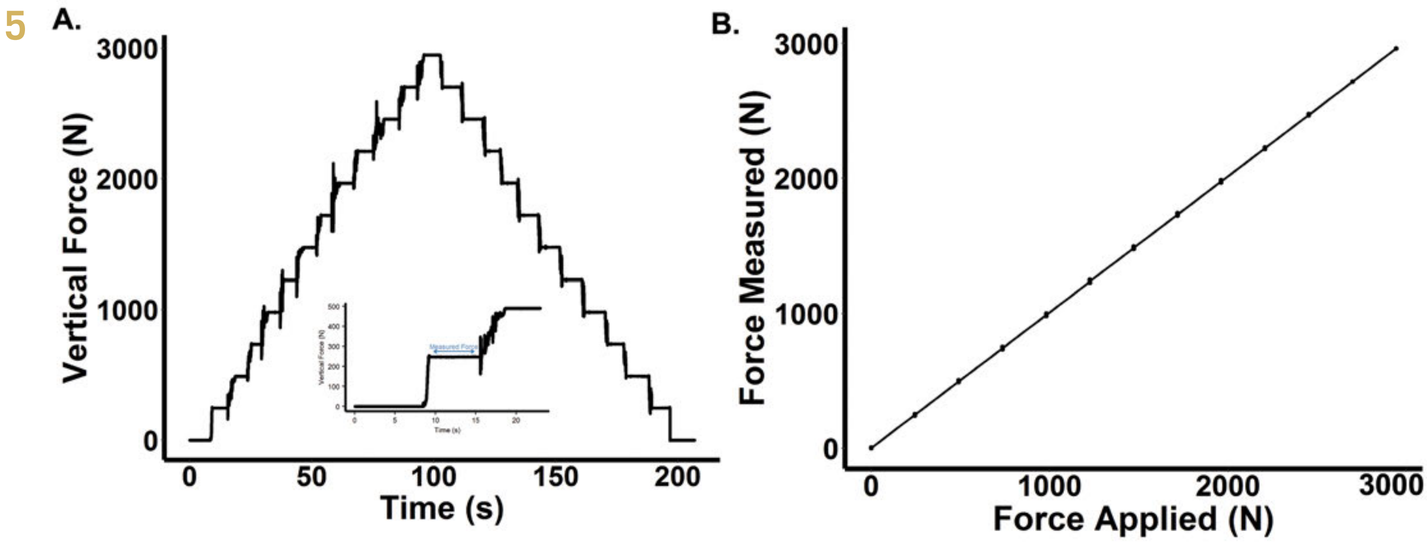

Figure 5: An example calibration procedure showing a stepwise external load application to a force plate (A). Assessment of the linear relationship between the applied force and measured force (B).

further illustrate this point, we can view the accuracy and precision of our testing instruments like a dart board (Figure 4).

The accuracy and precision of a force plate may change over time. This may be due to normal wear and tear, sensor damage and even changing the physical environment where the force plate is used (e.g. moving a portable force plate from a low traffic laboratory to a busy weight room). The best safeguard for ensuring the accuracy and precision of a force plate is routine calibration procedures that tests the force plate across the operating range. A simple calibration procedure is depicted in Figure 5A. In this example, an external load is applied in 25 kg increments up to a total of 300 kg. The linearity of the measured force versus the applied force is then assessed (Figure 5B). Importantly, the same external load should be used in each calibration session. The frequency of calibration depends on how much data we are willing to lose. Suppose we perform two calibrations separated by 6 months and detect a faulty force plate in the second session. We are justified to question all the data that was collected between the two calibration sessions.

Whether or not this is a problem depends on the practitioner and the scenario. For example, data that is collected for scientific purposes may require more frequent calibrations compared to data that is collected for the purpose of providing biofeedback to the athlete.

Force plate calibration may seem trivial or unnecessary; however, consider the example provided in Figure 6 that depicts four routine calibration sessions of a Pasco force plate, a brand that is often used in high performance sport settings because of the low cost and portability. Panel 6A indicates the accuracy of a Pasco force plate is sufficient for use in high performance sport, a finding consistent with other reports[34]. However, a progressive loss in accuracy is seen between the first calibration session and the three subsequent sessions. By the third session, forces that are typically measured in a vertical jump (≈ 2000 N) are impacted. Problematically, the loss of accuracy (3-5%) is consistent with what a practitioner might expect in terms of a physiological change in an elite athlete or a functional change that might occur with an ACLR athlete throughout rehabilitation.

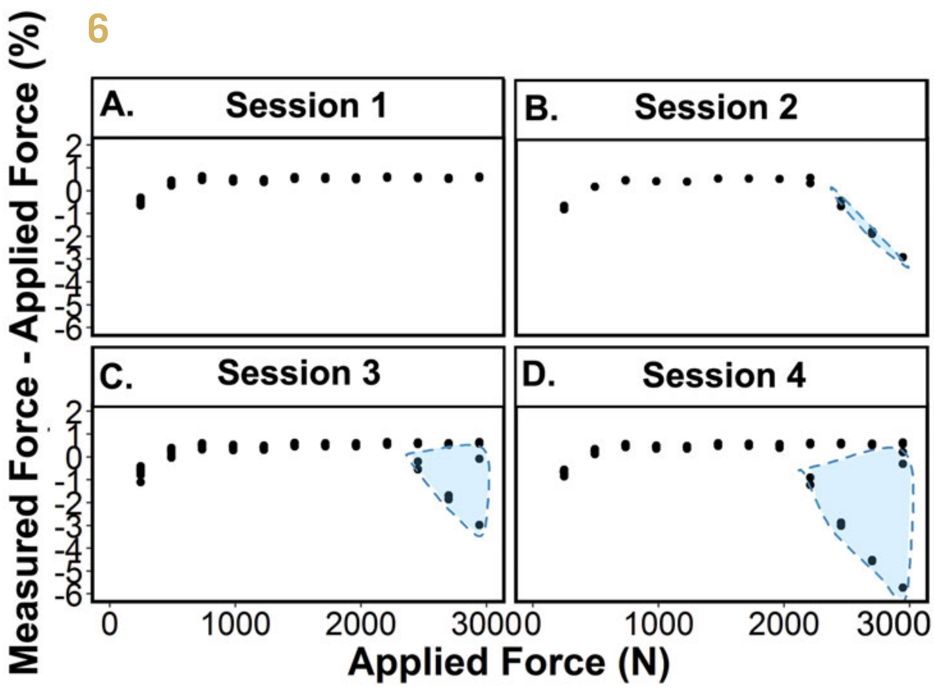

Figure 6: Routine calibration sessions to detect a malfunctioning force plate. The error observed in Sessions 3 and 4 can be easily mistaken for a physiological change or a recovery in interlimb asymmetry for an ACLR athlete.

The impact of failing to detect a faulty force plate is illustrated in Figure 7. Measurement error increases with the fast

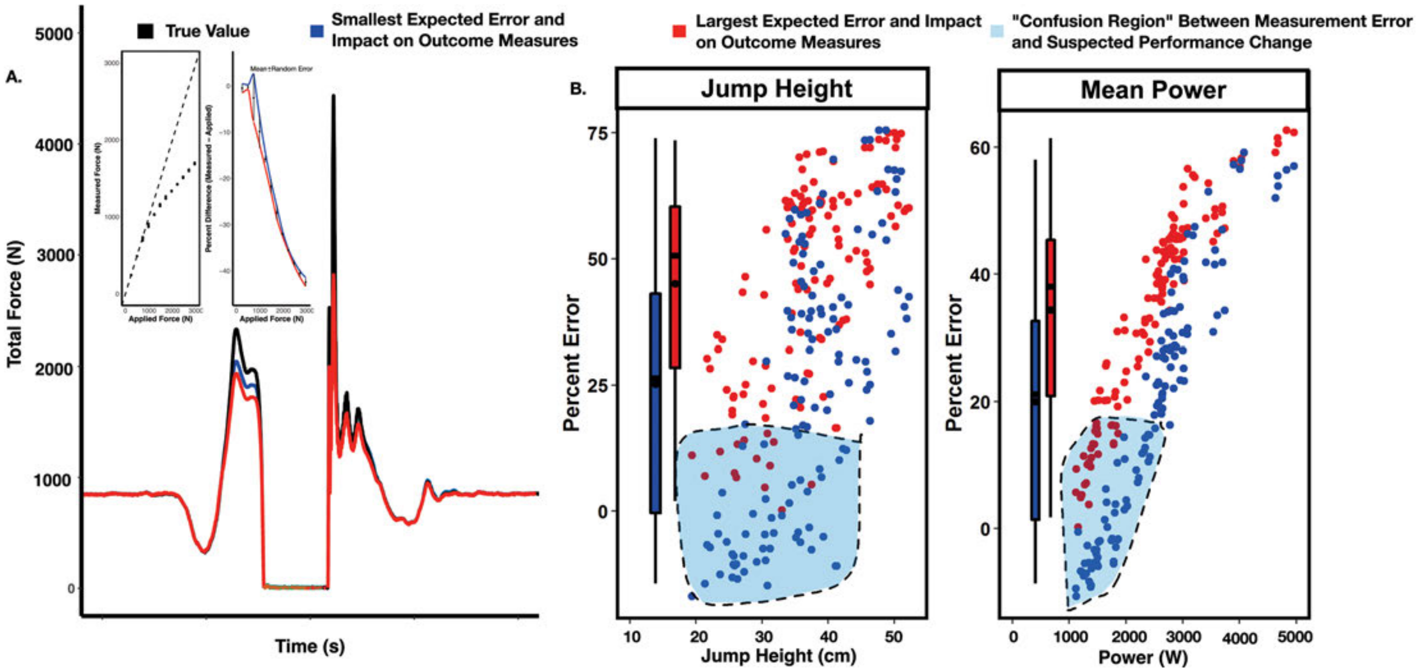

Figure 7: Consequences of a malfunctioning force plate on vertical jump force-time variables are shown. We established the measurement error of a faulty force plate (Panel 4A - inset). The lower and upper limits of agreement were used to adjust force-time curves in order to establish a 'best case' and 'worst case' scenario, had jumps been measured using the malfunctioning force plate (Panel 4A - main). Force-time analysis (see section below) was conducted for 'true', 'best case', and 'worst case' scenarios using 635 representative vertical jumps. The percent error from 'true' was calculated for common vertical jump outcome measures (Panel 4B). Note the overlap between the expected error as a result of equipment malfunction, and changes that could be expected from training (0-20%) shown in the shaded blue region. This highlights the potential for type I and type II training errors if equipment calibration is not performed (i.e. mistaking a performance change for measurement error or missing a performance change due to measurement error).

application of force, like in a vertical jump or when assessing rate of force development (RFD). The loss of accuracy of the force plate could be easily mistaken for typical performance changes in jump height and mechanical power (Figure 7B and 7C), or a functional change in vertical jump force-time asymmetry.

We have found that hard landings on the corner of a portable force plate will exceed the load cell capacity, accelerating the loss of accuracy. To mitigate this problem, a practitioner might decide to use a force plate with a higher load capacity. However, there is a tradeoff between the capacity of a load cell and its accuracy at the low and high end of its operating range. While a force plate with > 2000 kg load capacity can withstand a high force jump landing, the accuracy of the plate may be less than ideal when measuring forces associated with jumping and squatting movements.

Cumulatively, we can improve our data quality processes when assessing interlimb asymmetries with dual force plate systems using a few simple steps:

- Purchase a force plate carefully. Consider the types of movements and tests that will be performed on the force plate. Ask the supplier about the accuracy and precision of the force plate across its operating range. Consider the force plates load capacity and required accuracy for the types of testing that will be performed.
- Calibrate force plates regularly across the operating range. Pay close attention to non-linearities between the measured force and applied force. The calibration frequency depends on the purpose (e.g. biofeedback vs. scientific research), the amount of data we are willing to lose in the event a faulty force plate is detected, the force plate brand/durability, and the testing environment.
- If possible, compare the new force plate to an existing system. Assess the test-retest reliability of specific jump protocols using a new force plate, and ensure it is consistent with previously collected data and what is reported in the scientific literature.
- As vertical jump force-time analysis involves mathematical calculations like time integration, it is important to accurately determine the athlete's body weight with a quiet standing period that is obtained for each vertical jump force-time recording[35]. Choose a sampling frequency of at least 500 Hz especially if more detailed vertical jump force-time analysis is planned[36].

NORMATIVE ASYMMETRY DATA

Normative vertical jump asymmetry data is shown in Figure 8, obtained from 96 competitive alpine ski racers (ACLR: n=23). These athletes collectively performed 1030 CMJ tests and 629 SJ tests over a 9-year time period on a dual force plate system during routine athlete monitoring, lower body strength testing, and throughout the post-surgical period after ACLR. A 5-jump mean asymmetry index was calculated for each jump test between 4 months and more than 5 years post-surgery. Athletes with other lower extremity injuries including leg fractures, tendinopathies, osteochondral disease, meniscal tears, and knee collateral ligament sprains were excluded along with those who reported acutely symptomatic lumbar spine injuries. The interlimb asymmetry index was calculated for specific phases of the CMJ including the eccentric

The interlimb asymmetry index (AI)

$$AI\ Non-Injured\ Athletes = \left(\frac{Right\ Limb\ Impulse - Left\ Limb\ Impulse}{Maximum\ of\ Left\ and\ Right\ Impulse}\right) * 100$$

$$AI\ ACLR\ Athletes = \left(\frac{Contralateral\ Limb\ Impulse - ACLR\ Limb\ Impulse}{Maximum\ of\ Left\ and\ Right\ Impulse}\right) * 100$$

deceleration, concentric and landing phases, and the SJ early takeoff, late takeoff and landing phases using the formulae above and according to the procedures described elsewhere[20–22]:

Using this formula, a positive value for non-injured control athletes indicates right limb dominance and a negative value shows left limb dominance. For ACLR athletes, a positive value reflects non-injured limb dominance whereas a negative value designates ACLR limb dominance. The data shown in Figure 8 is specific to alpine ski racers, but alpine ski racers perform bidirectional turns in training and racing, suggesting that there are no sport-specific requirements for a dominant limb.

A summary of the median and range for phase-specific asymmetries is provided in Table 1. ACLR athletes demonstrated a higher asymmetry index for the concentric phase of the CMJ and late takeoff phase of the SJ, which is consistent with other reports[20,22,33].

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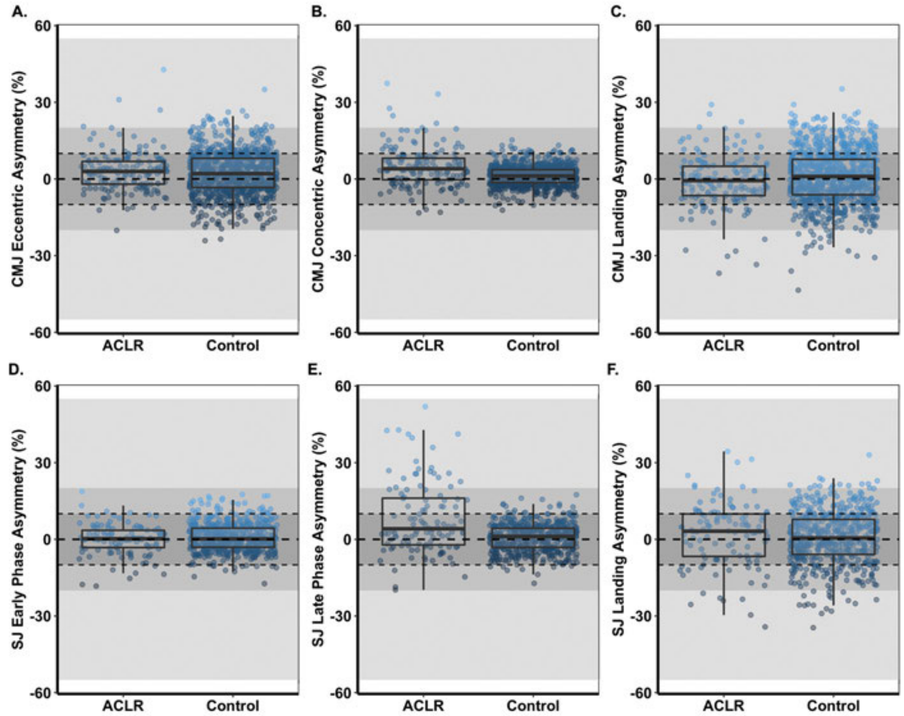

Figure 8: Vertical jump interlimb asymmetries for ACLR (n=23) and non-injured competitive alpine skiers (n=73) for the countermovement jump (CMJ) eccentric deceleration phase (A), CMJ concentric phase (B), CMJ landing phase (C), squat jump (SJ) early takeoff phase (D), SJ late takeoff phase (E) and SJ landing phase (F). The dark grey band represents an asymmetry index of ± 10% and the light grey band represents an asymmetry index of ±20%.

Table 1

	CMJ Eccentric Phase Asymmetry (%)			*CMJ Concentric Phase Asymmetry (%)*			*CMJ Landing Phase Asymmetry (%)*		
	Min	*Max*	*Median*	*Min*	*Max*	*Median*	*Min*	*Max*	*Median*
ACLR	-20.1	42.8	3.0	-13.3	37.4	4.0	-36.9	29.1	-0.6
Control	-24.2	35.0	2.1	-12.2	15.3	1.2	-43.5	35.3	1.0
	SJ Early Takeoff Phase Asymmetry (%)			*SJ Late Takeoff Phase Asymmetry (%)*			*SJ Landing Phase Asymmetry (%)*		
	Min	*Max*	*Median*	*Min*	*Max*	*Median*	*Min*	*Max*	*Median*
ACLR	-18.3	18.7	0.2	-19.8	51.9	4.1	-34.3	34.4	3.2
Control	-17.4	17.6	0.2	-17.2	17.4	1.1	-34.6	33.0	0.5

Table 1: Summary of the median, minimum and maximum asymmetry indices for the squat jump (SJ) and countermovement jump (CMJ) in anterior cruciate ligament reconstructed (ACLR) and non-injured (control) competitive alpine skiers.

Landing asymmetries were variable for both groups. The non-injured athletes displayed greater variability in the eccentric deceleration phase of the CMJ compared to the concentric phase of the CMJ, and the majority of non-injured athletes displayed an interlimb asymmetry index less than 10% over the jump tests, which is similar to other reports (Figure 9)[32].

The relationship between elevated vertical jump asymmetries and risk for lower body injury is unknown. However, we may be able to develop some simple heuristics using the normative data presented in Table 1 and in Figure 9 to improve the training process. Injury prediction is challenging but sport science and sport medicine practitioners are often seeking to identify trainable deficits that either lead to a performance improvement or mitigate a perceived injury risk factor. For example, suppose we observed a 50% asymmetry in a non-injured athlete. This value is extreme and highly atypical. The new information would allow us to adjust our decision making, particularly around exercise prescription and training program design to reduce the interlimb asymmetry.

Let's consider a real-world example shown below in Figure 10. Vertical jump asymmetry testing was conducted with 66 competitive athletes prior to the start of the competitive season (baseline). Athletes performed 5 CMJs and 5 SJs but only the CMJ data are shown. The occurrence of knee injuries was tracked in a prospective manner. No training decisions were made from the baseline test results. Suppose we chose a cutoff of > 20% asymmetry to flag an athlete requiring our attention. This heuristic would capture half of the athletes who eventually go on to suffer a knee injury and none of the non-injured athletes. Notably, four athletes who went on to suffer a knee injury presented with an eccentric deceleration asymmetry greater than 20%.

Using the normative data shown above in Figures 8 and 9, we can further contextualize the chance of observing an eccentric deceleration asymmetry greater than 20% in a group of non-injured athletes. Of the 876 CMJ tests performed by the non-injured alpine skiers, only 2.7% of the asymmetry scores were greater than 20%. We can summarize our section on normative vertical jump asymmetry testing data with the following bullet points:

- ACLR athletes present with higher vertical jump force-time interlimb asymmetry in the late takeoff phase of the SJ and the concentric phase of the CMJ compared to non-injured athletes.
- Non-injured athletes typically present with vertical jump interlimb asymmetries less than 10%.
- Based on our real-world training example, if we used a cut-off of 20% to indicate an atypical asymmetry score for a non-injured athlete, we would have only captured athletes who went on to suffer a knee injury. Further, an eccentric deceleration asymmetry > 20% occurs infrequently, and may provide us with new information on which we can base training program design and exercise prescription decisions.

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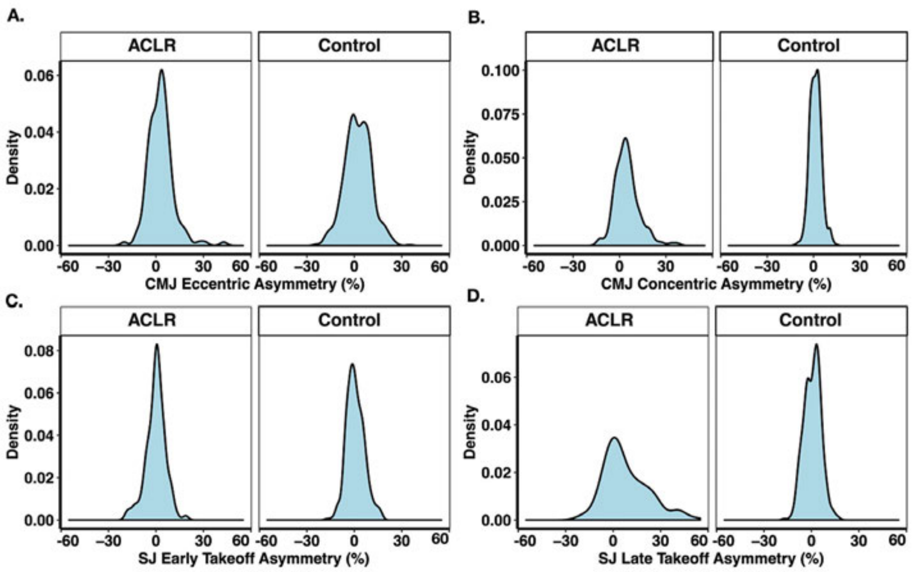

Figure 9: Vertical jump interlimb asymmetries density plots representing the distribution of the asymmetry indices for the countermovement jump (CMJ) eccentric deceleration phase (A), CMJ concentric phase, squat jump (SJ) early takeoff phase (C), SJ late takeoff phase (D).

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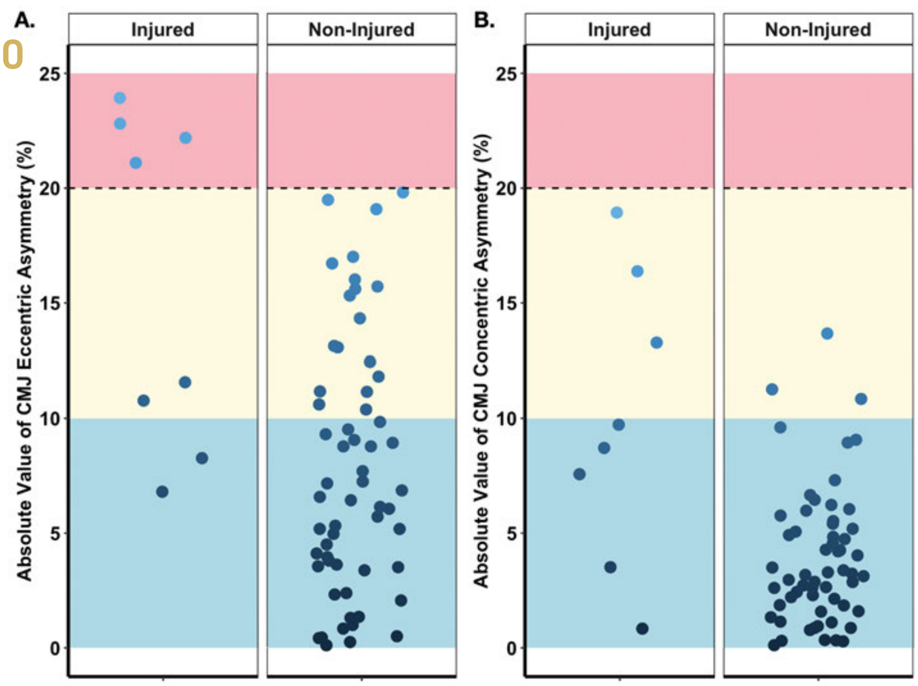

Figure 10: Prospective data from 66 competitive athletes undergoing countermovement jump (CMJ) interlimb asymmetry testing at the start of the pre-competitive training period. Injury surveillance was conducted to track knee injuries. A cut-off threshold of an eccentric asymmetry > 20% captured 50% of the injured athletes and none of the non-injured controls. Panel A shows the CMJ eccentric deceleration phase asymmetry and Panel B shows the CMJ concentric phase asymmetry.

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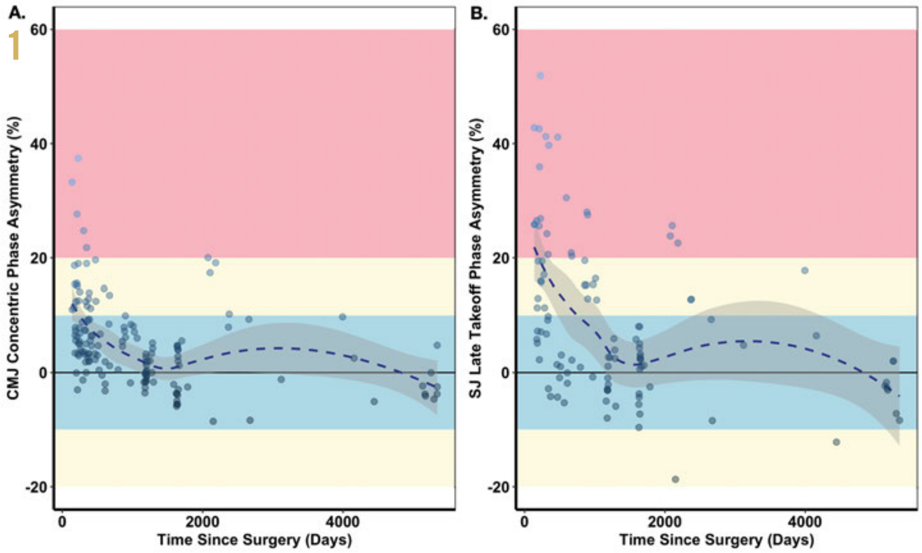

Figure 11: Time-course recovery of countermovement jump (CMJ) and squat jump (SJ) interlimb asymmetries in competitive alpine skiers after anterior cruciate ligament reconstruction (ACLR) surgery. Panel A depicts the CMJ concentric phase asymmetry and Panel B shows the SJ late takeoff phase asymmetry.

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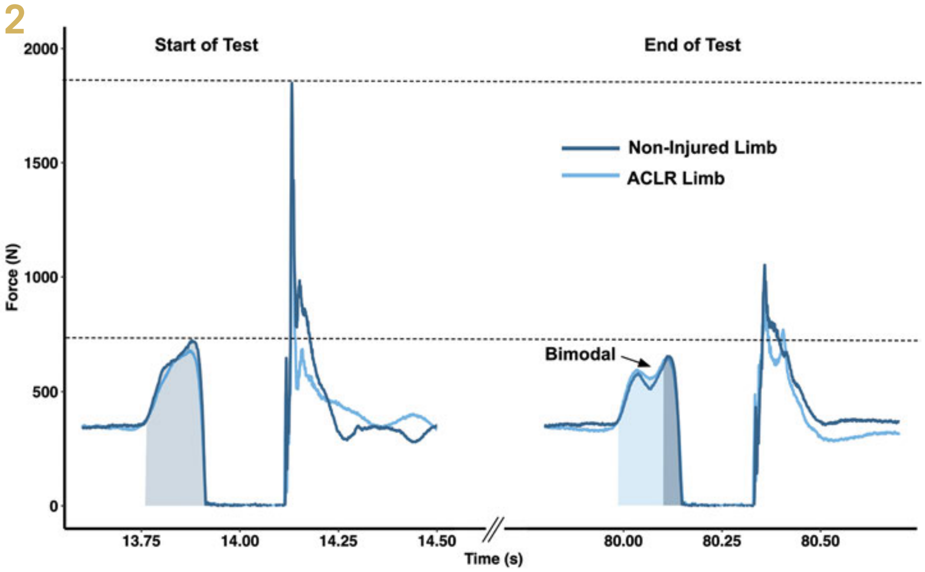

Figure 12: An 80-second repeated squat jump (SJ) test force-time curves obtained from a competitive alpine skier with anterior cruciate ligament reconstruction (ACLR) surgery. The athlete becomes more symmetrical in the late takeoff phase at the end of the test and the force-time curve becomes bimodal. Black dashed lines show a reduction in the vertical ground reaction force for the propulsion and landing phases of the SJ.

- While injury prediction is inherently challenging, simple heuristics and data-informed decision making using vertical jump asymmetry testing can assist sport science and sport medicine practitioners to identify trainable deficits in non-injured and injured athletes.

VERTICAL JUMP FORCE-TIME ASYMMETRIES IN ATHLETES WITH ACLR

Standardized and repeatable neuromuscular assessments are important for athletes returning to sport after ACLR[10,16,18,19,23]. While there is evidence supporting the use of long-standing assessments like quadriceps strength testing[18], the predictive validity of functional performance tests like the single leg hop for distance are equivocal[26]. It may be the case that ACLR athletes compensate during performance-based testing to achieve benchmarks while masking deficits[27]. In addition to the performance outcomes obtained from vertical jump testing such as jump height and mechanical power, we can also assess how an athlete achieved performance outcomes by analyzing the CMJ and SJ force-time recording as described above.

In individuals with ACLR, CMJ concentric phase force-time interlimb asymmetries are associated with knee extensor strength interlimb asymmetry assessed using isokinetic dynamometry[32], suggesting a potential surrogate or complementary neuromuscular measure for a known risk factor for ACL reinjury (i.e. quadriceps strength deficits)[18]. Vertical jump force-time asymmetries also persist in athletes who have returned to sport after ACLR[20–22] and following lower body injury[33]. While there is currently no scientific evidence linking return to sport outcomes after ACLR with elevated vertical jump force-time asymmetries, jump asymmetry testing appears to be sensitive to the recovery process after ACLR. Figure 11 depicts the recovery in CMJ concentric phase asymmetry and SJ late takeoff phase asymmetry for 20 ACLR competitive alpine skiers who performed serial testing throughout the return to health, return to sport and return to performance transitions.

It took just over one year for the mean interlimb asymmetry index (dashed blue line) to fall below 10%, a common threshold used for return to sport readiness. However, more than 2 years were required for the interlimb asymmetry index to return to a value comparable to that of non-injured alpine skiers. This notion is consistent with other reports that suggest more than 2 years may be required for recovery after ACLR[25,41]. Building sport-specific recovery timelines using vertical jump asymmetry testing can be valuable for sport science and sport medicine practitioners in order to manage coach/athlete expectations after injury, improve injury recovery forecasting and to develop recovery norms against which new rehabilitation strategies or medical interventions can be compared.

However, a reductionist interpretation of vertical jump asymmetry testing can be misleading. For example, a well-known effect of lower limb injury is contralateral limb strength loss. An athlete with ACLR who has two symmetrical, but weak lower limbs may have different challenges with a safe return to sport compared to an athlete who has two strong lower limbs that are asymmetrical (e.g. an asymmetry index > 20%). Further, CMJ and SJ testing may not reflect the sport-specific demands. For instance, alpine ski racing is energetically demanding, and skiers are exposed to high force eccentric/quasi-isometric loading that exceed the forces produced in the vertical jump. Other sports like basketball or soccer may have a greater emphasis on single leg propulsion/energy absorption. Interlimb asymmetries are also task-dependent[40] and movement phase dependent (c.f. Figure 7).

Consequently, practitioners may be best served by building a sport-specific envelope of function and a risk profile for athletes returning to sport after ACLR[42]. While vertical jump asymmetry testing using a dual force plate system is practical and conducive for routine athlete monitoring, additional assessments may be useful when evaluating ACLR athletes. Tests of interest include single leg jumping and landing tests[19], repeated jump testing to assess the effects of performance fatigability on force-time characteristics[21,43], and loaded vertical jump testing (functional force-velocity profiles). Consider the example shown in Figure 12 depicting a SJ force-time curve for the first jump and the last jump of an 80-second repeated SJ test in which the athlete performed one jump every 4 seconds (total jumps: n=20). The 80-second repeated SJ test was developed for alpine ski racers to assess neuromuscular function over a time frame comparable to a typical race[21]. Outcome measures of interest include a fatigue index (drop-off in mechanical muscle power from the start to the end of the test), total mechanical power over the test and the acute effects of fatigue on interlimb asymmetries.

The force-time curves in figure 12 also show the athlete becoming more symmetrical with fatigue consequent to a reduction in force generated by the non-injured limb. The force-time curve shape in the final jump is also bimodal, suggesting a potential change in the vertical jump strategy. As the contralateral limb is particularly susceptible to ACL injury after a primary ACL injury is sustained[26,41], objective assessments that challenge the athlete in a sport-specific manner in terms of the energetic demands can be helpful for exposing trainable deficits for the non-injured and injured limbs alike.

Summary recommendations for incorporating dual force plate asymmetry testing with ACL injured athletes include:

- There is limited scientific evidence supporting return to sport testing batteries after ACLR and no statistical relationship between elevated vertical jump interlimb asymmetries and outcome after ACLR, so caution is warranted.
- Vertical jump asymmetries persist in athletes with ACLR and lower body injuries despite their return to sport. However, force-time interlimb asymmetries diminish over time, suggesting the relevance of vertical jump asymmetry testing as a monitoring tool for sport science/sport medicine practitioners.
- Athletes with ACLR may present initially with very high vertical jump interlimb asymmetries (> 50%). It often takes more than 1 year for the asymmetry index to return below 10%, and more than 2 years may be required for interlimb asymmetries to return to values observed in non-injured athletes.
- An interlimb asymmetry index is inherently problematic. What if an athlete is symmetrical but has two weak lower limbs? What if an athlete has two strong limbs but is asymmetrical? These questions are important to consider.
- Sport science and sport medicine practitioners may be best served by developing a return to sport testing battery that is sport-specific and uses multiple tests to build a risk profile aimed at exposing trainable deficits.

FUTURE DIRECTIONS

More scientific inquiry is required to examine the value of vertical jump interlimb asymmetry testing for assessing athletes with ACLR throughout the return to health, return to sport and return to performance transition. Dual force plate systems are becoming increasingly common in clinical and high-performance sport settings. Practitioners should be careful to ensure data quality given the implications of return to sport decision making. There are no short cuts for ensuring a force plate is working properly. Routine calibration is essential to limit the possibility a malfunctioning force plate is misconstrued for a performance or functional change in an athlete with ACLR.

Vertical jump asymmetries are variable and task dependent. Consequently, more sophisticated approaches to force-time curve analysis like statistical parametric mapping and machine learning may provide sport science and sport medicine practitioners with better insights and predictive validity. Further, many commercially available systems ignore the bulk of the ground reaction force signal including horizontal forces. There may be valuable information in these planes, especially when evaluating athletes with ACLR. The high fidelity nature of the data obtained from dual force plate asymmetry testing and the many unanswered questions will provide sport science and sport medicine practitioners with plenty of fruitful research opportunities to explore new approaches for optimizing the return to health, return to sport and return to performance transition for athletes recovering from ACLR.

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SINGLE VS DOUBLE LEG COUNTERMOVEMENT JUMP TESTS

NOT HALF AN APPLE!

– *Written by Daniel Cohen, Adam Burton, Carl Wells, Matt Taberner, Maria Alejandra Diaz, Philip Graham-Smith*

INTRODUCTION

Historically, following anterior cruciate ligament reconstruction (ACLR), limb symmetry indexes calculated using post-injury contralateral performance in a series of single leg hop tests have been used to guide return to sport (RTS) decision making[1]. However, two major limitations of this approach have been highlighted:

1. Declines in contralateral healthy limb performance undermine the value of a limb symmetry index as a benchmark for RTS[2].
2. Normalisation of output variables such as distance hopped does not equate to recovery of underlying functional deficits identified by biomechanical assessment of movement strategy[1,3].

In most sports and clinical environments, financial and/or time costs limit systematic use of 3D motion capture and tri-axial force plates for biomechanical assessments. However, assessments use of dual force platform single axis technology, allowing the assessment of vertical ground reaction forces (vGRF), and asymmetries thereof, during double and single leg jump-land activities is now commonplace in these settings. This has led to an increase in the availability of healthy individual limb kinetic data, reducing the dependence on contralateral limb as a benchmark during rehabilitation. In addition, while these measurements do not permit the quantification of joint-specific contributions that 3D kinematics provides; however, associations between vRGF and knee kinetic asymmetries following ACLR[4,5] mean that these data are considered clinically relevant in the context of rehabilitation to quantify the magnitude of inter-limb asymmetries[5-8] and the effect of specific interventions[9]. Furthermore, specific bilate-ral (combined limb output) variables in the countermovement jump (CMJ) also appear to be provide additional insight on injury induced alterations in movement "strategy"[9,10].

It is well documented that dual force platform jump-land tests reveal kinetic asymmetries months to years after RTS following ACLR, with landing phase asymmetries in the double limb (DL) drop jump (DJ) a consistent finding, particularly in female athletes[11]. More recent reports show similar associations between heightened asymmetries in the take-off (eccentric and concentric) and landing phases of the DL- CMJ- and prior ACLR and other lower-limb injuries[10,12,13]. The increased use of force platforms in performance settings and published research[14] has however highlighted that an athlete's inter-limb asymmetries derived from single leg (SL) and the double leg (DL) CMJ tests may not align either in their magnitude or direction. This observation has in turn led many practitioners to ask: which of these provides a better or more accurate measure of asymmetry? We highlight two opposing viewpoints from the literature which frame this question, and suggest that a simple answer is likely not apparent:

"the SL test provides a more valid measurement of a limbs strength or power

and inter-limb symmetries, while data from the DL CMJ should be interpreted with caution"[14]

"bilateral movements were more suited to reveal possible asymmetries in GRFs, because the patients could spread the load between the legs and use inter-limb compensation strategies"[5]

We aim to reconcile these apparently contradictory conclusions and share the reasoning behind the adoption of the DL-CMJ as a core test in assessing athletes post-ACLR, while recognising the value of single leg jump tests. We also highlight that given the very different demands of the SL and the DL-CMJ, it is expected that different information will be derived from this test, and we suggest the original question should be reframed as:

"Does combining bilateral and unilateral tests improve our understanding of the impact of ACLR on neuromuscular performance and the effects of specific types of loading during rehabilitation, and can this information enhance exercise prescription and progression decisions through rehabilitation and RTS?"

A greater understanding of neuromuscular performance deficits and individual responses post-ACLR can enhance the individualisation of exercise prescription and underpin a "precision medicine" approach in rehabilitation. The ultimate aim of a reduction in the figure of < 1/2 of players returning to competitive sport after ACLR[15] and reducing risk of re-injury.

Why the DL-CMJ?

Evidence from training and fatigue-response literature demonstrate bilateral DL-CMJ variables provide valuable insights on underlying movement/kinetic strategy and in particular, the potential to quantify eccentric or "deceleration" performance[5,6,9,18] during a high velocity triple extension activity. Force platform assessment of CMJ performance following fatiguing exercise or after training interventions have shown that compared to "conventional" output variables such as jump height and peak power, specific bilateral "alternative-variables" such as flight time :contraction time (FT:CT) are more sensitive markers of acute and residual fatigue and chronic training adaptations[19]. For example, acute and residual fatigue following competition or high intensity intermittent activity, may not manifest in a reduction in jump height but is expressed in alterations in jump strategy including increased duration of the eccentric and concentric phases and total contraction time[19,20] and changes in other kinetic variables. Therefore, while there is a justifiable interest in phase-specific asymmetries and /or deficits[5,7,9,10,12,13], evidence[10] case studies[9] and the authors' experience with athlete rehabilitation informed by force platform data for over two decades suggests that bilateral DL-CMJ strategy variables also add insight into athlete status and response to loading during rehabilitation and RTS. This aligns with the evidence that recovery of performance output (i.e. distance hopped) in clinical hop tests may mask persistent strategy deficits following ACLR[3,21,22]. Further supporting this, a recent review concluded that single leg hop for distance (SLHD) asymmetries post-ACL do not reflect residual functional deficits detected by biomechanical alterations in take-off and landing strategy[1]. For example, kinematic analysis of hops in patients post-ACLR showed both those with and without hop distance symmetry off-loaded the ACLR knee[3]. An asymmetrical hop distance was associated with an ankle dominant strategy while symmetry was associated with a hip dominant strategy. Similarly, King[21] found no significant inter-limb differences in either hop distance or performance times in change of direction tasks 9 months post-ACLR but did identify several significant kinetic and kinematic asymmetries during the performance of these movements. Therefore, achieving symmetry in performance outputs in common clinical tests does not appear to equate to either knee kinetic symmetry during the tests or to symmetry in other athletic tasks. While defining the precise nature of these biomechanical alterations requires kinematic analysis, and in the absence of this technology, CMJ vGRF derived eccentric, concentric and landing phase bilateral variables and asymmetries may provide a surrogate means to identify and quantify alterations and deficits in both neuromuscular strategy and capacity that underpin movement[4,5].

Since horizontal hop test variants are more commonly used clinically, fewer studies describe SL-CMJ performance post-ACLR, yet SL-jump height asymmetries are reported both at 6 months[23,24] and > 2 years post ACLR[5,25]. Therefore, while SL-CMJ is moderately correlated with isokinetic knee strength,[23,25] in parallel with the observations around SLHD post ACLR, SL-jump height may not reflect knee kinetic deficits due to inter-joint compensations at the ankle and hip[23,24].

It is argued that SL-CMJ asymmetries represent a purer measure of limb capacity than the DL-CMJ which is "contaminated" by variations in output across the lower limb, trunk and pelvis. However, inter-joint (hip and ankle) compensation in the SL-CMJ makes performance and kinetic asymmetries a poor measure of knee deficits.

DL activities provide more options to unload the previously injured knee; primarily via inter-limb (involved limb to uninvolved), compensatory or avoidance strategies[7,8,10] easily quantified by vGRF alone, and also inter-joint (involved knee to involved ankle and hip) strategies[5,26] which require kinematics to quantify. When considering the "value" of SL Vs. DL-CMJ asymmetry data and relevance to functional outcomes, Baumgart and colleagues' work[5,7] which assessed individuals 32 months post-ACLR with both tests, provides an important observation; all DL-CMJ vGRF asymmetries they evaluated showed large and significant differences in individuals with high compared to low subjective knee function, while asymmetry in SL-CMJ jump height did not.

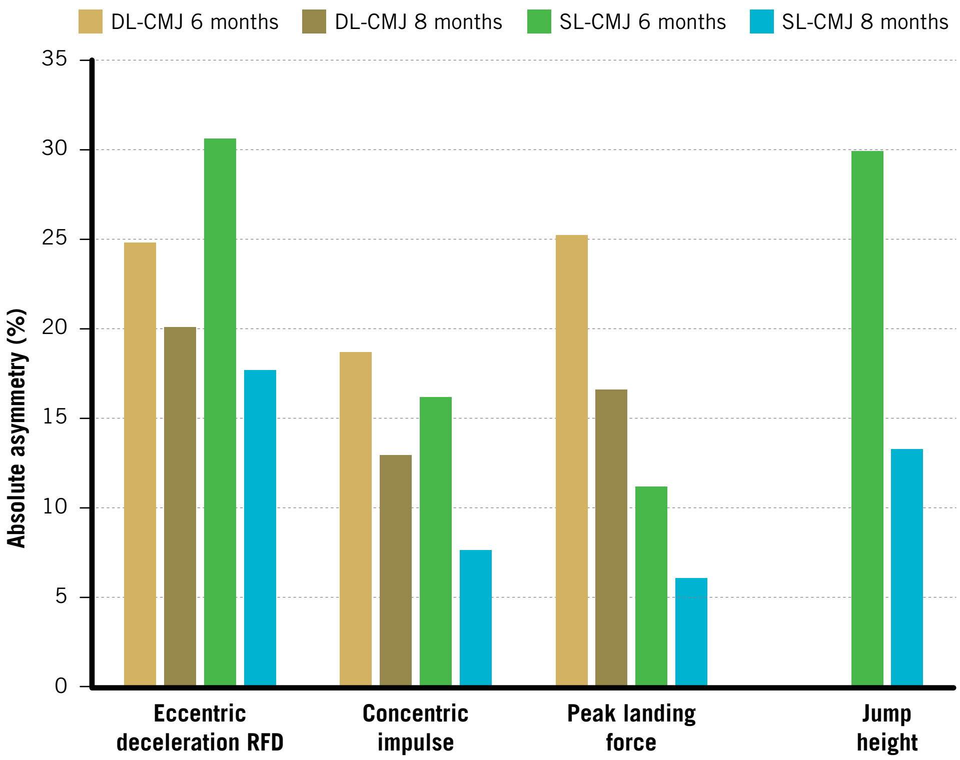


Figure 1: Selected DL- and SL-CMJ asymmetries in pro-footballers 6 and 8 months post-ACLR.

SL vs. DL jump – Strategy vs. Capacity?

A mismatch between single v double limb asymmetries is also observed in supported SL v DL isometric knee extension tasks[27], indicating that this phenomenon is not exclusive to jump-land activities. Furthermore, as asymmetries are also expressed during submaximal bilateral contractions where maximal limb capacity is not limiting, researchers and clinicians have emphasised the neural origins of bilateral task asymmetries[27,28]. In recent work in post-ACL patients, Chan & Sigward[28] showed that asymmetries during (submaximal) squat and sit-to-stand tasks could be acutely corrected with instructions and real-time feedback, indicative of their loading behaviour not reflecting their capacity to load. Chan & Sigward suggest that asymmetries in DL activities may be driven by "learned non-use", a phenomenon described in post-stroke patients, whereby individuals with unilateral neurological deficits with the ability to use the involved arm choose not to when given the option of preferred limb selection, but do so when the uninvolved arm is constrained[29].

Given evidence that asymmetries in SL-CMJ and drop jump performance are associated with poorer change of direction (COD) ability[30], and SL-CMJ landing force asymmetry with lower limb injury risk in youth footballers[31], SL measurements clearly provide valuable information, at least in healthy athletes. However, quantifying kinetic compensatory strategies following ACLR by simultaneous capture of vGRF in both limbs during the same task[18] is a critical part of understanding progress during rehabilitation and in light of the persistence of these asymmetries in player's post return to competition (RTC), of informing "post-hab" i.e. conditioning to address residual deficits not addressed prior to RTS.

SL v DL asymmetries post-ACLR in professional footballers

Figure 1 shows selected SL-CMJ and DL-CMJ asymmetries in post-ACLR professional footballers (mean 24 weeks and 32 weeks' post-surgery) (un-published data). These values broadly align with that reported in non-elites 18 months post-ACL[7] and in professional footballers with various prior lower limb injuries post-RTC[10,12], both underlining the persistence of specific asymmetries, and also suggesting that the inter-limb compensatory strategies are not exclusive to ACL injury. In terms of load reduction/acceptance capacity, data derived in the CMJ eccentric deceleration (ED) and landing phases are of specific interest. The magnitude and effect sizes of asymmetries observed in these phases in healthy individuals with prior injury suggest that inter-limb compensatory strategies which reduce eccentric loading and impact forces are highly persistent[10,12] and may require special attention.

"Anatomy" of the SL- and DL-CMJ

Using body segmental mass ratios, it can be estimated that active leg load in a SL movement is ≈1.62 times of those in a DL movement. Similarly, using SL and DL-

Table 1

	SL-CMJ		DL-CMJ	
Concentric peak ground reaction force (N)	*Left*	*Right*	*Left*	*Right*
	1615	*1589*	*991*	*1016*

Table 1: SL and DL-CMJ peak force data recorded in professional soccer players.

CMJ peak force data in (N = 15) healthy professional male players (Table 1), we estimate a similar ratio in concentric peak force of 1.60.

Figure 2 demonstrates other key differences between the tests, with eccentric peak velocity and countermovement depth (CMD) particularly relevant to test selection and to the interpretation of differences in output/asymmetries between the two tests. The lower forces individual limbs are exposed to during the DL-CMJ means that in cases where unilateral jump-landing activities are contraindicated, practitioners can obtain objective data on status and progress of individual limb and bilateral performance markers and compensatory strategies, at an earlier stage of rehabilitation.

In our experience, while most players are cleared to perform the SL-CMJ 6 months' post ACLR; due to lack of confidence or familiarity with the test, many have difficulty in performing it, resulting in "noisy" force-time curves which undermine the reliable calculation of strategy variables. While eccentric peak velocity (EPV) and CMD in both the DL-CMJ and SL-CMJ reflect a combination of capacity and willingness to load eccentrically and to do so at deeper knee flexion angles, these variables also reflect technique and therefore coaching cues. CMD and EPV should be monitored for consistency across trials, and we suggest as potential EPV targets of 0.6 m/s in the SL-CMJ, and 1.2 m/s in the DL-CMJ. Coaching to jump high and descend "deep and fast" have helped to improve consistency, but there are SL-CMJ trials in particular in which eccentric data does not "qualify" and only jump height and concentric data (highly consistent even when eccentric outputs are not), is used. However, it cannot be emphasised enough that challenging eccentric deceleration ability is a prerequisite for quantifying it!

Inadequate acceleration in the countermovement descent is analogous to testing car brakes at 5 mph – yes it provides information, but would you consider data obtained under those conditions valuable in informing decisions you need to make on the readiness of those brakes for use on the highway at 70 mph?

As such, EDRFD asymmetry, as well as trends in injured limb absolute EDRFD and DL eccentric mean / peak power provide information relevant to decisions around pitch-based deceleration progression. While the SL-CMJ is more demanding from a strength and balance perspective, and may provide value on that basis, in healthy and post-ACLR athletes, the higher EPV in the CMJ (Figure 2) supports the characterisation of status and progress in high velocity eccentric deceleration capacity and strategy even when the athlete lacks confidence to

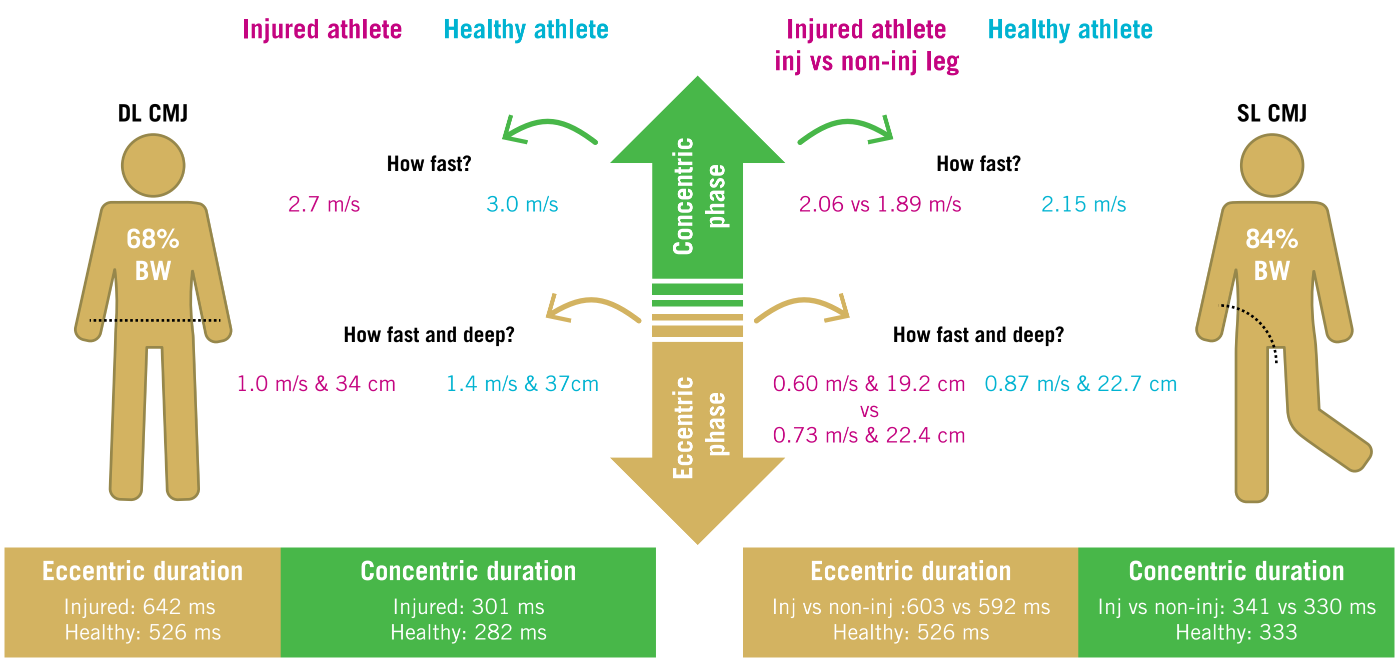
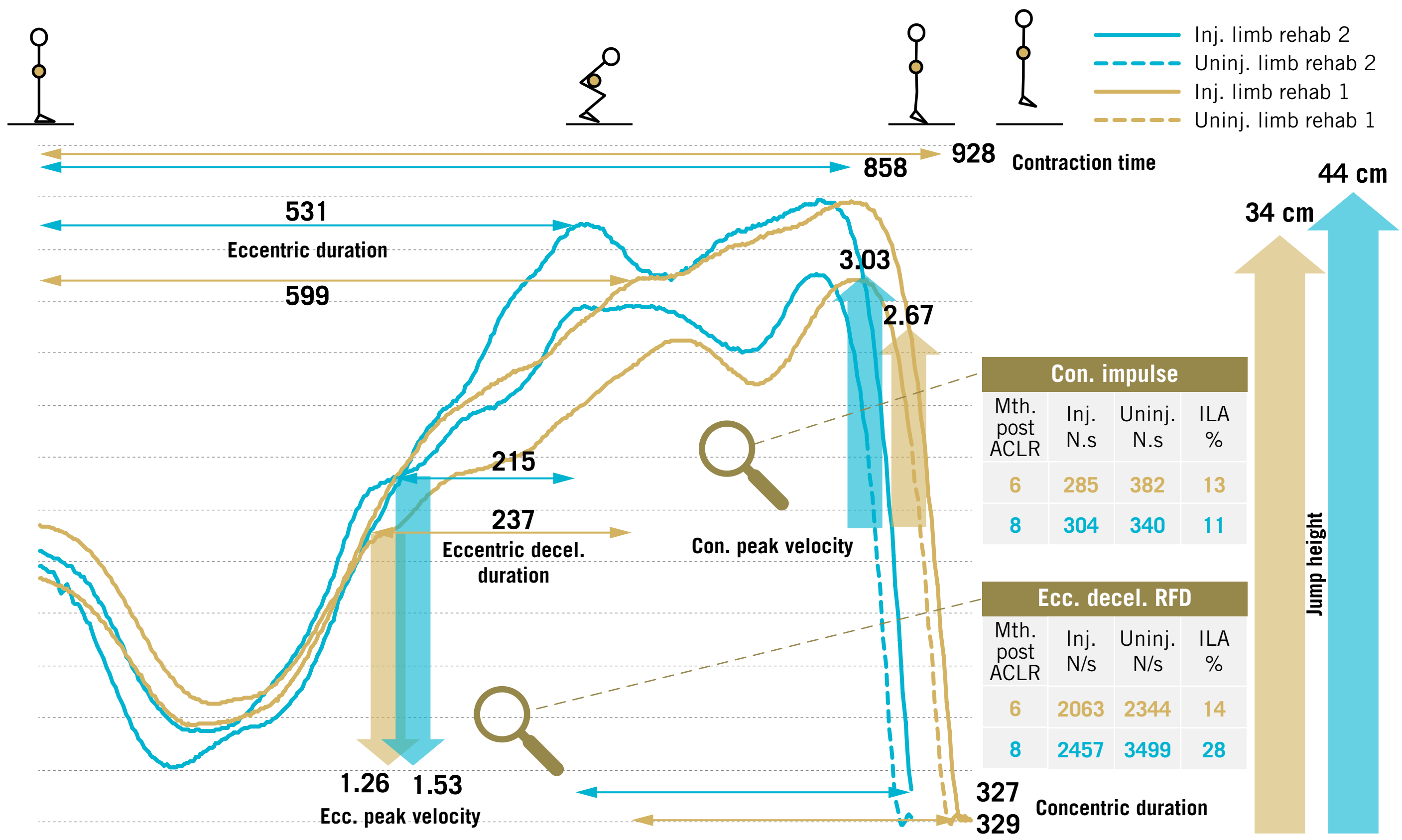


Figure 2: What are the speed and depth differences in Bilateral Vs Unilateral CMJ?And how do these differences change in ACL-R at 6 months vs healthy athletes? % BW refers to the % of body weight each limb is supporting.



Con. impulse			
Mth. post ACLR	Inj. N.s	Uninj. N.s	ILA %
6	285	382	13
8	304	340	11

Ecc. decel. RFD			
Mth. post ACLR	Inj. N/s	Uninj. N/s	ILA %
6	2063	2344	14
8	2457	3499	28

Figure 3: DL-CMJ injured and injured limb force-time curves, and selected outputs and asymmetries in an elite player measured at 6 and 8 months post-ACLR. Inj. = Injured; Uninj. = Uninjured; Con. = Concentric; Ecc. = Eccentric; decel. = deceleration; RFD = Rate of force development; ILA=Absolute inter-limb asymmetry (%).

produce adequate velocity in the SL-CMJ to acquire valid, usable eccentric data.

It is important to be aware when interpreting EDRFD data, that this variable is heavily influenced by both EPV and CMD such that: higher EPV drives a higher EDRFD, while a deeper countermovement tends to decrease it. As such, consider EPV and CMD trends when interpreting trends in EDRFD and when interpreting the inter-trial variability (i.e. the coefficient of variation) of EDRFD and other eccentric variables influenced by EPV such as eccentric mean or peak power. The variability of these eccentric variables, often misinterpreted as inherent poor reliability, is principally due to improper/inconsistent technique (in terms of speed and depth of the countermovement) which can be improved with appropriate and consistent cueing or excluding trials based on inadequate EPV. Eccentric deceleration impulse (EDI) is also used to quantify performance and asymmetries in this phase,[18] however while a more reliable variable than EDRFD, it appears to be far less sensitive marker of prior lower limb injury following RTC. Hart et al.[10] observed a small (Cohen's d= 0.33) non-significant difference in EDI between those with and without prior injury in contrast to a large (Cohen's d=1.05) and significant difference in EDRFD. Aligning with this in players post-ACLR, we often observe a common pattern of parallel EDI and EDRFD asymmetries at 6 months, followed by normalisation of EDI asymmetries between 6 to 9 months while EDRFD asymmetries persist.

Moving towards better utilisation of data collected during the DL- and SL-CMJ

Consider the force-time curves, selected output and asymmetry data of a player measured at two time points (rehab 1 and 2) post ACLR (Figure 3). This case study shows a trend we commonly see in players: improvements in bilateral performance markers, increased EDRFD in the injured limb (500N/s or +25%), but a large increase in EDRFD asymmetry. Sports scientist Drew Cooper explains this apparent paradox using the following analogy: Rehab time 1 can be likened to testing a spare tyre (i.e. the injured limb) on a jalopy in a parking lot, whereas at rehab time 2, the spare tyre is on a performance car on the highway. In the first instance, the modest mismatch between the structural integrity of the spare tyre and requirements of driving in a parking lot is minimal and hence so is the necessity for limb off-loading (expressed as low DL-CMJ asymmetry). However, with increased confidence, an overall improvement in bilateral performance and a large increase in EPV, the demands imposed at rehab 2 now expose a mismatch between the heightened eccentric deceleration demands, and capacity which the spare tyre can only partially cope with (or has "learned" to avoid loading). Thus, off-loading increases substantially – manifesting as increased asymmetry. While similar DL-CMJ trends (bilateral performance improvements, increased EPV, increased EDRFD asymmetry), are seen in player 1 (Table 2), notably EDRFD asymmetry in the SL-CMJ shows the reverse trend; specially, a reduced EDRFD asymmetry.

Monitoring trends in asymmetry percentage only is a blunt instrument when interpreting progress. Equal or greater consideration should be given to the magnitude of change in the left and right limbs, and when assessing the eccentric phase (at least in the context of rehabilitation), trends in eccentric peak velocity.

For example, if the trends shown for the player in figure 3 were interpreted solely on the BASIS of changes in EDRFD asymmetry %, one might conclude that performance in their injured limb had deteriorated. The player does however exhibit some progress, indicated by the absolute increase in the magnitude of EDRFD in that limb, their increased asymmetry being due to the healthy limb taking a larger share of the increased deceleration demand resulting from higher EPV. Ideal deceleration capacity progress is however exemplified by player 2 (table 2); increased overall eccentric demands (increased EPV and total EDRFD) accompanied by a decrease in injured limb off-loading (reduced EDRFD asymmetry) due to a larger increase in EDRFD on the injured vs. uninjured limb. Also note their large increase in FT:CT, alongside a minimal increase in jump height – showing that these bilateral strategy/kinetic variables are able to identify underlying deficits where output might otherwise indicate full recovery[10] and also reveal important progress indicators when jump height is stable and suggestive of ineffective programming/poor response.

Finally, we have observed that in professional footballers, SL-CMJ asymmetries tend to decrease to a greater extent than DL-CMJ between 6- and 8-months post-surgery (Figure 1). Notably, despite large improvements in injured limb SL jump height and reduced SL jump height asymmetry, > 20% EDRFD asymmetry in the DL-CMJ persists, values similar to that reported previously post-RTS[14-17]. We suggest that this finding is likely due to the variability in response to the increase in EPV and overall performance as highlighted in the case studies presented.

SL vs. DL peak landing force asymmetries

We monitor trends in both SL-CMJ and DL-CMJ peak landing force (PLF) asymmetries, with lower values commonly reported on the involved side following ACLR in DL[5,6,7,11,32,33] tests and higher values in SL landings. Higher PLF is indicative of a "stiffer" landing (i.e. less knee flexion)[34], with greater PLF in the DJ a risk factor for 2nd ACL injury in female athletes[33,34]. Comparison of landing force asymmetries obtained in SL-CMJ and DL-CMJ may indicate the adoption of different involved knee unloading strategies. With regard to divergent trends in SL vs DL Drop Jump asymmetries observed in the 2 years

Table 2

	Player 1		Player 2	
Date	08/04	03/06	20/05	01/07
	DL-CMJ		DL-CMJ	
Jump Height (cm)	21.6	27.9	40.1	41.4
FT:CT	0.43	0.70	0.63	0.76
Con Peak Velocity (m.s)	2.1	2.34	2.88	2.94
Ecc Peak Velocity (m.s)	0.66	1.11	1.15	1.33
CM Depth (cm)	25.8	26.8	34.8	32.2
Ecc Decel RFD (N)	681/821	1871/2582	2149/3044	4558/5923
%	8	27	29	14
Con-Impulse (Ns)	138/181	138/166	190/232	184/226
%	23	17	18	19
Peak Landing Force (N)	1560/1656	2200/2180	1651/2367	2335/2740
%	6	-1	29	16
	SL-CMJ		SL-CMJ	
Jump Height (cm)	8.1/13	12.3/16	15.3/21.3	18.8/22.4
%	37	23	28	16
Ecc Peak Velocity (m.s)	0.33/0.43	0.73/0.74	0.71/0.81	0.89/0.94
%	25	1	14	6
CM Depth (cm)	14.9/15.9	16.5/17.9	22.3/27.0	24.4/27.5
%	6	9	20	12
Ecc Decel RFD (N)	321/1232	2255/3303	2102/2557	3514/3693
%	74	32	18	5

Table 2: Case examples showing selected DL and SL-CMJ variables and asymmetries at two time points post-ACLR. Injured limb indicated by red font.

FT:CT=Flight:contraction time. Con=Concentric. Ecc=Eccentric. CM=Countermovement. RFD=Rate of force development.

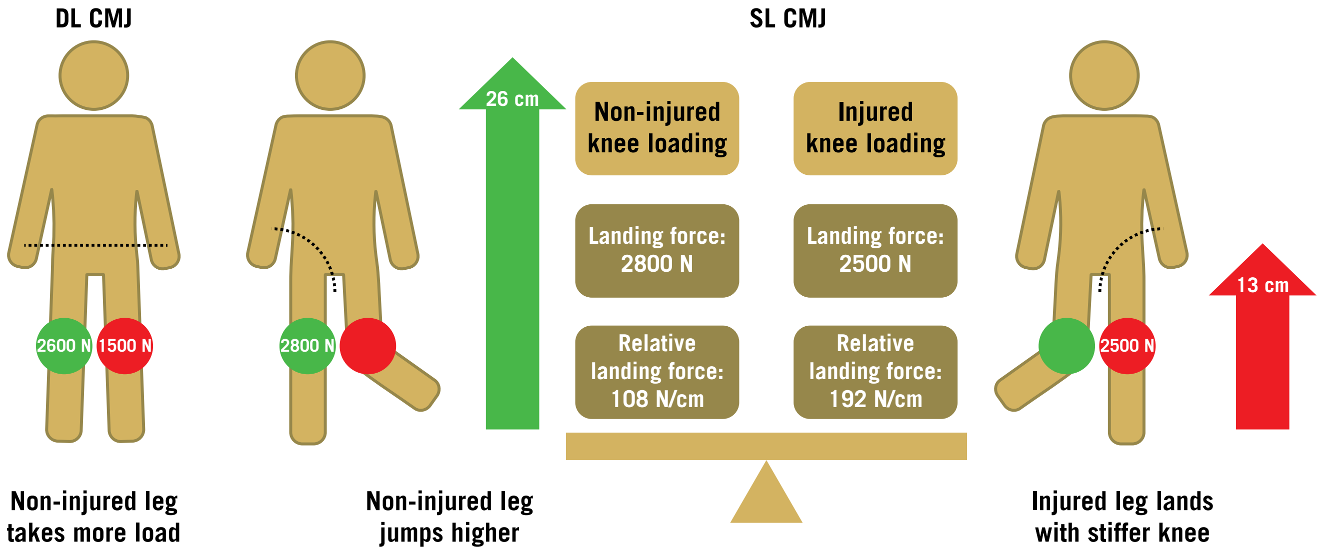


Figure 4: What goes up must come down – use of different strategies on landing to unload the injured knee?

following ACLR[35], the differing demands of the two tests may reveal variations in the strategies adopted at different time points during and post RTS. We have observed that at 6 months, > 2/3 players display SL and DL-CMJ landing force patterns representative of those shown in Figure 4. A point of consideration in peak landing force analysis and permitting a comparison of injured vs. uninjured limb landing asymmetries in the SL-CMJ, is the use of a jump height adjusted peak landing force index (peak landing force(N)/jump height (cm)) to try and account for the greater passive impact load on the uninjured side due to landing from a greater jump height.

How we use the SL and DL-CMJ to inform decision making

The aforementioned jump tests, in combination with other movement and strength related tests (isometric single leg squat, isokinetic dynamometer, repeated hop) are used to inform training prescription and rehabilitation progression. The DL-CMJ provides an assessment of overall triple extension performance output and strategy, indicative of the contribution of each limb in the actions of accelerating, decelerating and landing at high velocity. When an athlete is beginning low speed linear running, the magnitude of affected limb off-loading during the DL-CMJ can inform the programming of running volume. As benchmarks for individual limb outputs for variables such as concentric impulse, EDRFD or landing, are yet to be established and until individual limb trends generated on subsequent visit are available, asymmetry % provides some guidance. For example: >20% difference in DL-CMJ EDRFD may indicate a preference to brake their stride during on-pitch deceleration tasks with their first step using the uninjured leg – an avoidance strategy driven by lack of confidence/ capacity in loading the injured limb. While deceleration preferences are observed during on-pitch sessions and use of the injured limb to brake is progressively coached, the intensity of prescribed deceleration/ change of direction drills is influenced by the magnitude of EDRFD asymmetries. For example, selecting predictive drills and lower approach velocities over more demanding reactive drills for players with larger asymmetries. While exercises which address the eccentric force-velocity spectrum should be programmed, when players present with large DL-CMJ EDRFD, landing force asymmetries or low eccentric power, a greater emphasis is placed on fast accentuated eccentric loading to develop high velocity eccentric strength such as: flywheel training, drop split squats and altitude drops.

Future directions

While compensatory strategies that shift mechanical load away from the injured joint may be an appropriate adaptation during the early post-operative phase, they could be considered maladaptive if they persist beyond the recovery of mechanical loading capacity[28], and manifest in low load activities such as the squat and sit to stand[26,28]. Landing asymmetries are a secondary risk factor for subsequent ACL injury[33] while chronic joint under loading can increase risk of osteoarthritis in the unloaded limb[36]. This poses an important question – *are unloading strategies observed in the eccentric deceleration and landing phases at 6, 8 months post ACLR, and beyond, appropriate adjustments to some degree relative to the capacity and tissue status or should they be viewed simply as learned patterns of underuse which should be corrected?* Chan & Sigward[28] suggest that addressing underuse early in rehabilitation with real-time load-feedback during exercises may be critical to prevent maladaptive unloading. In addition, given the persistence of eccentric/landing phase avoidance strategies observed post ACLR, and the importance of eccentric control of knee flexion, these deficits in particular should be identified and addressed.

In this article we have emphasised the rich insights on status and progression that consideration of both bilateral strategy variables and individual limb outputs derived from DL-CMJ vGRF data can provide. We also suggest that examining the concordance between SL-CMJ and DL-CMJ asymmetries might enhance the specificity and effectiveness of training prescription. For example, presenting with much larger DL than SL asymmetries (players circled in Figure 5) may indicate an increased emphasis on bilateral exercises with loading feedback, while SL (capacity)

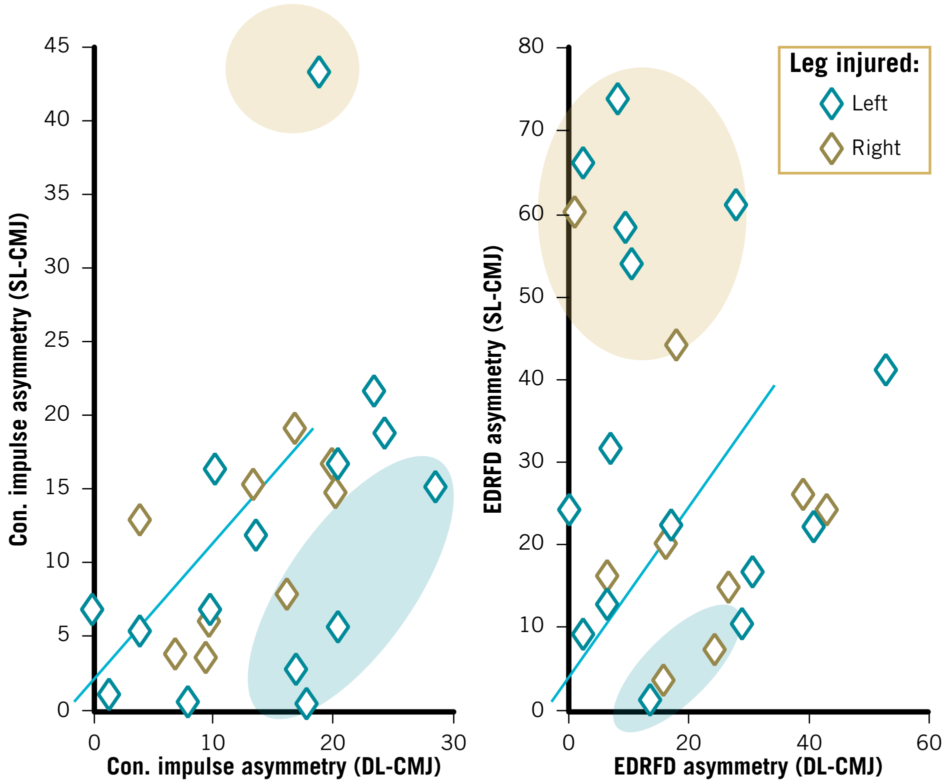


Figure 5: Associations between DL-CMJ and SL-CMJ asymmetries at 24 weeks post-ACLR.

deficits warrant an increased emphasis on unilateral strength training[37]. The differing load and eccentric velocity demands of the SL- and DL-CMJ and resulting outputs and asymmetries might also be considered as a proxy eccentric strength-velocity profiling tool to direct emphasis towards high load versus high velocity eccentric loading. This approach can also be further complemented by assessing kinetics during more demanding DJ and SL-DJ activities. Concentric force-velocity profiling is a popular aspect of exercise program design in the healthy athlete[38]. In the post-ACLR athlete, attention to observed force reduction and deceleration qualities with varied load, loading rates and velocity demands is warranted to better understand individual response to loading during rehabilitation and inform prescription. While recognising the additional information that full biomechanical analysis of SL and DL jump-land and cutting movements provides, the wealth of reliable and often benchmarked, intelligence on athlete performance, strategy and asymmetries that the dual platform DL-CMJ generates in a single, rapid and simple to implement test makes it an essential practical tool for frequent monitoring during and post-RTS.

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TAKING A STEP BACK TO RECONSIDER CHANGE OF DIRECTION AND ITS APPLICATION FOLLOWING ACL INJURY

– Written by Philip Graham-Smith, Qatar, Paul Jones, United Kingdom and Paul Read, Qatar

INTRODUCTION

Research into changing direction has become increasingly frequent due to observations that 'agility' performance tests can differentiate between levels of playing ability[1,2] and these movements are characterised as high-risk, potentially leading to anterior cruciate ligament (ACL) injuries. For example, rapid changes of direction are cited as a key mechanism in sports such as handball[3], soccer[4,5], rugby union[6] and American football[7].

This article revisits some fundamental concepts and provides alternative arguments pertaining to the risks and performance indicators of changing direction. The aim is to provide some clarity around key factors for consideration when developing a framework for enhanced return to play/performance after ACL injury.

What is the 'Real' Risk of an ACL injury?

An ACL injury is a catastrophic event which may or may not occur in a player's career. The actual exposure of a sportsperson to this risk can be estimated based on the number of turns they are likely to make in their playing career. If we make a conservative estimate that soccer players start training and match play at the age of 10 (and it is likely to be younger), and they finish their professional career at the age of 35, this equates to 25 years of exposure. The season typically last for 9 months of the year, or approximately 40 weeks. Players may train or play 5 times per week and perform 40 changes of direction per session (conservative). Baptista et al.[8] recently reported players make on average around 40 turns at angles > 90 degrees per game. Bloomfield et al.[9] reported 100 turns and Withers et al.[10] reported 50. Doing the math, this equates to somewhere in the region of 200,000 turns in a playing career. The majority of players will never get an ACL injury, whereas some may be unfortunate to have two (or more likely a reoccurrence of the same injury). Using this example, is it any wonder that predicting the occurrence of an ACL injury to a specific player has proven difficult? Even if we estimate that 10% of these will be performed at high intensity, we're still looking at up to a 1 in 20,000 chance of sustaining a knee injury specifically due to changing direction.

What are the underlying causes of an ACL injury?

In mechanical terms, a structure will break or rupture when the force it is exposed to exceeds its failure tolerance. An ACL rupture is likely to occur as a result of a combination of tensile, shear and torsional loading due to concurrent movements of knee flexion, and slide and rotation of the tibia relative to the femoral head whilst the athlete accepts force and rotates about the turning foot.

It is more likely that an ACL will rupture as a result of an abnormal movement with a slightly different loading pattern that occurs maybe once in a career, probably due to a combination of factors which include a higher intensity (speed/deceleration), possibly in a fatigued state or where shoe-surface friction is excessive.

Any attempt to reduce the stresses placed on the ACL should therefore address ways in which the load it is exposed to can be reduced, preferably without any detrimental effect on performance.

Is CoD research really helping us to make the right interventions?

We know that the turning leg is most at risk in the first 17-50ms of contact and between 5-30 degrees of knee flexion[11,12]. Given the lack of preparation time and limited range of motion in which a player can respond to this loading, it is highly unlikely that looking at discrete body parts in isolation will help to identify ways in which to reduce the ACL load. Despite this, a large propensity of the available research has examined the mechanics of the turning leg in the hope that a golden nugget will appear highlighting that it's the trunk, hip, knee or ankle position that somehow reduces the external knee abduction moment (a surrogate variable that is often used to quantify ACL risk).

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A critical appraisal of the research in this area reveals that the methods are often far removed from reality and therefore the findings become meaningless. The most obvious and heavily debated is assessment of planned versus unplanned tasks. This is a valid discussion, but it has detracted people's attention away from something much more relevant – a fundamental lack of appreciation and understanding of the horizontal ground reaction force (GRF). In addition, standardisation of footwear and appropriate combinations of shoe-surface interaction are rarely reported. This factor alone can have huge implications on how an athlete orientates their body as they accelerate and decelerate. It could be argued that we have been blinded by technology and an obsession over the use of integrated motion capture systems in laboratories and accepted that the lab surface and the subjects self-selected shoe is a reasonable limitation – we believe it is not! Finally, the limitations, inherent errors and trial to trial variability present when using inverse dynamics to measure 'net' joint moments are ignored and these variables are presented as the 'gold standard'. The 'net' moments about the knee are then taken as the surrogate variable that implies injury risk or entered into more sophisticated modelling software to predict load in the ACL.

We must move on from our current practice and perceived limitations, re-evaluate the task and focus on fundamental factors that can be modified or manipulated to improve performance and reduce injury risk.

Re-evaluating the task

First and foremost, we must consider changing direction as a performance attribute. When players change direction in sport, the intention is generally to find or close down space by committing an opponent, or to make/ avoid a tackle. For example, in a sport such as basketball it is often beneficial for the attacking player aiming to take a shot to avoid making contact with an opponent and stay far enough away from arms reach.

If we consider any change in direction that is 90 degrees or greater relative to the initial direction, it is a requirement that the athlete must reduce his/her speed (momentum) momentarily to zero. This is a significant factor and relates to the outcome of being able to perform the movement quickly and avoid being tackled. This is where the horizontal GRF (the friction force) and how the player decelerates is critical. If the player brakes predominantly on his/ her final foot plant (the turning leg), he/she will spend more time in closer proximity to the opponent, leading to a greater chance of being tackled. If they can brake harder on the penultimate contact they can react quicker on the turning foot, and more importantly the line of the foot is parallel to the thigh meaning the braking force is taken in a stronger position for the quadriceps to decelerate[13,14]. In contrast, braking harder on the final contact where the foot placement angle may not be in alignment poses a greater risk of injury. Here we can see that a technical intervention may be a key factor for safer and faster changes of direction.

Breakdown of the movement

To illustrate our point, we have used a 180 degree turn, but the key principles can be applied to all forms of direction change. We have separated the movement into 4 phases; acceleration-in, preparation for turn, turn, and acceleration-out. The total time to perform the task would be the sum of each of the 4 phases.

1. Acceleration – in:

Acceleration is an important metric for heightened team sports performance and has been a recent focus for many in recent years, but it can also be assumed that practitioners are less likely to know what speeds a player can attain in a specific distance? The maximum speed that an athlete can attain prior to changing direction dictates how much braking impulse needs to be imparted. In game scenarios there is no pre-determined 'approach' distance, so in order to understand the loading demands we first need to evaluate our athletes' ability to accelerate and decelerate within set distances. Using a Laveg speed gun, Graham-Smith et al.[15] determined the typical speeds players can attain over a range of short distances (relative to their maximum sprint speed). This was achieved using a test where athletes were required to accelerate from specified distances and stop dead on the zero point (Figure 1). Results revealed that 54% of maximum speed is typically attained within the first 2.07m, requiring 2.93m to decelerate (within a total distance of 5m).

Regression equations were then developed to determine what % of maximum speed could be attained with a given acceleration distance, and subsequently what stopping distance would be required to decelerate from that speed (Figure 2). This approach allows practitioners to build a profile of their acceleration and deceleration capabilities. For example, a player who accelerates 10m will attain 87% of their maximum speed and this would typically require around 7.4m to decelerate and stop within a total movement distance of 17.4m. This gives us context for understanding the first part of change of direction performance.

2. Preparation for turn

This phase has two functions, to commence deceleration so that the player arrives at the final foot contact with minimal speed, and secondly to ensure that the final step length is short enough to allow double leg support. Deceleration has both technical and physical qualities attributed to it. In the study mentioned above the deceleration gradient in the acceleration-deceleration test, (denoted by the gradient of changes in mean speed relative to changes in mean stopping distances in the 10m and 5m trials) had moderate associations with combined left and right leg eccentric strength in the knee extensors and flexors, R^2 = 0.281 and 0.219 respectively. From a technical perspective, greater braking impulse on the penultimate contact has been shown to relate to faster turns[13,14]. Positioning the centre of mass further behind the point of contact into the penultimate contact via, rearward inclination of the trunk, the leg planted in front of the body and making contact with the heel will promote greater braking forces (Figure 3). Providing the foot is planted in the same direction of the thigh, and the athlete displays good levels of eccentric strength, this will provide a sound platform to decelerate quickly. However, this strategy should not be promoted if the foot is already rotated into the turn. The length of the last step should also be short enough to permit dual foot support, as this helps to establish a firm base, increased stability

Trial	*Speed (m/s)*	
	Mean	*SD*
30m Max Sprint	*8.1*	*0.6*
5m	*4.4*	*0.1*
10m	*5.8*	*0.2*
15m	*6.7*	*0.2*
20m	*7.2*	*0.3*

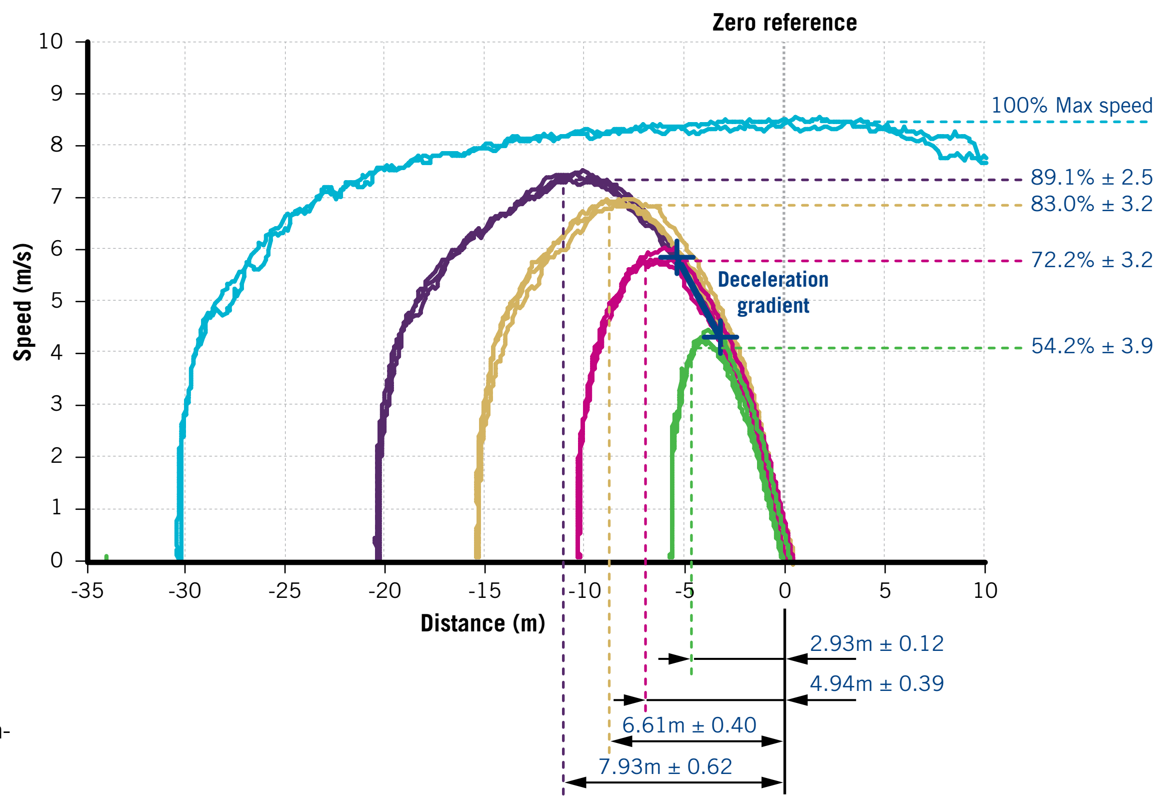

Figure 1: Absolute and % maximum speed and stopping distances (Graham-Smith et al, 2018).

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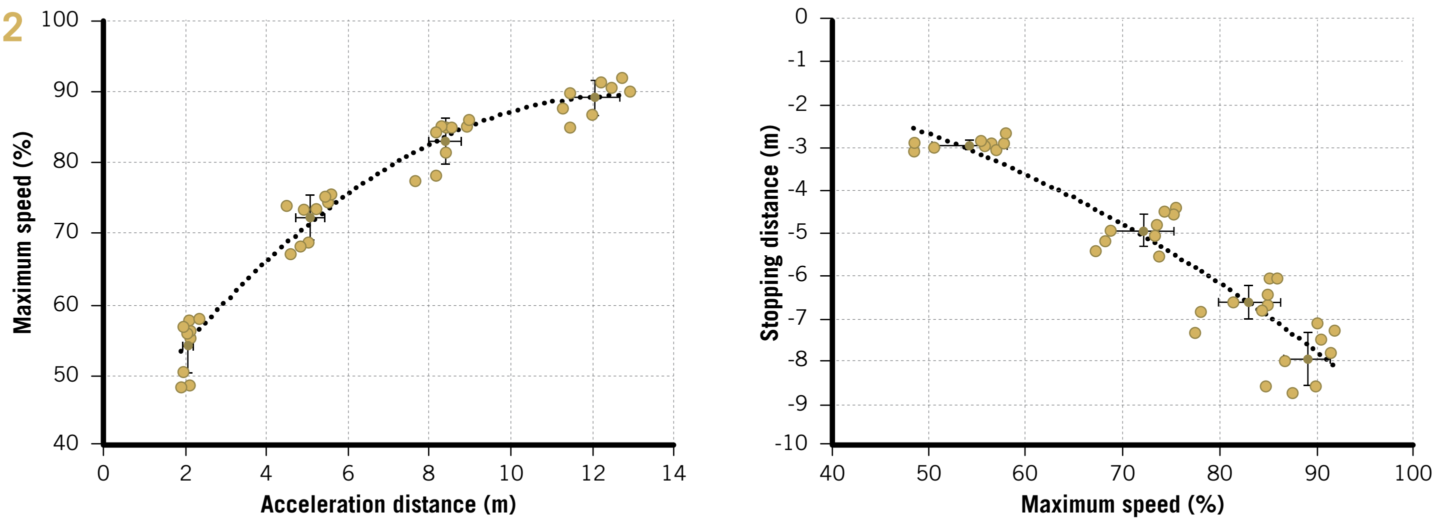

Figure 2: Regression Equations for acceleration distance, %maximum speed and stopping distance (Graham-Smith et al, 2018).

and faster re-orientation of the feet prior to accelerating out.

3. The turn
A successful turn will be one which has the lowest contact time on the turning foot (thereby ensuring less time in close proximity to an opponent), and where the body doesn't travel too far forward. If there is excessive forward trunk rotation the centre of mass travels a greater distance than is necessary and puts more load directly over the turning foot. The trunk, head and upper limbs account for approximately 60% of an athlete's body weight; therefore, controlling the trunk movement is critical to performance and managing the joint loads at the knee. Rotating the feet when the greatest force is over the foot produces greater torsional friction and risk to the knee. Reducing torsional friction can be achieved by timing the re-orientation of the feet with weight shifts, primarily through the repositioning of the trunk. As the trunk rotates forward in the initial part of contact, the vertical force over the rear leg reduces. This is the time to re-orientate the rear foot. The greatest vertical force over the turning leg is when it reaches maximum knee flexion. Prior to rotating the turning foot, the player should reduce vertical force by repositioning the trunk into the intended direction of movement. As the rear leg is already orientated in the intended direction of travel, the purpose of the turn leg is to generate enough force to overcome inertia and shift the centre of mass ahead of the rear foot (thereby promoting faster application of horizontal propulsive force).

3

Foot contact

Maximum knee flexion

Figure 3: Body alignment at contact into the turn emphasising rearward trunk inclination, leg planted in front of the body, forward orientation of feet and short step length.

Timing foot rotations with weight shift can be taught to help reduce torsional friction due to interaction between the shoe (boot) and surface.

4. Acceleration-out
With correct alignment of both the athlete's feet and legs, their body is now facing the intended direction of travel and the trunk is inclined forwards over the rear foot (now effectively the front foot). All that remains is for the player to accelerate away.

The importance of eccentric strength
Eccentric strength in the quadriceps and hamstrings have shown associations with the ability to change direction quicker[13,14,16,17,18] and more specifically to decelerate[15,19]. Eccentric strength in the quadriceps and hamstrings has an additional benefit as it helps to provide dynamic stability of the knee when subjected to high shear forces, brought about by rapid decelerations. Graham-Smith et al.[20] suggested that dynamic stability of the knee musculature could be assessed using the 'angle of crossover' from an isokinetic dynamometer. This metric represents the angle where the eccentric torque of the hamstrings is equal to the concentric torque of the quadriceps. Within a cohort of professional football players, the average angle of crossover was 31 degrees (0 being full extension) with a range of 16 to 55 degrees. It was suggested that if the angle of crossover is closer to mid-range then there is a greater 'safe' range where hamstrings can resist more than the quadriceps can generate.

Implications for ACL rehabilitation and return to play/performance

The decision to release a player back into competitive situations requires practitioners to have the confidence that the player can withstand the demands of the game.

Many rehabilitation exercises are performed in a vertical direction, for example, double and single leg drop and hold, progressing to reactive drop jumps (double and single legs). While this approach helps the athlete to accept load vertically, we cannot overlook exercises that also build in horizontal braking forces. Hopping is a good progression, but typically the centre of mass is above the foot on landing. This means that eccentric loading is still mainly directed vertically, although we cannot dismiss that within the knee joint itself shear forces will be present.

Whilst slow speed forward, backward and lateral movements should be encouraged to reintroduce the athlete to more game related movements, later stage rehabilitation and return to 'performance' must incorporate drills that expose the athlete to greater levels of horizontal braking forces. In addition, it would be prudent to develop eccentric strength in the quadriceps and hamstrings as a pre-requisite to give the athlete confidence in their ability to decelerate.

Deceleration drills should be introduced as the athlete makes good progress in their ability to accelerate and attain speeds of over 7.5m/s.

Using the regression equations in Figure 2, progressive drills can be developed to mark out appropriate acceleration and deceleration distances, gradually reducing the stopping distance. For example, if a 10m acceleration distance was marked out, the practitioner would aim to progressively decrease the stopping distance to ~ 7.4 m, which would be acceptable. Technical interventions could play a vital role in offsetting reinjury, something that until recently[21] does not seem to have been promoted in rehabilitation programmes or within the available literature. Emphasis should be on keeping the feet aligned in the direction of travel and gradually encouraging the athlete to lean backwards and plant the leg further in front of the body. The practitioner should also observe to see if the athlete is able to confidently decelerate on both injured and non-injured legs.

Concurrently with deceleration drills, technical interventions can be introduced for changing direction at angles equal to or greater than 90 degrees, but at relatively slow speeds. Technique should focus on a short last step for dual foot support and synchronising feet re-orientation with unloading as a result of weight shift from trunk movement.

Speeds and deceleration into the turn can then gradually increase whilst still adopting confident and 'safer' technique.

A word of caution when using total time alone to assess change of direction performance as part of an athletes return to play criteria. Deficiencies in strength and control when turning off either leg can be masked by compensation strategies, leading to similar performance times.

Common sense tells us that the overall performance time is a function of acceleration and deceleration abilities of both limbs. King et al.[22] has confirmed this recently and identified that turning off the ACLR leg is potentially less hazardous as a result of stronger braking off the non-injured limb in the penultimate contact. In this regard, if a direct assessment of penultimate and final contact braking forces and impulses is not possible, simply comparing contact times on the turning leg along with a qualitative analysis of technique (as described above) will at least give the practitioner some indication of the athlete's ability to return to play. For example, if the overall performance times

> **When using total time alone to assess change of direction performance as part of an athletes return to play criteria, clinicians should be aware that deficiencies in strength and control when turning off either leg can be masked by compensation strategies, leading to similar performance time.**

are similar, poor decelerative ability of the ACLR limb in the penultimate contact is likely to equate to a longer contact time on the non-injured limb in the turn (because there will be more speed and load to accept in the final contact). Contact times can be assessed accurately by filming the movement in high speed mode (120 / 240 fps) on iPhone, Casio Exilim or GoPro and counting the number of frames in contact when reviewing through free software such as Quintic Player or various mobile phone applications such as Dartfish Express.

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PERSPECTIVES FROM THE FIELD

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SAME SAME, BUT DIFFERENT?

SHOULD FOOTBALL BOOT SELECTION BE A CONSIDERATION AFTER ACLR

– *Written by Athol Thomson, Qatar*

INTRODUCTION

Anterior cruciate ligament (ACL) injury in football players carries a high burden for the player, club, and medical team[1]. The mechanisms underlying ACL injury are multifaceted and complex. Despite their unpredictable nature, identification and subsequent reduction of modifiable risk factors is of paramount importance.

High traction between a players' football boot and the playing surface is thought to increase risk of anterior cruciate ligament (re) injury[2]. "My studs got caught on the playing surface while my body kept rotating" is a common phrase used by players to describe the mechanism of injury in a non-contact situation (Figure 1). However, high quality evidence for this premise is limited to American football only with no prospective studies in soccer football or Australian rules football to date[3-5].

Football boot selection is one of the few immediately modifiable factors that a player can influence just before kick-off when the surface properties and climate are largely pre-defined. Surprisingly, there are no prospective studies which link shoe-surface traction and injury to date in soccer; thus, many questions remain.

Surgical reconstruction of the ACL is still (at present) the treatment option most elite football players choose when their goal is to return to the same level of sport. However, obvious questions exist with pertinent considerations about shoe-surface interaction during the return to sport continuum. As usual it's complex and the context matters, but some examples include:

1. What should a player put on their feet for the first field-based rehabilitation sessions after ACL reconstruction (ACLR) in football?
2. Is it best to use running shoes first or go straight into football boots from the outset?
3. Are there any playing surface considerations at the different stages of the rehabilitation, return to train, return to sport continuum?
4. Should the same advice be given for male and female elite players?

MIND THE GAP

Evidence-based practice is said to optimise the decision-making process in sports medicine and science. Yet, in this case, there is a clear lack of empirical evidence to support how the players feel about the mechanism of injury and what has been published to date in scientific journals[6].

Even if/when good applied research is produced there are issues with translation of the findings into real-world elite sport settings[7]. Our research showed that shoe-surface rotational traction varies with different football shoe outsoles (studs, blades etc), grass types, and climatic conditions. Metrics on this paper show it was widely accessed and discussed[8]. However, it is still unclear if this type of research is applied enough to translate into what happens every day at pitch-side practice?

We were interested to find out so what follows is an insightful discussion on ACL injury and shoe-surface interaction with some top practitioners in elite soccer, Australian rules and American football (NFL). We asked each expert three questions about shoe-surface interaction and the journey back to football after ACLR. In addition, we have separated responses from those involved with male and female sports respectively to determine if there are any apparent differences / considerations.

AN INTRODUCTION TO OUR EXPERTS

Daniel Bonanno podiatrist (B.Podiatry, PhD) is the consultant podiatrist to the Carlton Football Club (AFL) and Melbourne City Football Club (A-League). He is also a Senior Lecturer in the Discipline of Podiatry at La Trobe University. @DanielRBonanno

David Rennie physiotherapist Leicester City football club recently completed his PhD investigating "whether the natural turf pitch can affect injury and performance within elite football". He has been Head Physiotherapist at Leicester City Football Club since 1999, during which time he has contributed to the team success in winning the League Cup, as well as League 1, the Championship and the Premier League. @ rennie_physio

Philipp Jacobsen physiotherapist is Medical Rehabilitation & Performance Manager at Liverpool football club. He has previously worked as physiotherapist for the Qatar national football team, Panathinaikos FC, and Portsmouth FC. @helasphil

Matt Konopinski, Physiotherpist The Football association is rehabilitation specialist physiotherapist at the English football association. Former head physio Liverpool football club. @Matt_Kono

NFL practitioner chose to stay anonymous is working in franchise that won the NFL championships several times in the last 20 years.

Brooke Patterson, physiotherapist, PhD Candidate, La Trobe University is currently investigating the impact of anterior cruciate ligament injury on the lives of young adults, particularly the risk of osteoarthritis at a young age. Brooke played for Melbourne FC in the first 3 seasons of the Australian rules football league for women (AFLW) and has sustained an ACL injury herself. Brooke is involved in current AFL projects, aimed at monitoring and reducing injuries, and improving coach education. @Knee_ Howells

Kate Beerworth, physiotherapist for Australian Women's National Football Team Physio (Matildas) 10 years (2007-2016) has worked in football since 2004 starting with FFA as physio for U20 Women's National team and since 2016 as National ACL prevention & injury prevention co-ordinator in a consulting role. In May 2019, Kate started working with Cricket Australia as the Australian Women's Team Physio. @ KBeerworth

Sam Blanchard physiotherapist has worked elite men and women at Brighton & Hove Albion, Buffalo Sabres in NHL, Scottish rugby union, and Arsenal FC. Sam is currently working at Manchester City FC with the academy. @SJBPhysio_sport

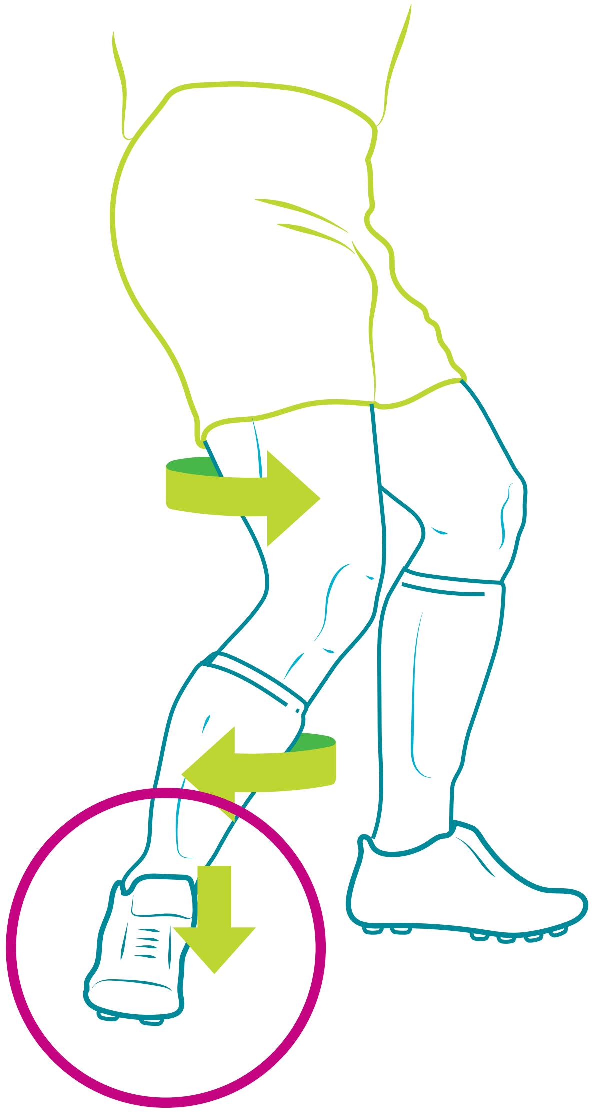

Figure 1: Non-contact mechanism of ACL injury with "foot fixation" where studs get trapped in playing surface.

RESPONSES FROM MEN'S FOOTBALL CODES

Question 1: After Anterior cruciate ligament reconstruction, what does a usual pathway look like for progression back to 'on-field' rehabilitation in football boots?

DR – It goes by feel. The player must be physically and psychologically ready to return to 'on-field' rehabilitation. Players will pass agility or change of direction tests in trainers on an indoor surface before progression to 'on-field' rehabilitation session in boots. The first pitch session in football boots is somewhat of a regression. Velocity is taken down a notch along with complexity of movement tasks. Speed of movement is a major issue for re-injury risk so there is a graduated progression there.

PJ – ACL injuries are relatively rare in elite male football. Players generally start running on the pitch in their trainers (running shoes). Things like 2 × 10min runs predominantly linear and then some longer runs to get the volume in. Boots are used for change of direction type movements, but we recommend the players go by 'feel'. They can try different football boots to perform some movements at low speed to see which shoes feel like they provide the correct amount of traction for the surface (and climate) on the day (see Figure 2)[10]. Often the same make and model of football boot will come with several different outsole options suited to firm ground or soft ground for example (See Figure 3).

MK – This is a real 'landmark' moment for any player after long-term injury. Putting their boots on again to run our on the pitch seems to do plenty of psychological good. The first 'on-field' session tends to be linear so no real issues with using football boots for this. Generally, we are happy with the strength or levels of graft healing before heading outside again.

NFL – Important to respect the healing time required and individual variability among athletes. Players must earn the right to get to the next stage of rehabilitation. In our set-up they must back-up reaching certain criteria again and again rather than hitting a number for a one-off test.

Players will have run on the AlterG treadmill and then also completed various movement and running tasks before the first pitch session. We use running shoes first but for sure look to get them back into cleats at the earliest opportunity.

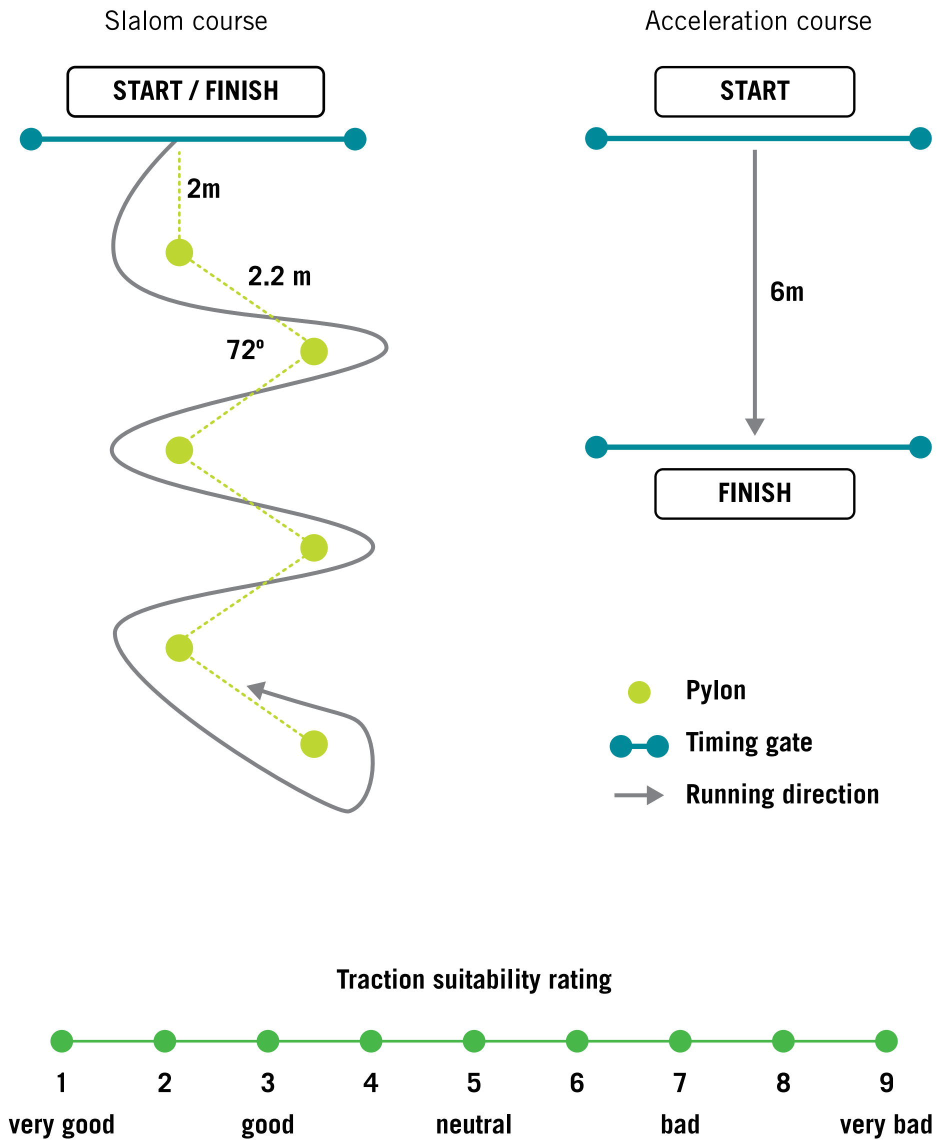

Figure 2: Football specific functional traction course adapted from Sterzing et al[10].

Question 2: Do players ask about optimal footwear choices on their return to field-based training?

DB – Some do. Any conversation with the player must be nuanced when encouraging a shift to boots with smaller round studs which will have lower rotational traction. The last thing you want to do is add fear to footwear selection, especially if the player is contracted to a specific brand and model of shoe.

Recently, a young professional AFL player (with no history of knee injury) came to ask what he could do to ensure his boots were correct for him. His aim was to minimise risk of injury while still having adequate shoe-surface traction to compete at the highest level.

AFL players are more used to being advised on what to do in terms of footwear selection, whereas soccer football players in the A-league often have strong preconceived ideas about what they want from their footwear, often with the goal of maximising ball touch, so boot changes can be more difficult to influence.

AFL Clubs must supply a minimum of 3 pairs of boots, and 2 pairs runners, to all players (players can also elect to have alternative sponsor). If a player has a medical reason for not wearing the club sponsored footwear, then they are supplied footwear from an alternative brand (as recommended by the club medical team, including the podiatrist). Lack of choice in terms of boot width is a huge issue for us in AFL.

In AFL there is also a podiatrist at every team in the league.

DR – Not often. Players tend to use boots from the very first pitch session as they have already passed complex movement tasks inside with shoe and surface combinations that can have relatively high friction coefficients. This means it's not a huge step-up, in terms of shoe-surface traction, once they lace-up their boots and head out on the pitch for the first time. Players don't often ask about boots but do enquire about the surface and how that might affect their fatigue levels.

PJ - Most players have boot sponsorship agreements so they will wear what is provided for them without giving it much thought. However, some do like to give input into what type of outsole the shoe will have. For example, one senior player gets Nike to add an outsole from a few seasons ago that consists of mostly round moulded studs on the outsole rather than use new blade or cleat versions of the shoe.

MK – It doesn't come up often. We try to steer players away from lace-less or super flexible boots for this stage of rehab. Most players choose boots on 'feel' and appearance of the

Figure 3: Different football boot outsole types currently available.

boot. Design style really seems to matter to most players rather than any inherent biomechanical parameters the shoe may have.

NFL – Most players I have been involved with in American football do ask for footwear advice. However, very few blame the shoe itself. More often they will question the playing surface rather than the shoe.

Question 3: Any concerns about playing surface conditions and risk of (re)injury?

DB - We try to have players ready for shifts in surfaces by having multiple outsole types. For example, they may train on artificial grass in an AG outsole shoe and then play on natural grass or hybrid reinforced grass in a firm ground outsole shoe. This was directly informed by research conducted at Aspetar[8] so for that we say thanks!

DR – We did have an issue once where two players sustained an ACL injury during a shift to a sub-standard artificial grass surface that had high shoe-surface traction. Both players were wearing the same boots. Combination of a high friction surface and high traction shoe seems to have been at least partly implicated in the mechanism of injury here.

Depends on the style of football they must eventually return to. For our club we are looking to use a firm surface that returns more energy and possibly decreases fatigue for a given movement like sprinting. Therefore, the player must get accustomed to moving on a surface with particular mechanical properties again. We have the benefit of great ground-staff that can set-up the training surfaces in a graduated manner (increasing levels of surface hardness for example). This allows us to provide the players with a surface which mitigates the risk to the healing tissue but one which also enables performance in the most efficient way.

PJ – If the pitch is too soft (or too hard) it might increase player fatigue. Our excellent grounds staff work to keep the surfaces within a certain window for properties like surface hardness. We also teamed up with an independent company to come in and test our pitches and provide objective data that can help inform footwear selection.

MK – Players are generally concerned about artificial grass or some of the playing surfaces on pre-season tours. I have been very fortunate at both Liverpool and the English FA to have fantastic playing surfaces.

NFL – Our players train on natural grass but compete on everything from artificial grass, hybrid reinforced grass, to fully natural grass match day playing surfaces. The players prefer (love) the natural grass training surface our excellent grounds staff prepare for them.

RESPONSES FROM WOMAN'S FOOTBALL CODES

Question 1: After Anterior cruciate ligament reconstruction, what does a usual pathway look like for progression back to 'on-field' rehabilitation in football boots?

BP – Players are usually encouraged to return to their boots as soon as possible for on-field rehab, which may include running or modified skills. Use of trainers is limited when they return to the pitch but may be used for volume running at the end of on-field rehab session. Psychologically, players like getting into their boots where possible, as they feel like they are a part of training, and the idea is that feet should be conditioned to tolerate training in football shoes again early in the rehabilitation and RTS continuum.

A podiatrist comes to the club to give broad footwear recommendations, and one-to-one appointments are up to the individual. However, shoes made with a female-specific last are hard to come by. Two footwear companies are developing a female specific shoe for the female football players. This is super exciting, and players have been involved by providing feedback on comfort, fit and performance on existing and new models. The volume around the upper at the forefoot of the boot reflects the shape of a female feet rather than using a men's' B-width fitting (common in footwear manufacturing). Comfort is queen! - unless they are comfortable, they are going to change their movement patterns, which has implications for injury.

KB – Before players return to the pitch, they have generally completed movement tests in training shoes in gym. Complexity and chaos are gradually progressed so that the shift outside seems less of a jump.

Players tend to start in running shoes with linear tasks for the first on-pitch session. A large reason for this also is to control the variables and avoids introducing running on pitch and a change of shoes at the same time. If the knee doesn't tolerate the running load, sticking to the same shoe can help decide whether it's an impact related issue, training load issue or change of footwear. Then move into boots as change of direction and football specific drills are progressed.

SB – Firstly, it's important to mention that each individual situation is managed according to various contextual factors.

Initially, an "ideal-world' scenario for a 9-month rehabilitation plan is mapped out. with an emphasis on the fluid nature of this (e.g. timeframes change as criteria are met etc).

Running is often delayed until 16-18 weeks. Easier transition to running at this stage after working on running or movement drills. Return to running at 16-18 weeks is just my approach, not necessarily what should be done. Some people will comfortably run at 10 weeks... but when they probably have 6 months of running ahead of them, I just think "what's the rush" and find it a smoother transition to work on running type drills up until 16 weeks. We find running can look a little laboured if started early (<12 weeks). Everyone is different though in how this is progressed.

We move players back into boots for linear on-field running at the earliest opportunity. Players are so used to being in boots that it makes sense to use them early. The linear work is combined with some rotational (slightly higher risk) movements in the gym lead by the S & C staff. e.g. lateral bounds

Question 2: Do players ask about optimal footwear choices as they return to field-based training?

BP – Not usually. Some players feel very strongly about a particular football boot brand and/or model being implicated in their ACL injury or re-injury. Ex-players have vented frustration about boots designs, with some believing their careers were cut short due to poor footwear choices.

KB – No not really. Only if a player "blames" the boot or feels it was responsible for the mechanism of injury. For example ..."felt like my shoe got trapped on the grass and wouldn't release". Occasionally players have felt nervous returning to the on-field sessions. At this stage we have a conversation about footwear options.

SB – No not in my experience.

"Players tend to stay in their chosen boot model regardless of injury. They are very closed to changing types of shoes in my experience".

Question 3: Any concerns about the playing surface conditions and risk of (re) injury?

BP – In pre-season sub-elite female Australian Football teams compete with cricket due to the limited number of pitches available. Training can often shift to artificial surfaces or natural grass of wide-ranging quality. Players don't tend to change their boots for the surface shifts, and are either not aware of different footwear options, or they are not available. Some will wear different shoes for training and matches. For example, a more supportive shoe during training, and a shoe with greater performance benefits (i.e. lighter, more flexible upper) for matches.

KB – W league in Australia deal with surface shifts between artificial and natural grass of varied quality. Often players do not have other shoe (outsole) choices to match to the surface. In some cases, they tend to be driven by cost and will wear shoes that are provided by sponsors for free. A lack of smaller and narrow boot sizes for females can also dictate or limit the options and is a significant issue for the female athlete. Some have to use children' sizes which means the material quality of the shoe is not adequate. (eg kangaroo leather upper is not common in kids football boots).

SB – Varied quality of playing surfaces in the elite female competition is a concern in the (FA Women's super league UK). Some clubs are well backed and spend money on the surfaces while other simply don't have the money. Add to this that female players often don't have a kit man to carry different boots around or quite often don't even bring another boot option to away matches.

CONTEXT AND COMFORT ARE KING/QUEEN.

In the preceding discussions, some key themes were apparent in the responses of our front-line elite sport practitioners across the different football codes and these have been summarised below:

1. There is a large gulf in playing surface quality and football boot choice in elite female soccer and Australian rules football. This likely comes down to (television) funding which is a debate for another day considering the record crowds and television viewing figures in female football of recent times. Elite female players are at greater risk of sustaining an ACL injury than male players due to several risk factors[9]. Female specific football boots should be very high priority for footwear manufacturers to develop. Simply using a men's' version with a narrower last will not do. Having comfortable boots that fit female foot anatomy, with several outsole (traction) options is overdue. It is pleasing to see some companies making inroads in this area.
2. There is no exact recipe for what players should wear on their feet during rehabilitation following ACLR. It is pragmatic to suggest shoes with reduced rotational traction when returning form ACLR. How long players should use these shoes or weather they ultimately reduce (re)-injury risk in elite football is yet to be determined. Most practitioners mentioned going by "feel" with the athlete on top of both functional and time-based criteria.
3. Getting back into football boots is a momentous milestone along the return to sport continuum.
4. More must be done to mitigate risk of the foot fixation. This is how the players feel and we should listen. This might include superior maintenance to bring rotational traction down on certain playing surfaces (e.g. verti-cutting lateral root growth in warm season grass species). Likewise, improved individual tailored footwear programs such as having a podiatrist in each club like many have adopted in AFL would appear an intuitive step forward. Tailored footwear programs have proved successful at reducing lower limb injuries in professional rugby league[11].

In summary, these practitioners chat to players day-in day-out and get to hear their thoughts, hopes and fears. To that end, listening to how a player "feels" about certain playing surface characteristics or football boots may be the best approach at present. Future research will utilise wearable technologies and advances in shifting the testing labs to the field. Until then, subjective comfort and players' rating of perceived traction after completing a functional traction course is still King/Queen.

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RECONDITIONING STRATEGIES

THE USE OF BLOOD FLOW RESTRICTION IN EARLY STAGE REHABILITAION FOLLOWING ACL INJURY

IMPLICATIONS FOR ENHANCING RETURN TO PLAY

– *Written by Stephen D Patterson, UK, Johnny Owens, USA and Luke Hughes, UK*

INTRODUCTION

Anterior cruciate ligament (ACL) injury is one of the most prevalent musculoskeletal (MSK) conditions worldwide, totalling approximately 250,000 cases per year[1]. ACL injuries are common in both males and females, occurring at an average age of 30 years with an increasingly high annual incidence in all activity levels from recreational to professional sport[2,3]. While conservative treatment options exist, more often patients require ACL reconstruction (ACLR) surgery by means of allograft or autograft to restore the ligamentous structure, and thus anterior-posterior stability, of the knee joint[4].

The typical approach to ACLR rehabilitation has shifted from full limb immobilisation post-surgery to early restoration of range of movement (ROM) weight bearing and increased muscle activation[5,6]. However, even with more accelerated and aggressive rehabilitation a major consequence of ACL injury and subsequent reconstruction is significant thigh muscle atrophy[7,8] and muscle weakness[9] in the first weeks post-surgery[10] and can persist for several years post operation[11]. There are many short-term[12] and long-term[13] consequences of ACLR such as decreased protein turnover[14], strength loss[9], arthrogenic inhibition[15], an increased risk of osteoarthritis[16] and reinjury[17]. The effects of muscle atrophy are unavoidable given the reduced weight bearing and unloading context of ACLR rehabilitation[18] related to concerns of graft strain[19], cartilage damage[20], bone bruising and meniscal injury[21], which often serve as contraindications to heavy load exercise to regain muscle strength and size. Additionally, muscle physiology appears to be altered after ACLR with signs of greater extracellular matrix and fewer satellite cells than prior to surgery[22]. Thus, clinicians are faced with the task of finding alternative rehabilitation tools.

Blood flow restriction (BFR) is a novel training method that aims to partially restrict arterial inflow and fully restrict venous outflow in active musculature during exercise[23]. BFR training has been proposed as a tool for early rehabilitation post ACLR[24,25] because of its low-load nature and hypertrophic capacity[26]. Our recent meta-analysis indicated that low-load BFR training is a safe and effective clinical rehabilitation tool when applied correctly[27].

BACKGROUND TO BFR

Since its early emergence as a form of exercise training, restriction of blood flow is commonly referred to as 'BFR training'[28]. This technique of restricting blood flow to the muscle using a pneumatic tourniquet system involves applying an external pressure, typically using a tourniquet cuff, to the most proximal aspect of the upper and / or lower limbs. When the cuff is inflated, there is compression of the vasculature underneath the cuff resulting in an ischemic environment, which subsequently results in hypoxia within the muscle[29].

Early research identified the capability of BFR to stimulate muscle hypertrophy and strength gains when combined with low-load resistance[28]. To date, the definitive mechanism(s) underpinning adaptations to low-load BFR training have not been pragmatically identified; however, proposed mechanisms include: cell swelling[30] increased muscle fibre recruitment[31] increased muscle protein synthesis[32] and increased corticomotor excitability[33].

The low-load nature of BFR training and ability to create muscle hypertrophy and subsequent strength gains make it a powerful clinical rehabilitation tool; an alternative to heavy-load resistance training in populations that require muscle hypertrophy and strengths gains but in which heavy-loading of the musculoskeletal system is contraindicated [27,63].

EFFECTIVENESS OF BFR IN THE EARLY STAGES OF REHABILITATION

Recently published research provides promising evidence of the effectiveness of BFR training in the early phases of rehabilitation post ACLR. In the UK National Health Service, we examined the effectiveness of BFR training compared to standard care rehabilitation in the first three months following ACL surgery[7]. Using a criteria-driven approach, patients began resistance training at approximately 21 days post-surgery. Using a leg press exercise, patients were randomised to either BFR training (4 sets (30, 15, 15, 15 reps) at 30% 1RM) or standard care heavy load training (3 sets (10, 10, 10 reps) at 70% 1RM), performing this twice per week for 8 weeks. Over 8 weeks of training, significant and comparable increases in muscle thickness (5.8±0.2% and 6.7±0.3%) and pennation angle (4.1±0.3% and 3.4±0.1%) were observed with BFR-RT and heavy load training respectively. Alongside this, significant and comparable increases in leg press strength were observed in the injured limb with BFR training (104±30%) and heavy load training (106±43%). Interestingly, BFR training appeared to attenuate knee extensor strength loss at fast speeds, possibly indicating a reduction in arthrogenic inhibition. In addition to muscle hypertrophy and strength adaptations, clinically meaningful improvements in several measures of physical function (International knee documentation committee score, lower extremity function scale, Lysholm knee-scoring scale and the Knee injury and osteoarthritis outcome score) were observed with BFR training, which were all significantly greater than heavy load training. This may be due in part to the greater reduction in knee pain and swelling found with subjects performing BFR training.

Cumulatively, studies indicate that BFR training performed at a much lower exercise intensity improves physical function, pain and swelling to a greater extent than traditional resistance training, without any detrimental effect on muscle hypertrophy and strength adaptations.

Using BFR training during rehabilitation post ACLR appears to be safe and practically feasible. No adverse effects on knee laxity have been found with BFR training compared to heavy load training[7,34]. It has also been shown both acutely and chronically that patients experience less knee pain during and for up to 24 hours post-exercise with BFR training[35,36], with a greater overall reduction in pain following 8 weeks of training[7,36]. Moreover, the perceived exertion and muscle pain responses to BFR training appears not to limit application or adherence to training. Similar findings have been found in post-surgical BFR studies in the US military[37].

PHASES OF BFR USAGE FOLLOWING ACLR

The primary post-operative goals of ACLR are to reduce joint effusion, pain control and combat muscle atrophy and strength loss[38]. During this early phase (phase 1), unloading of the muscle causes muscle atrophy[39,40]; thus, passive BFR, which is the application of BFR without exercise, may be performed. Passive BFR creates an increase in cellular swelling that is evident after release of the cuff[30], which may increase muscle protein synthesis and suppress breakdown[41,42].

Table 1

	Guidelines
Frequency	*1-2 times per day (duration of bed rest / immobilisation)*
Restriction time	*5 minute intervals*
Type	*Small and large muscle groups (uni or bilateral)*
Sets	*3 to 5*
Cuff	*5 (small), 10 or 12 (medium), 17 or 18 (large)*
Rest between sets	*3-5 minutes*
Pressure	*Uncertain - higher pressure may be needed (70-100% LOP)*
Restriction form	*Continuous*

Table 1: Phase 1 – Passive BFR guidelines.

Table 2

	Guidelines
Frequency	*2 to 3 times a week (> 3 weeks) or 1-2 times per day (1-3 weeks)*
Load	*20 to 40% 1RM*
Restriction time	*5-10 mins per exercise (reperfusion between exercises)*
Type	*Small and large muscle groups (uni or bilateral)*
Sets	*2 to 4*
Cuff	*5 (small), 10 or 12 (medium), 17 or 18cm (large)*
Repetitions	*(75 reps) - 30x15x15x15, or sets to failure*
Pressure	*40-80% LOP*
Rest between sets	*30 to 60 seconds*
Restriction form	*Continuous or intermittent*
Execution speed	*1 to 2 seconds (concentric and eccentric)*
Execution	*Until concentric failure or when planned rep scheme is completed*

Table 2: Phase 2 – Resistance training with BFR guidelines.

Passive BFR can be applied using a protocol of 5 sets of 5 minutes full restriction followed by 3 minutes of rest and reperfusion to attenuate atrophy and strength loss of the quadriceps muscles[25,43,44]. In addition, voluntary isometric contractions during BFR may increase metabolic stress and cell swelling levels above passive BFR and contribute to muscle hypertrophy[23,45], acting as a preparation phase to subsequent low-load BFR exercise. This first phase should begin a few days post-surgery provided that inflammation, pain and swelling is not excessive, and patients have passed a risk assessment questionnaire[46]. Neuromuscular electrical stimulation (NMES) combined with BFR has become more common in clinical practice in the acute phase of ACLR. Although this is a novel concept, studies combining low intensity NMES with BFR have found increases in muscle size and strength[47,48]. NMES of the quadriceps does not involve transmission of large forces through the tibiofemoral joint, thus exhibiting a low risk of damaging the graft or exacerbating any cartilage, meniscal, or bone injuries. Mitigating the loss of muscle strength and size in the acute stages of rehabilitation are necessary to perform voluntary training later in the rehabilitation process[49]. Thus, we are proposing NMES with BFR as an updated and potentially more effective approach to the early first postoperative phase.

As range of motion is returned and gait is normalized, low-load resistance with BFR should be introduced to accelerate muscle hypertrophy and improve strength. A synthesis of the available literature indicates that low-load BFR training is an effective, tolerable and useful clinical MSK rehabilitation tool[27]. Low-load resistance training with BFR has been shown to increase muscle protein synthesis[32] which may be a result of activation of the mTOR signalling pathway that is thought to be an important cellular mechanism for enhanced muscle protein synthesis with BFR exercise[50]. Such increases in muscle protein synthesis with low-loads can help recover and increase muscle size without loading the post-operative knee joint with heavy loads traditionally required for such adaptations. Low-load BFR resistance exercise may also be used to combat the reduced muscle satellite cell abundance observed during periods of unloading following ACLR[51,52]. Regarding strength, the early preferential recruitment of type II fast-twitch fibres at low-loads generated during BFR exercise is thought to be an important mechanism behind strength adaptations at such low loads. With BFR exercise, it appears that the normal size principle of muscle recruitment is reversed[26]. Fast-twitch fibres, which are more susceptible to atrophy and activation deficits during unloading[53] are normally only recruited at high intensities of muscular work. During low-load resistance training with BFR it appears they are recruited earlier. Indeed, several studies have demonstrated increased muscle activation during low-load BFR resistance exercise[54,55]. Greater internal activation intensity has been found relative to external load during low-load BFR resistance exercise[31], suggesting type II fibres are preferentially recruited. This preferential recruitment of the type II fibres that are more susceptible to atrophy during the early stages of ACL rehabilitation may help combat arthrogenic inhibition while also triggering muscle hypertrophy and recovery of strength

HOW TO IMPLEMENT BFR TRAINING

So how do we go about using BFR in a practical setting? Recent research supports individualisation of BFR application, where BFR is prescribed as a percentage of 'arterial limb occlusion pressure' (LOP), which represents the minimum pressure required for total arterial occlusion[23]. Manipulation of BFR protocols has been shown to influence the perceptual, hemodynamic, and neuromuscular responses to BFR exercise. Therefore, a brief overview of the current consensus on BFR application during rest and exercise is provided in Table 1 & 2[56].

HOW BFR CAN ENHANCE THE RETURN TO SPORT PROCESS

When to return to sport following ACLR is a controversial issue. It is common for patients to be at a higher risk of re-injury compared to healthy controls[57,58]. Strength and conditioning coaches, rehabilitation specialists and surgeons utilize a range of assessments to determine an athlete's readiness to return to sport, including: subjective rating scales, knee laxity testing, isokinetic testing, functional hop testing, balance testing, and movement assessment. Whilst this has improved over recent years, several studies have demonstrated deficits in muscular strength, kinaesthetic sense, balance, and force attenuation 6 months to 2 years following reconstruction[58-60]. With this in mind, the return to sport following ACLR should not be rushed. Furthermore, we suggest BFR be used to mitigate some of these residual deficits that athletes experience.

By using BFR earlier in the rehabilitation to offset atrophy and strength loss (phase 1) and improve strength and hypertrophy (phase 2), practitioners can spend more time focussing on neuromuscular control, functional strength, rate of force development, and psychological readiness which are necessary for a successful return to competition and reducing the risk of re-injury

CONCLUSION / FUTURE WORK

BFR provides a low-load safe and efficacious treatment modality for athletes following ACLR. As it gains more acceptance in clinical settings and more robust clinical trials are published, there has been a shift in the acuity of its usage and adoption across clinical conditions. Clinical trials have advanced to not just explore the ability of BFR to preserve and restore lost muscle mass and strength, data are now available which report its ability to preserve bone loss after ACLR[61], provide a reduction in pain, swelling and function[7,36].More recent advancements have also advocated its use in prehabilitation prior to ACLR[62] where a reduction of muscle fibrosis and upregulation of satellite cells have been shown along with accelerated return to play. Thus, we propose that these findings provide an important message for clinicians and athletes alike - train hard, train smart and start early!

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APPLYING THE PRINCIPLES OF MOTOR LEARNING TO OPTIMIZE REHABILITATION AND ENHANCE PERFORMANCE AFTER ACL INJURY

– Written by Alli Gokeler, Germany and Anne Benjaminse, The Netherlands

INTRODUCTION

Most athletes who wish to continue sports participation after an anterior cruciate ligament (ACL) injury are advised to undergo ACL reconstruction (ACLR)[1]. Traditionally, rehabilitation programs have mainly focused on restoring symmetry in range of motion, balance, strength and neuromuscular control. For young athletes (<25 years of age) returning to competitive sports involving high intensity jumping and cutting activities, secondary ACL injury rates of 23% have been reported, and these frequently occur early during the return to sport (RTS) period[2].

Restoration of symmetry alone is not sufficient to reduce an athletes risk of reinjury. Focus should also be placed on addressing underlying deficits that likely contributed to the primary ACL injury[3]. In addition, a series of inciting events are likely to occur prior to the actual injury[4], and different playing situations provide further complexity. For example, ball possession, position of team mates and actions of opponents all impose different challenges and problems for the athletes to solve[5,6]. Thus, perceptual capacities play an important role in team and ball sports[7] by enahncing perception in rapidly changing environments. Interpreting situational information correctly and efficiently allows them to select the most appropriate response. The impact of these chaotic environments should not be ignored when second ACL injury prevention is the goal. However, components of neurocognitive training are often not addressed in current ACL rehabilitation programs[8].

An ACL injury induces neurological changes to the central nervous system (CNS), due to the loss of information from mechanoreceptors, pain and developed motor compensations[9]. This neuroplastic disruption progresses until altered motor strategies potentially become the norm. Subsequent restoration of baseline function then becomes a fight against maladaptive neuroplasticity developed in the wake of altered CNS input and motor output compensations[10]. Rehabilitation should therefore also consider central neurological (brain) drivers of control and ultimately these strategies should be incorporated into secondary injury prevention programs[11]. Considering the high re-injury rates, current approaches may not be effective in fully targeting residual deficits related to the initial injury and the subsequent surgical intervention[12]. Furthermore, rehabilitation after ACLR should focus on addressing the underlying neuromuscular control deficits that led to the initial injury and that may be amplified subsequent to ACL injury and reconstruction. The purpose of this article is to present novel clinically integrated motor learning principles to support neuroplasticity that can improve patient functional performance and reduce the risk of second ACL injury.

WHAT IS MOTOR LEARNING?

Motor learning is defined as the process of an individual's ability to acquire motor skills with a relatively permanent change as a function of practice or experience[13]. Currently the most used method to test motor learning is to assess the behavioral resultant outcome[13]. To assure that motor learning takes place, a skill must be rehearsed repeatedly. However, there are many variables to consider when planning and structuring practice. Even for commonly used factors such as instructions and feedback, clinicians should be cognizant of the effects that the amount, type, and schedule of instructions respectively can have on long term skill retention.

Optimal practice should ensure long-term learning and this is measured by retention and transfer of skills. In addition, task-specific practice should be used that is meaningful to the patient

Further, it is important to ensure the task being practiced is meaningful, challenging and motivating for the patient. Examples of important influencing factors to support the motor learning processes during ACL rehabilitation will be described in this article.

ATTENTIONAL FOCUS

In almost any training situation where motor skills are to be learned, patients receive instructions about the correct movement pattern[14]. Is is important to be aware that instructional language has an influential role on motor learning outcomes[15]. Typically, a physical therapist instructs the patient to flex the knee more when landing[16] (see Figure 1). Instructions that direct the patient's attention to their own movements induce an internal focus of attention[17].

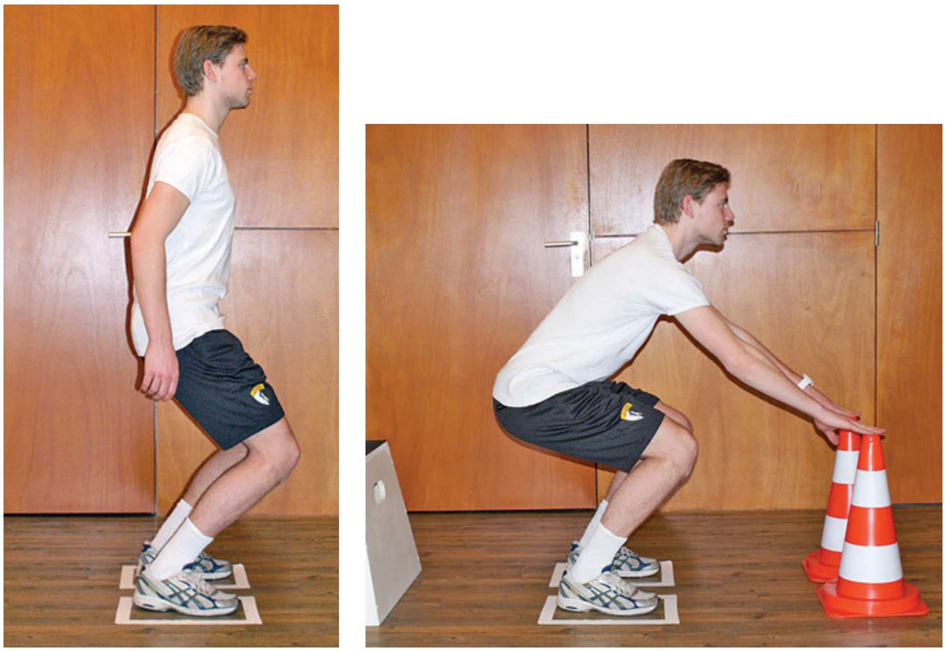

Figure 1: Internal focus (a) versus external focus (b) instructions during a drop vertical jump. In (a), the patient was instructed to land while bending the hips and knees; in (b), the patient was instructed to touch the cones when landing. Note the increased flexion of trunk, hips and knees (as shown in Figure 1b compared to 1a) indciating a 'safer' landing strategy despite the fact that no specific task instructions were provided

It has been shown that 95% of physical therapists provide instructions with an internal focus[18]. However, a growing body of evidence shows that this type of attentional focus may not be as effective as previously thought[19].

Interestingly, a simple change in the wording of instructions can have a significant impact on performance and learning. For example, directing the patient's attention to the effects of the movements on the environment promotes an external focus of attention. In this case, to increase knee flexion when landing from a jump (promoting a soft landing), a physical therapist instructs the patient to touch cones when landing (Figure 1)[16]. A focus on the movement effect promotes the utilization of unconscious or automatic processes, whereas an internal focus directs attention to one's own movements results in a more conscious type of control that constrains the motor system and disrupts automatic control processes[20]. Wulf et al. have termed this the 'constrained-action hypothesis' as the explanation for the attentional focus phenomenon[21]. Support for this view comes from studies showing reduced attentional demands when performers adopt an external as opposed to an internal focus, as well as a higher frequency of low-amplitude movement adjustments, which is seen as an indication of a more automatic, reflex-type mode of control[22]. The cumulative body of evidence indicates the beneficial effects of using external focus instructions over internal focus instructions[22,23].

IMPLICIT LEARNING

The aim of implicit learning is to minimize the amount of explicit knowledge about movement execution during the learning process. An example of this would be trying to describe in as few words as possible how you ride a bicycle. Commonly, we have a hard time explaining this using a verbal description. The reason is that we 'just do it' (riding a bicycle) and we really don't need a large pool of conscious detailed knowledge to outline how to execute the movement. If we accept this premise, we can also ask ourselves what we do in a clinical situation with a patient. Commonly, we as clinicians provide a lot of detailed information to the patient. Interestingly, physiotherapists working with children can't use the explicit instructions and often use implicit learning methods. An example of how implicit learning can be induced is by providing analogies rather than explicit instructions during the acquisition of motor skills[24].

Analogy, or metaphorical description of the action, connects with a visual image, e.g. 'pretend you are landing on eggs', to promote a soft landing.

Implicit learning reduces the reliance on the working memory and promotes more of an automatic process[24]. It is for this reason that it can be more effective in the execution of complex tasks. Competitive sports can be psychologically demanding, and decision-making accuracy deteriorates in athletes when they are under pressure and must deal with increased task complexity[25]. The negative influences of pressure can be observed in several ways. Of interest in connection to learning is 're-investment', when an athlete begins to direct attention to the skills and movements which should already be automatic, and do not need conscious control. This re-investment may cause the athlete to make sudden mistakes in technical actions, which are relatively simple and have been performed, without error, a thousand times before[26].

Explicit learning can promote re-investment because the athlete reverts to memory by a detailed, step-by-step explicit instruction about movement execution. Under stress, an athlete may unwillingly start to follow this guidance and divide smooth and fluent execution into separate blocks that would be detrimental for expert performance (choking). Additionally, such excessive attention to the technical details can draw working memory resources from other aspects of athletic performance[24].

One of the most interesting and widely unexplored aspects of implicit learning in rehabilitation is its connection with anticipation and decision making. This may be important in the later stages of rehabilitation when the patient is approaching the RTS phase. An athlete should be progressively exposed to physical, environmental, and psychological stressors that are comparable to those they will experience in the sport they participate in. Considering secondary ACL injury prevention and an increased need to re-establish sports performance skills, training in this phase of the rehabilitation should emphasize motor control factors such as anticipation, responses to perturbation, and visual-motor control within complex task and environmental interactions. Heightened anticipatory and sensorimotor skills obtained through implicit learning may give the athlete an improved capability to anticipate the need for corrective motor actions and avoid potentially high injury-risk scenarios. Evidence of this is present whereby implicit training using limited visual information about the direction of the ball in tennis, improved athletes' prediction accuracy after the intervention[27]. Conversely, an explicit learning group, who received specific kinematic information about the tennis serve of the opponent, didn't demonstrate any improvement in anticipatory skills[27].

"It has been shown that 95% of physical therapists provide instructions with an internal focus. However, a growing body of evidence shows that this type of attentional focus may not be as effective as previously thought."

Progressing the learning challenge through contextual interference

Practice has a key role in the acquisition of motor skills during ACL rehabilitation. When a movement is executed, a learner strengthens his/her motor schemas, storing information about (a) the initial conditions, (b) the response specifications of the motor program, (c) the sensory consequences of the produced response, and (d) the effects of the movement on the environment[13]. Hence, the way the practice is scheduled influences the acquisition of motor skills. Random, or variable practice involves performing variations of the task or completely different tasks throughout a rehabilitation session. For skill transfer to occur, a review of the literature has suggested that variable practice may be more effective[28]. Contextual interference in motor learning is defined as the interference in performance and learning that arises from practicing one task in the context of other tasks[28]. Contextual interference is the effect on learning produced by the order of skills changing across trials. A non-systematic order of skills execution, as well as a non-consecutive execution of the same skill (A-C-B-C-A-B-A-B-C), is observed during random practice. The amount of contextual interference may vary and is generally low in blocked practice and high in random practice. Practicing under conditions of high contextual interference (i.e., with a random practice order) degrades performance during acquisition trials compared with low contextual interference conditions (i.e., with a blocked order, where practice is completed on one task before practice on another task is undertaken)[28].

While higher contextual interference (random practice) may lead to poor(er) immediate performance, it frequently leads to better learning (as measured by retention and transfer tests) compared with blocked practice[29].

Clinicians must decide how to best schedule practice to facilitate learning. As mentioned, the skill level of a patient is a factor that may need to be considered in terms of the amount of contextual interference provided[29]. In general, lower level athletes benefit more from low contextual interference, whereas elite athletes often thrive in learning environments where high levels of contextual interference are present.

Table 1

Examples of autonomy supportive language	*Examples of controlling language*
1. You have the opportunity to....	*1. Your job is to....*
2. Once you begin....	*2. You may not begin until....*
3. Feel free to....	*3. Make sure you....*
4. You may organise in a way you prefer	*4. Do not!*

Table 1: Comparison of wording that support autonomy versus wording that is more controlling.

MOTIVATION

Practice conditions that support fundamental psychological needs such as competence, autonomy, and social relatedness[30] appear to create circumstances that enhance motivation and optimize performance and learning[31] and further details and practical strategies for each are outlined below.

Autonomy

In most rehabilitation situations, clinicians determine the content and specific details of the training session. For example, they decide the order in which tasks are practiced, the duration, and when or if instructions, demonstrations or feedback will be provided. Thus, while clinicians generally control most aspects of practice, patients assume a relatively passive role. Self-controlled learning (where the patient has the choice when to request feedback or may choose an exercise) is a powerful tool in motor learning and has shown advantages in comparison with prescribed training schedules[32-34], some examples include:

1. Encourage the patient to choose three exercises for any given rehabilitation session (while considering variation in level or equipment).
2. Ask the patient to choose the type of material of a given exercise.
3. Suggest the patient determines when to receive feedback during selected exercises.

In practice you may provide the patient with three options when practicing a squat:

1. practicing on a BOSU ball,
2. practicing in front of mirror with barbell,
3. practicing as a goblet squat.

When you give the patient the option to chose one of these exercises, in all likelihood, patients will chose what they like best[35]. This choice is based on:

1. feelings of competence ('yes, I can do this!') or
2. feeling of relatedness ('I feel most comfortable / challenged when doing this variation of the exercise').

Of note, the physiotherapist is still responsible for creating the (safe) environment for learning, offering exercises with similar difficulty level, where a range of materials can be chosen.

Positive feedback and autonomy supportive language

It is also important to realise that athletes have a preference to receive positive feed-back. Experiencing competence through feedback on good trials positively affects motor learning through motivational influences such as intrinsic motivation, interest, and enjoyment[32,36]. For example, providing feedback after good trials (e.g. "That was an excellent jump, you landed very softly') plays a strong role in confirmation of competence, provides confidence and enhances intrinsic motivation[37]. Self-controlled feedback schedules also have the potential to help patients become more involved in their learning process by inducing an active role during rehabilitation sessions which subsequently enhances motivation and increases effort and compliance[38-40].

Finally, the way in which task instructions are phrased can have a profound influence on learning. Instructions that suggest to learners a certain degree of choice in how they perform a task can promote a more effective learning environment than over utilisation of prescriptive instructions that imply no room for choice. This is very easy to implement through the use of subtle changes in wording. For comparison see the wording in Table 1.

SUMMARY

Enhancing movement quality and training transfer are key outcomes of rehabilitation to reduce the risk of reinjury and enhance performance. While the development of physical capacities is of fundamental importance, a large part of the movement solution is grounded in neuromechanics (i.e., the interaction of the brain and muscles to produce coordinated movements in different conditions). Strategies to optimize motor learning can begin early in the rehabilitation process and should continue as the athlete aims to return to sport and optimal performance. Some examples have been outlined in this article including the use of positive, externally focused feedback and increasing levels of contextual interference. However, the optimal solution also needs to be individually tailored to the athlete, and they should also be encouraged to play an active role in their rehabilitation journey. Future research should focus on which combinations of the techniques presented here are most effective for long term skill retention, create the least dependence on external feedback, and provide the greatest transfer to the sporting environment.

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NEUROPLASTIC MULTIMODAL ACL REHABILITATION

INTEGRATING MOTOR LEARNING, VIRTUAL REALITY, AND NEUROCOGNITION INTO CLINICAL PRACTICE

– *Written by Adam L. Haggerty, Janet E. Simon, Cody R. Criss, HoWon Kim, Tim Wohl, Dustin R. Grooms, USA*

INTRODUCTION

Non-contact rupture of the anterior cruciate ligament (ACL) is a common sports-related injury typically warranting extensive rehabilitation and\or surgical intervnetion[1–5]. Athletes that return to full participation are at an elevated risk for re-injury or injury to the contralateral limb with an estimated 1 in 4 athletes sustaining a second injury after returning to high-level sport[1,6]. The high re-injury rate among athletes has been a focus for researchers attempting to identify modifiable risk factors for rehabilitation techniques to improve return-to-sport (RTS) outcomes. Traditional rehabilitation after ACL injury has focused on both 1) time-based, knee-specific exercises, and 2) isolated physical abilities (e.g., muscle strength, hop distance) for RTS readiness[7]. Recently, a multifactorial approach to rehabilitation (in which exercises incorporate the sensorimotor spectrum, are multi-segmental, and combine the person, task, and environment in a dynamic systems approach) has received attention as a means to improve motor coordination and decrease re-injury risk[6,8].

Orthopedic rehabilitation must move beyond the traditional emphasis on mechanics and muscle strength and consider nuanced sensorimotor control deficits to ensure complete recovery and readiness for RTS. ACL injuries during sport are predominantly non-contact, suggesting injury may be a product of sensorimotor errors that result in a neuromuscular control strategy unable to accommodate deleterious joint loading[6,9,10]. Further, the vast majority of non-contact injury events occur while athletes are cognitively distracted, attending to complex visual demands or environmental stimuli[9,11,12], suggesting that neural mechanisms may directly contribute to the athlete's ability to safely interact with the dynamic sport environment[13,14].

Rehabilitation efforts that incorporate multimodal aspects of motor learning and neurocognition may improve functional outcomes for ACL reconstruction (ACLR) patients. These modalities include training with an external focus of attention, implicit feedback, differential learning, novel sensory reweighting, and virtual reality technologies. Below we introduce several key concepts regarding motor learning principles, neurocognition, and new technologies that clinicians may incorporate into modern rehabilitation practice. In addition, we outline a theoretical ACLR rehabilitation program that incorporates these concepts and gives clinicians an immediate practical application.

1

Figure 1: Strobe glasses rapidly cycling OFF (left) and ON (right) to knockdown visual feedback.

2

Figure 2: Strobe glasses used during a jump task to facilitate sensory reweighting from visual dependence to increased proprioception reliance.

WHY DO WE NEED TO CONSIDER MOTOR LEARNING PRINCIPLES IN REHABILITATION?

Motor learning is a term that corresponds to the relatively permanent acquisition and refinement of motor skills[15]. The principles underlying motor learning incorporate fundamentals of neuroscience, psychology, and rehabilitation science to explain how motor development and re-learning occurs after injury. The use of motor learning principles can improve rehabilitation outcomes and be implemented with a variety of clinical populations such as stroke, amputee and motor speech disorders[16,17]. Traditional musculoskeletal rehabilitation approaches tend not to integrate motor learning principles explicitly or with a goal to induce neuroplasticity, or sensory reweighting, or virtual reality technologies that support optimized functional performance and recovery. Incorporation of these new technologies and therapies may provide a means to reduce the high reinjury rate after ACLR, as the ACL injury event is essentially a coordination error in sensory, visual or motor processing[18,19]. Furthermore, emerging evidence has demonstrated the existence of central nervous system changes following acute traumatic knee injuries, which may influence motor control and functional outcomes of ACLR patients[20–22]. As such, motor learning strategies, and other modalities, may constitute a potential solution to mitigate neuroplastic effects of injury that can impede rehabilitative progress[23].

KEY MOTOR LEARNING PRINCIPLES TO AUGMENT REHABILITATION

Effective rehabilitation prepares an athlete for return to play through the transfer of clinically learned motor skills to the athletic environment and modifications to exercise prescription that optimize learning may facilitate beneficial neuroplasticity[23]. As discussed in the article by Gokeler and Benjaminse in this special edition (see pages 62-65) it is recommended that athletes transition to **an external focus of attention** movement strategy as soon as possible to enhance attentional processing during movement performance, freeing up cognitive processing[24–26]. Similarly, rehabilitation that imparts **implicit learning**, rather than offering explicit directions, may reduce the cognitive demand on athletes to successfully perform safe movements[27–30]. New biofeedback technologies also hold promise to induce implicit learning that is tailored to reduce multi-variable injury-risk factors[31–33].

Differential learning encourages athletes to readily adapt their movement strategies to perform a task under constantly changing parameters[34]. These include changing the technique of a task, the environment where the task is performed, and the duration or intensity. The main goal for differential learning is to modify how the task is performed after every 1-3 repetitions to force the athlete to continuously adapt to the variable conditions and promote biomechanical adaptations that are best suited for the individual. This is counter to common training practices that focus on continuous repetition of the "correct" form; however, rarely in competition are there opportunities to perform repetitive "ideal" movements. Thus, clinicians are encouraged to alter task, context and\or environmental constraints to improve learning over time, despite potential reductions in immediate performance[35–37].

EMERGING TECHNOLOGIES TO ADDRESS SPECIFIC POSTINJURY NEUROPLASTICITY DURING NEUROMUSCULAR TRAINING

Incorporating new technologies into therapy also provides unique avenues to increase the neurocognitive demand placed on athletes during rehab. The use of *stroboscopic glasses* to induce **sensory reweighting** is one such modality[38–41]. Sensory reweighting describes how the central nervous system integrates separate sensory stimuli (e.g., visual, vestibular, proprioceptive) by weighting them according to reliability, essentially decreasing the weight of *unreliable* stimuli and thereby increasing the weight of others[42,43]. Stroboscopic glasses (Figure 1) may facilitate sensory reweighting by allowing clinicians to induce a standardized knockdown to visual feedback that can be progressed in difficulty as their patients recover (Figure 2). This modality may enhance proprioceptive processing, which is damaged after injury, by decreasing the salience of visual feedback for motor control (hence reweighting).

A strength of stroboscopic glasses is they may be used during any therapy or exercise as an adjunct tool since this modality varies the degree of visual feedback without entirely removing an athlete's vision. After verifying that their athletes can complete an exercise with the glasses at the easiest setting (i.e., shortest duration of the opaque state), clinicians may increase the difficulty level (i.e., reducing the amount of visual feedback) by increasing the duration of the opaque state (range: 25 to 900 milliseconds) while the clear state remains constant (100 milliseconds)[41]. Examples of exercises that may be coupled with stroboscopic glasses include agility drills, balance tasks, plyometrics, running, cutting, pivoting, etc. Additionally, clinicians may increase the neurocognitive demand for their athletes by introducing external visual targets/goals (e.g., jumping to hit an overhead target) or dual-tasking (e.g., have the athlete countdown from 100 by 7 while performing a balancing on a single leg) while wearing the stroboscopic glasses.

Virtual reality also brings new potential to induce **contextual interference** (see article by Gokeler and Benjaminse – pages 62-65) and additional visual-spatial and neurocognitive challenges to rehabilitation[44-46]. The advent of virtual reality headsets that utilize a typical smartphone display has reduced upfront costs, allowing this technology to become broadly available[44]. Promising uses include augmenting typical rehabilitation "downtime" such as during passive modalities like cryotherapy or electrical stimulation to allow **mental practice**[47] with visual immersion on a virtual field of play. As therapy becomes more demanding, more advanced exercises can implement visual-vestibular perturbations through observing moving environments (e.g. riding a roller coaster) for postural control training. For further examples of how virtual reality can be integrated within rehabilitation see the article in this special edition by Bonnette et al (pages 72-77).

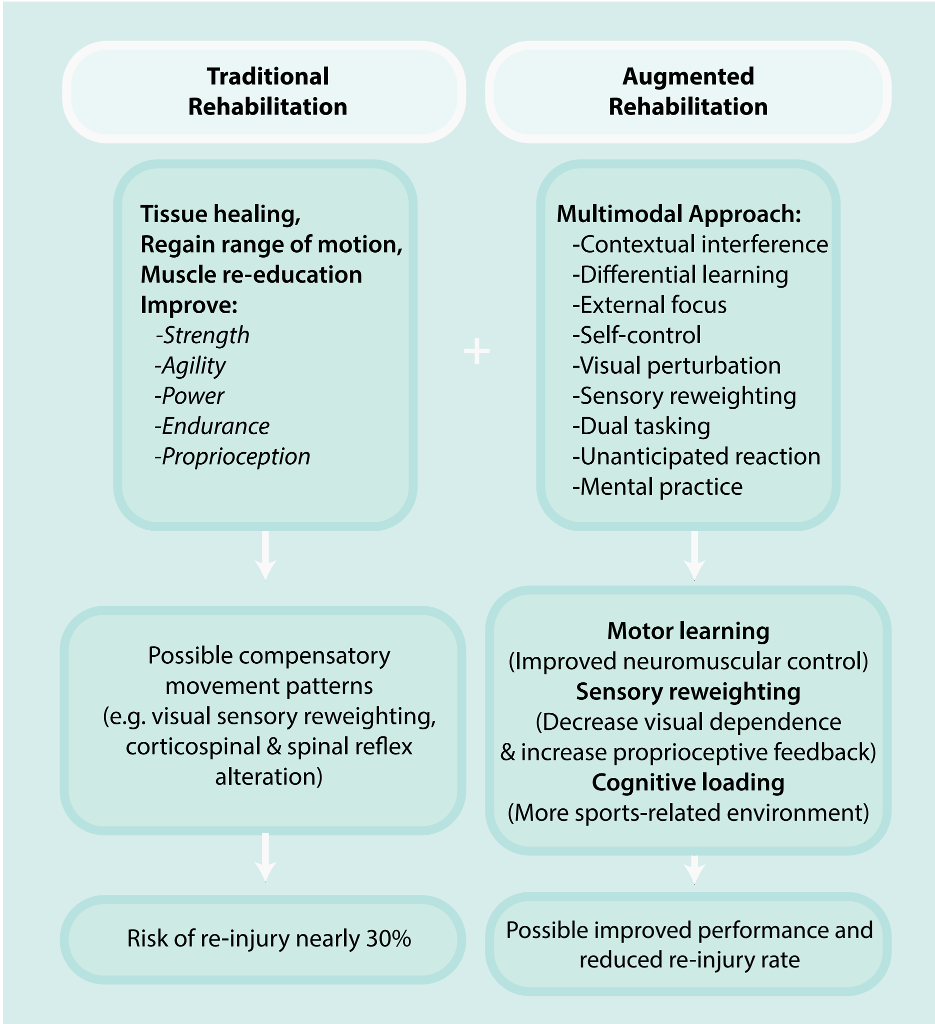

Figure 3: Multimodal rehabilitation builds on the traditional rehabilitation model by incorporating motor learning and neurocognition into clinical practice. The integration of these principles is not time specific or tool dependent. Instead it is highly customizable to the goals of the patient and practitioner.

PRACTICAL APPLICATION

To incorporate these novel aspects of multimodal rehabilitation, we have outlined a theoretical case study below to give clinicians an example on how to augment their current therapy with the tools and methods outlined in this article. The case study is divided into four generalizable phases of rehabilitation progression (early, mid, late, and return). We advocate an *augmentative* approach (Figure 3) when incorporating these principles or modalities, they do not replace any exercise or rehabilitative goal, they are to be used as adjuncts during the exercises you are already prescribing. The fundamentals of rehabilitation including range of motion, strength recovery and basic movement pattern restoration are still the primary goals. Multimodal rehabilitation can be implemented using a variety of tools and exercises as outlined earlier in this article.

THEORETICAL CASE STUDY

Patient: 17-year-old female soccer player
Position: Goalie
Exposure: Starter
Repair: Ipsilateral patellar tendon graft
Mechanism of injury: Non-contact ACL injury when pivoting to make a save.

EARLY PHASE

In the early phase of rehabilitation, the main goal is to manage pain and swelling while regaining range of motion (ROM) and quadriceps activation. Clinicians need to be cognizant of prescribed exercise protocols that may vary based on type of surgery, degree of injury or other related factors and therefore limits that may affect ROM and load-bearing exercises for proper allotment of time for tissue healing. See Figure 4 for examples of a novel treatment plan that can be incorporated to complement traditional rehabilitation approaches suitable for this phase in the 'athletes journey'.

4

EARLY phase

Mental Practice

Equipment:
Virtual Reality Goggles

Watch immersive soccer game in VR or play VR soccer game for goal keeping while getting treated with cold modality

Rehab Focus
Decrease Joint Effusion

External Focus

Equipment:
Blood Pressure Cuff

Patient supine, blood pressure cuff beneath involved limb, perform knee extension to compress cuff, attempt to reach a target force

Rehab Focus
Increase ROM (extension)

Contextual Interference

Equipment:
TV, Computer or Phone

Numbers randomly appear on the screen:
ODD: Do straight leg Raise
EVEN: Do Quad Set

8 1 72 17 9 2 55 16 7 33

Rehab Focus
Neuromuscular Re-education

5

MID phase

External Focus

Equipment:
Laser Pointer

Perform lunge with laser pointer attached to thigh, aim pointer at target on the floor or trace a target outline on the floor

Rehab Focus
Neuromuscular Control

Self-Controlled

Equipment:
Optional- weights

Squat: allow athlete to take control of the treatment ONLY providing feedback when requested

Rehab Focus
ROM & Strength

Visual Perturbation

Equipment:
Virtual Reality Goggles

Use Virtual Reality to add perturbation to a balance task, stand on single leg while watching an Immersive Roller Coaster Video

Rehab Focus
Balance Training

6

LATE phase

Unanticipated Reaction

Equipment:
FITLIGHT

Use 6 Meter Hop Test method for training

Rehab Focus
Reaction time & Focus of Attention

Sensory Reweighting

Equipment:
Strobe Glasses

Perform ball passing, single leg stance, alternating feet with Strobe Glasses

Rehab Focus
Focus of Attention

Dual Task

Equipment:
TV, Computer or Phone

Patient Jumps off ground, then a TV prompt shows a math problem, solve to determine landing leg

3+4 =7

Odd- land on **LEFT**
Even- land on **RIGHT**

Rehab Focus
Cognitive loading

7

RETURN phase

Differential Learning

Equipment: *Ball*

Clinician varies throwing of ball to patient, patient varies blocking style (catch, punch single hand/two hand, dive, kick, trap, header)

Rehab Focus
Strength / Agility

Dual Task

Equipment:
FITLIGHT

Lights at periphery, touch "blue" light ONLY, Lights randomly cycle after each touch, perform ball toss with clinician as quickly and accurately as possible

Rehab Focus
Cognitive loading

Unanticipated Reaction

Equipment: *Ball, 2 people*

Ball shot on goal, patient makes save, quickly stand and prepare to pass, clinician calls out 2 digit number, 21 1st number determines **where** to pass, 2nd number determines **kick** or **throw**.

Rehab Focus
Cognitive loading

Figures 4-7

> ***Rehabilitation must move beyond the traditional emphasis on mechanics and muscle strength and consider nuanced sensorimotor control deficits to ensure complete recovery and readiness for RTS. Incorporating multimodal aspects of motor learning and neurocognition may improve functional outcomes after ACL reconstruction.***

MID PHASE

During the Mid Phase of rehabilitation, typically between 3-6 weeks post-surgery, the main goals for patient progression are retention of full ROM while continuing to improve strength. Typically, proprioceptive exercises to improve balance and kinesthetic awareness are worked into treatment as tolerated. See Figure 5 for three tasks that can be implemented to further incorporate an augmentative approach during rehabilitation suitable at this phase.

LATE PHASE

The Late Phase of rehabilitation refers to a time point typically between 6 to 12 weeks post-surgery. Following the traditional rehabilitation model, the main goals are to achieve full ROM with quadriceps strength greater than 80% of the contralateral limb, increase the difficulty of proprioceptive exercises and begin to implement agility and power tasks into treatment. This is an excellent time to integrate dual task, unanticipated reactions and sensory reweighting exercises that will challenge the patient to reduce their reliance on visual feedback and potentially rewire the brain to interpret proprioceptive feedback during increasingly complex tasks. See Figure 6 for several examples.

RETURN PHASE

There are many factors that must be assessed during the RTS decision or Return Phase. It is important to follow protocols that are best suited for each patient and supported in the literature. The implementation of multimodal treatment tasks is not intended to replace functional assessment but can be incorporated during the end stages of rehabilitation or as an add-on to a patient exercise routine after returning to full activity and cleared by a physician. In this phase, patients will focus on sport-specific exercises that are intended to be extremely challenging both physically and cognitively while performed in a controlled environment. All of the previously mentioned multimodal tasks can be implemented with a major focus on motor learning, cognitive loading and sensory reweighting that are real-to-sport and require quick decision making from unanticipated events. See Figure 7 for several novel examples.

CONCLUSION & FUTURE CONSIDERATIONS

With recent evidence in support of neural contributions to ACL injury[48] and rate of recovery, rehabilitation protocols may benefit from incorporation of approaches that target the sensorimotor system. The integration of motor learning principles (external focus and differential learning) and/or new technologies (virtual reality, FITLIGHT, stroboscopic glasses) may bolster current ACL rehabilitation protocols and improve patient recovery. Additionally, other recent investigations have also highlighted perioperative considerations that may impact ACL patient outcomes and readiness for RTS. These may include, but are not limited to, anesthesia alternatives[49] and advances in surgical approach[50]. Furthermore, other factors, such as psychological distress, kinesiophobia or fear of reinjury, have been implicated as an important determinant for not returning to sport.[51] Therefore, future protocols may warrant the incorporation of psychological readiness considerations within RTS criteria.

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THE FUTURE OF ACL PREVENTION AND REHABILITATION

INTEGRATING TECHNOLOGY TO OPTIMIZE PERSONALIZED MEDICINE

– *Written by Scott Bonnette, Manish Anand, Kim D. Barber Foss, Christopher A. DiCesare, Jed A. Diekfuss, Dustin R. Grooms, Adam W. Kiefer, Katie Kitchen, Danielle Reddington, Christopher Riehm, Michael A. Riley, Andrew Schille, Jessica Shafer, Staci Thomas & Gregory D. Myer, USA*

EPIDEMIOLOGY OF ACL INJURY AND SECONDARY INJURY

A recent meta-analysis revealed that one in 29 females and one in 50 male athletes rupture their ACL when monitored over the years of their athletic participation[1]. Despite widespread interest in research and application of injury prevention programs for athletic populations, the incidence of ACL injuries continues to rise[2-6]. This is at odds with a large volume of evidence supporting that implementing ACL injury reduction training programs, especially neuromuscular and strength-based training[5], reduces the risk of sustaining an ACL injury[7]. Unfortunately, up to 50% of injured athletes do not return to their prior level of sport[8]. As a result of several factors that contribute to re-injury[4,9], those who do return to sport are 30 to 40 times more likely to suffer a second ACL injury on the same or contralateral knee[4]. Specifically, within two years of an ACL reconstruction (ACL-R), up to 30% of athletes experience a second ACL tear[5,10,11]. It has also been observed that as many as 55% of the recurrent ACL injuries are noncontact events, which supports the suggestion that sensorimotor deficits are present following ACL reconstruction and rehabilitation[12-14]. Cumulatively, current evidence points toward shortcomings in current approaches to ACL injury prevention, rehabilitation, and risk assessment methods. These must be addressed to reduce the negative effects of ACL injuries such as pain[15], depression[16], lost athletic identity[17], fear of re-injury[18] and ultimately prevent initial ACL injuries on a wider scale[7,19-23].

CURRENT STRATEGIES FOR INJURY PREVENTION

Current injury prevention programs, while effective at curtailing risk factors in laboratory settings, have not reduced widespread ACL injury rates.

The shortcomings of current programs may arise from several common problems, including athlete noncompliance, the type of training program, and the resources needed to institute in practice. Further details are provided below.

a. Participant noncompliance

Participant noncompliance is a unique issue to consider in developing a successful injury prevention program because it is a source of variability typically not directly related to or measured relative to the empirical motivation for the designed intervention (e.g., what risk factors are targeted, what methods are used to reduce these factors, and when the program is implemented). High compliance and adherence are difficult to achieve at a cost-effective and widespread scale, and noncompliance is integrally intertwined with the success of a program to reduce ACL injury rates. For example, a participant with low compliance to ACL prevention training is at 4.9 times greater risk of an ACL injury compared to a participant with high compliance[20]. Although it is difficult to determine exact reasons for noncompliance, participant motivation seems to play a key role. Steffen et al. (2008) reported that low motivation of participants likely caused their study's high noncompliance, while incentives (such as free, personalized athletic training from an expert), though not as cost effective, do appear to increase compliance[24].

b. Types of training programs
Although several studies have demonstrated that training interventions can reduce rates of ACL injury and that specific biomechanical variables associated with ACL injury risk can be successfully targeted for improvement, there is considerable variation among the training design of these interventions[7,25]. The most salient differences are among the content, length, frequency, and total duration (for reviews see[7,21-23,26]). Most successful programs included more than one type (e.g., modality, exercise type, etc.) of training content[7,25]. Whereas, utilizing a single intervention modality, such as balance training or strength training alone does not appear to be successful[27,28]. Furthermore, programs of heightened intensity in terms of the length, frequency, and total duration have reported increased benefits which is an important consideration given the previously discussed issues related to compliance. There is currently insufficient evidence to provide specific prescription parameters; however, a meta-analysis determined that 70% of ACL injury risk could be alleviated with 30 minutes or more of training per week throughout a sports season[29].

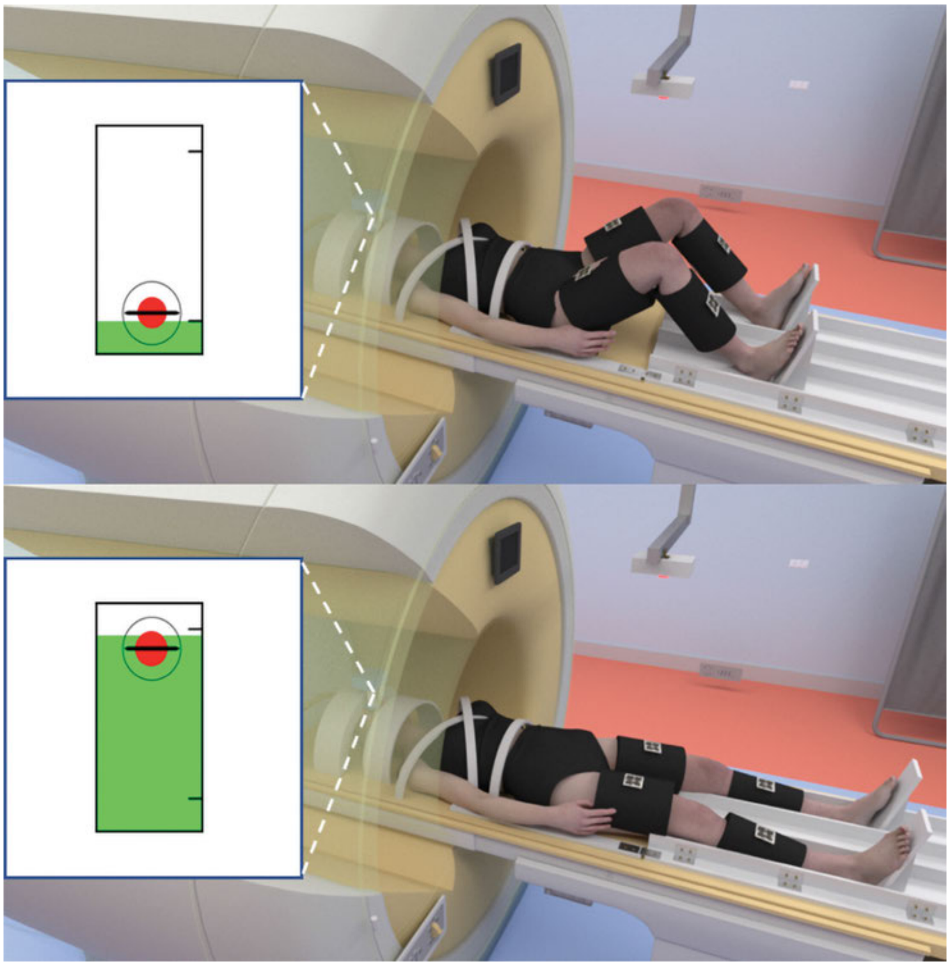

Figure 1: Displayed is a 3D rendering of our experimental configuration for obtaining fMRI data during lower extremity body movements. In this particular force production task, participants are asked to perform combined ankle, knee, and hip flexion and extension movements while interacting with a biofeedback stimulus driven from real-time biomechanical data. As seen in the left panels, real-time position is indicated by the horizontal center black line; the green bar indicates the target position for the patient. Real-time force is indicated by the size of the red ball and the patient is to keep the red ball within the black circle (the target force). Participants are first asked to 'match' their movements with the real-time biofeedback stimulus and are then asked to repeat these movements without the real-time biofeedback to assess movement error (kinematic and kinetic 'mismatches'). The amount of movement error is then associated with brain activity to identify disrupted neural processes.

c. Resources for instituting injury prevention programs
One of the most challenging practical difficulties to overcome in decreasing ACL injury rates is the amount of resources required to implement a prevention program. Monetary costs are reported to range from approximately $190-480.00* per athlete per season[26]. In addition, there are also personnel resources required. Although it appears that the source of training (who or what provides it) is less important than how an athlete receives and processes information relating to the proper execution of preventative training exercises[26,30-32], ensuring that the feedback received during training is correct usually requires the presence of a trained professional such as an athletic trainer or physical therapist. A trained professional increases the required resources, financial and otherwise required for implementing an effective ACL prevention program.

CURRENT STRATEGIES FOR ACL REHABILITATION
The primary objective for rehabilitation after ACL reconstruction (ACL-R) is to return the patient to their prior level of activity, which is typically participating in competitive sports. Through rehabilitation and physical therapy, recovery after ACL-R involves improving neuromuscular function through a variety of targeted behaviors including muscle activation, range of motion, strength, and proprioception[33-35]. At the end of rehabilitation, when an athlete approaches the time to return to sports (RTS), objective measures of neuromuscular and biomechanical functional control are commonly employed to determine an individual's readiness to do so. Historically, these assessments have included components such as bilateral comparisons of strength, single-leg-hop performance,

* The estimates provided by Hewett, Ford, and Myer (2006) are adjusted to 2019 prices using the Consumer Price Index (http://www.bls.gov/data/inflation_calculator.htm).

balance tests, and agility measures[25]. However, even with guidelines to assess RTS readiness in the ACL-R population, re-injury rates in the adolescent athletic population remain as high as 30% when returning to sport[4,11,36]. This indicates a potential shortcoming of the RTS assessment in that either the criteria or components of those assessments need further evaluation. One possible area to consider as an indicator for readiness to RTS is motor control. While the ACL provides structural stability to the knee joint, a rupture of the ACL likely creates more dysfunction in the knee joint than just stability since the ligament itself contains mechanoreceptors which play an important role in neuromuscular control of the knee[37]. The initial disruption of the ligament mechanoreceptors propagates deficits in motor control, proprioception, postural control, and strength that are difficult to restore and assess at RTS[38]. These sensorimotor disruptions lead to deficits in motor control, such as dynamic knee valgus during sport-specific tasks which has been associated with cognitive deficits, specifically in a visual memory task[39]. This relationship suggests that not only are physical assessments of motor control important, cognitive assessments of motor control should also be incorporated into the rehabilitation and subsequent assessment to RTS after ACL-R to possibly reduce the chance of an ipsilateral re-injury or a new injury to the contralateral side.

ADDRESSING OPPORTUNITIES TO IMPROVE ACL INJURY RISK AND OUTCOMES

Current strategies for ACL injury prevention and rehabilitation exhibit shortcomings that represent opportunities to improve ACL injury outcomes through the advancement of screening methods and neuromuscular training to reduce injury risk.

a. Brain mechanisms underlying ACL injury risk

Recently, our lab has published work on resting-state functional brain connectivity (using functional magnetic resonance imaging [fMRI]) related to ACL injuries in female and male athletes. In our first investigation, prospective longitudinal data indicated that female soccer players who went on to experience a non-contact ACL injury exhibited disruptions in connectivity between the primary somatosensory cortex and cerebellum (regions vital to maintain a safe knee position during sport)[40]. We also found that male football players exhibited similar prospective functional brain connectivity disruptions throughout similar regions important for sensorimotor control that were associated with their future ACL injury[41]. Collectively, our data in both sexes revealed potential neural biomarkers that may predispose an athlete to a traumatic ACL tear and indicate that dysfunctional neural processes are a potential key contributor to injury-risk neuromuscular control.

In addition to the functional connectivity results described above, we have also found differences in the electrocortical behavior of athletes who went on to injure their ACL and those who did not[40]. Prospectively injured athletes exhibited lower spectral power[40], a basic indicator of brain activity in cortical behavior associated with sensorimotor function, attentional demand, and task complexity[12,42,43]. Interestingly, while the fMRI results indicated less adaptive activity in sensorimotor regions, the decreased electrocortical activity associated with attentional demand and task complexity may reflect possible attempts at neurological compensation[40]. These findings highlight the need for additional prospective studies that investigate CNS function and its relationship to biomechanical performance in order to identify potential biomarkers for musculoskeletal injuries (i.e., ACL). It may then be possible to target known biomarkers related to ACL injury risk through innovative biofeedback designed to promote neuroplasticity and the discovery of optimal neuromuscular control strategies[14,44]. However, one limitation precluding our capability for discovering a neural biomarker of musculoskeletal injury has been the technical challenges for capturing lower extremity movement during active brain scanning (our previous prospective studies have primarily been at rest).

b. Motion analysis and fMRI integration

One of the challenges for using fMRI to better understand musculoskeletal injury is that participants must keep their bodies as stationary as possible, especially the head, as motion produces artifact within the fMRI data[45]. This is especially limiting for investigating brain activity associated with whole-body behaviors that is common during sport participation (e.g., running or kicking a soccer ball). Further, collecting data using fMRI requires that all equipment be free of metal, specifically ferrous metals that can result in additional artifact and/or result in injury to the researcher or participant (objects can become 'magnetic projectiles'). To overcome these limitations, we have developed custom 'MRI-safe' apparatuses

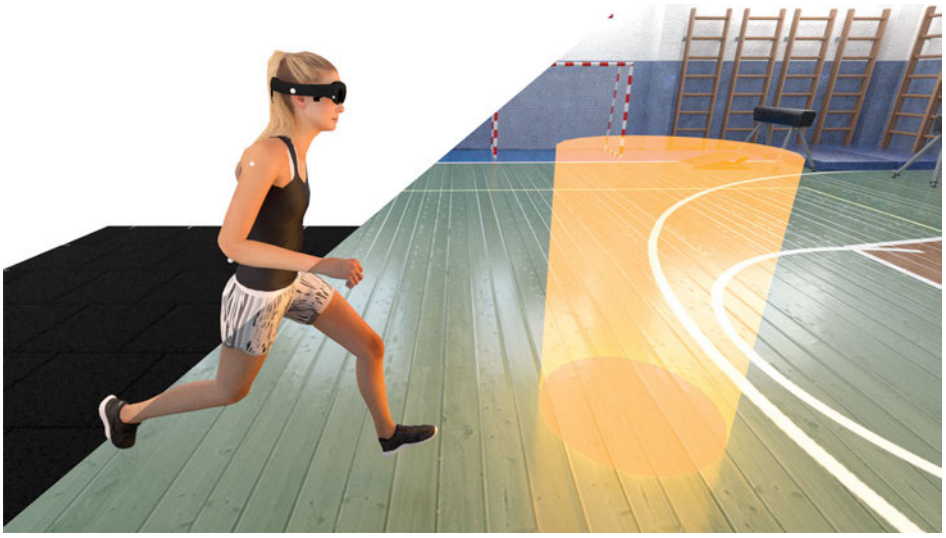

Figure 2: Shown above is an example of a VR scenario our lab has recently developed to investigate dynamic cutting. Participants' actual body movements are recorded by a motion capture system and translated to a virtual environment. In the above example it is an athletic gym where waypoints (indicators that direct participants to goal locations) are randomly placed to encourage participants to make sudden directional changes in response to the environment.

and associated paradigms to safely simulate lower extremity movement[14,46]. However, precisely quantifying lower extremity movement (e.g., knee flexion angles, force control) during our neuroimaging paradigms has been further challenging as standard technology to precisely measure movement is typically not MRI-safe (e.g., 3D motion analysis cameras).

Recent technological advancements are solving some of these experimental constraints. For example, MRI-safe motion capture equipment and force transducers are now available, and this makes it possible to capture precise kinematic and kinetic data during neuroimaging. Motion capture systems such as Metria (Metria Innovation, Inc.; WI, USA) are capable of tracking the position of a participant's body safely during fMRI[47-49]. When combined with MRI-safe force transducers[50,51], such as those produced by JR3 (JR3 Inc.; CA, USA), it is now possible to investigate brain activity during more realistic sport-like behavior. An illustration of our current method for obtaining fMRI data during a lower-extremity movement is displayed in Figure 1.

c. VR testing to identify deficits

Traditionally, laboratory-based biomechanical assessment of sport-relevant tasks, such as landing, jumping, and cutting, have been used to assess neuromotor deficits that are purported to increase athletes' risk of sustaining musculoskeletal injury during sport[52-54]. These screening assessments typically involve athletes performing a battery of tests in a standard, systematic manner (i.e., according to a prescribed set of instructions and in a specific order) and are subsequently used as proxies for assessing how these athletes are likely to perform in real-world sport environments. Assessing biomechanical deficits in this manner is beneficial in that it controls for confounding factors and unwanted variability in task performance, which can make isolation of various neuromuscular or physiological mechanisms that result in elevated injury risk difficult. Importantly, accurate insight into injury risk mechanisms is needed to deliver effective, targeted interventions to decrease injury risk.

The constrained nature of task performance in a laboratory setting differs significantly from the dynamic, sport-specific contexts in which athletes incur injury.

This may partially explain why interventions based on traditional biomechanical assessments are often ineffective at widespread reduction of injury rates[21]. Although on-field, sport-specific assessments would provide a solution to this issue, several factors make this impractical. For example, variable environmental conditions, such as poor lighting, uncontrollable weather (in the case of outdoor sports), or non-optimal vantage points from which to capture data make high-fidelity recording of real-world sport performance difficult. Moreover, as sport competition is inherently unpredictable, capturing desired events (e.g., risky landings, fast accelerations or change-of-direction cutting) is more challenging and time-consuming than laboratory-based assessments, and recreating the same experimental conditions (absent interrupting or otherwise modifying gameplay) in which these desired events occur for every athlete is virtually impossible.

Virtual reality (VR) based assessments offer an alternative solution with the potential to present athletes with closer to true-to-life sport-specific scenarios, while maintaining the control of a laboratory setting[55-57].

While there are useful non-sport specific VR assessments that can be used to investigate biomechanics in general (see Figure 2), VR assessments that utilize a wireless head mounted display (HMD) and custom-designed sports simulations (see Figure 3) allow for untethered, ambulatory movement and the presentation of visual

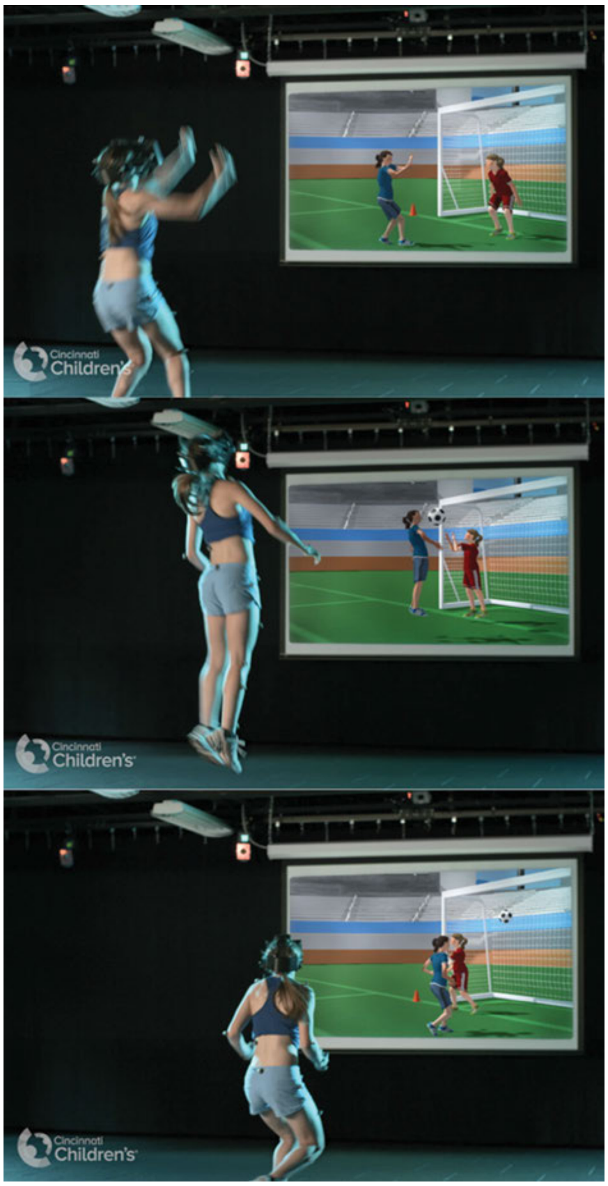

Figure 3: A sport specific VR scenario for soccer. In this particular scenario, the athlete's task is to head the soccer ball from a corner kick towards the goal. The participant is free to interact and move untethered within the virtual environment due to the wireless head mounted display and motion capture system. This creates a feeling of greater immersiveness, which encourages more sport like behavior and effort. The projector screen is not normally present during an athlete's participation, but is included in the current figure to demonstrate the participant's view during the VR scenario.

and auditory information that mimics what athletes experience on the field to a greater degree than is possible in standard laboratory assessments. As such, investigators are able to simulate dynamic, real-world sport performance while simultaneously preserving the experimental conditions by which athletes respond to and exhibit motor responses in these scenarios, thereby enhancing their reproducibility and generalizability to injury risk during actual sport performance[57].

d. aNMT Training

To the best of our knowledge, traditional training methods have not previously been quantified to induce successful transfer of injury-risk-reducing-movement-patterns to the VR sport-specific setting. We contend this is due to the inability of standard training to induce the required neuroplasticity for widespread injury risk reduction movement pattern adaptation, retention, and transfer[44,58-60]. Our lab has recently demonstrated that enhanced sensory integration neural activity[61, 62] that supports motor cortex efficiency[63] is vital for injury-risk reducing movement patterns to transfer from the intervention to VR simulated sport[44]. To target the neuroplasticity that enables injury-risk reduction in this regard, novel interventions are needed.

One such breakthrough is the use of augmented reality (AR), which like VR, can provide additional opportunities to design and develop new methods for screening and reducing ACL injury risk. Our lab has recently developed an augmented neuromuscular training system[64] that is designed to display objective information about multiple kinematic and kinetic variables related to ACL injury risk to participants in real time. The information is

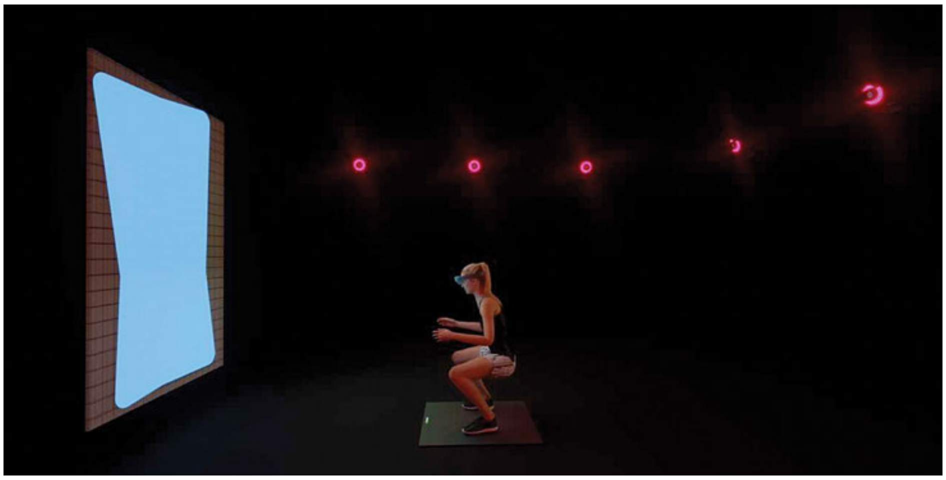

Figure 4: The figure is displaying an example of a participant interacting with our aNMT system. The motion capture cameras (the red circles), force platform (grey square with green light the participant is standing on), and a custom written program are used generate the stimulus (big blue polygon). It should be noted that the stimulus is displayed to the participant via a Microsoft HoloLens (Microsoft Corp.; WA, USA) and the above example is only a demonstration of what the participant is seeing—the stimulus is only visible with the HoloLens on.

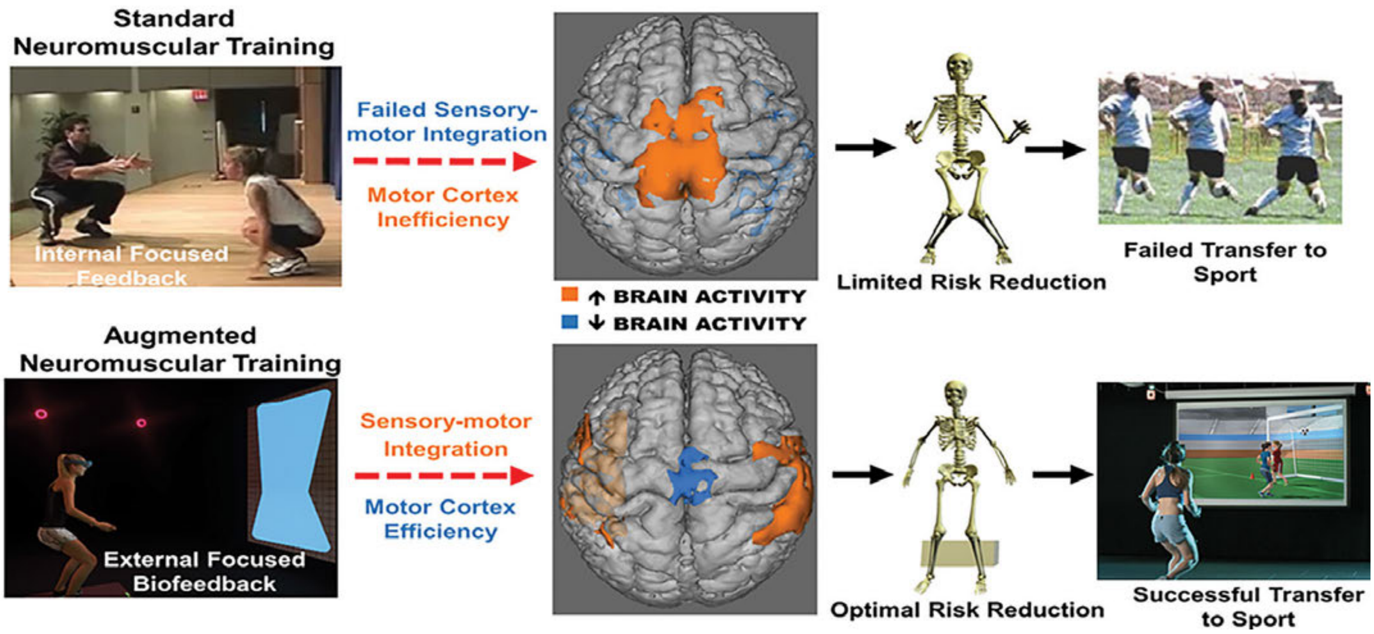

Figure 5: Top row demonstrates how contemporary neuromuscular training fails to induce the neuroplasticity required for transfer, even if immediate improvements in mechanics are achieved. Bottom row displays potential new therapies that can induce the neuroplasticity to ensure injury risk reduction transfer to sport. Blue indicates decreased brain activity; orange indicates increased brain activity. Standard neuromuscular training increases reliance on the motor cortex for knee control and fails to support the sensory integration required for injury risk reduction transfer. Augmented neuromuscular training decreases reliance on the motor cortex for knee control and supports sensory integration to ensure injury risk reduction transfer. Specifically, aNMT (bottom left panel) has been shown to increase functional connectivity between sensory areas of the brain and the thalamus (bottom middle brain panel).

displayed interactively to participants and their real-time biomechanical performance controls the display of information in the form of a simplified geometric shape viewed on a screen (see Figure 4). Participants perform specific exercises such as a body-weight squat using the shape as a guide to achieve correct movement form to enhance learning of injury-resistant movement patterns. While performing the exercise, the exact shape of the interactive biofeedback object is determined by the values of biomechanical variables related to ACL injury risk whereas the "goal" shape is a perfect rectangle. Participants are instructed simply to "move so as to create a perfect rectangle," using the interactive shape as a guide but not requiring any additional instruction or supervision beyond basic exercise definition. aNMT was designed to elicit external perceptual control and engage implicit motor learning strategies that can result in faster learning and improved transfer[65-68] while also permitting holistic learning of complex movements involving optimization of multiple, interdependent neuromotor and biomechanical variables. These factors are hypothesized to enhance the efficacy of aNMT relative to standard neuromuscular training by targeting the neural mechanisms supporting injury-risk reducing movement pattern adaptation and transfer to sport (see Figure 5).

Although aNMT requires technological resources, ultimately it is much less resource-intensive than current ACL injury risk reduction protocols. This is because it removes the need for one-on-one instruction from a trained professional. aNMT also has the advantages of being objective and highly precise, allowing detection and ultimately correction of sensorimotor deficits that even a trained professional may not be able to detect. It is also personalized to the individual athlete and allows customization of motor and feedback parameters. Our preliminary studies have provided evidence for the effectiveness of very brief and limited aNMT interventions (e.g., a minimal intervention of 4 sets of 10 body-weight squats) for enhancing motor performance[64] and transferring those improvements to an unrelated drop-vertical jump task that has been shown to be predictive of ACL injury[44,64]. In addition to biomechanical changes, aNMT has also been shown to increase the functional connectivity between sensory areas of the brain and the thalamus (responsible for relaying sensory and motor signals; see Figure 5)[44]. The results of a more extensive intervention (6 weeks of twice-weekly aNMT training with a progression of exercises including squats, pistol squats, overhead squats, and jump squats) are forthcoming (ClinicalTrials.gov identifiers: NCT04068701 and NCT02933008).

CONCLUSION

We have described some shortcomings of current strategies for ACL injury prevention and rehabilitation that may be associated with the continued increase in ACL injury (and re-injury) rates, along with opportunities for advancing the current standard of care. Technological resources including advanced neuroimaging methods, virtual reality for injury risk screening and RTS assessment, and interactive AR-based neuromuscular training methods offer new approaches and tools for researchers and clinicians to address this important biomedical problem. The cost and availability of many of these technologies will continue to decrease, providing greater availability, scientific rigor, and ultimately, utility for cost-effective and data-driven assessments. The future is now and the tools exist to finally stem the tide of ACL injury, with the methods laid out here as an initial roadmap to promoting a healthy and active lifestyle across the lifespan for these athletes.

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RECONSTRUCTING COGNITIVE FUNCTION FOLLOWING ACL INJURY

– Written by Darren J. Paul, Qatar

ACL INJURY AND SPORT DEMANDS

An Anterior Cruciate Ligament (ACL) injury is considered a traumatic event in an athlete's life. The expected duration of absence, high possibility of reinjury and in some cases, premature ending to an athlete's career signifies that strategies to mitigate the risk of ACL injury are warranted.

There has been much attention directed towards testing, prevention and rehabilitation methods in relation to ACL injury. Despite positive advancements, a recent study of ACL injuries in the English Premier Soccer League over the past 15 years reported that injury prevalence has remained essentially unchanged over this period[1]. Of equal concern is the six-fold greater injury incidence during competition compared with training[2]. Considering the match stimulus in soccer (based on 1-game week) accounts for approximately 20–30% of total weekly activity; this distribution is worryingly disproportionate.

It is increasingly evident that the mechanism of ACL injury is complex and multifactorial, influenced by the sport and individual characteristics. Movement sequences in many invasive intermittent sports (e.g. soccer), are unique and cannot be predicted with 100% accuracy. Each player will approach a situation in their own individual way, relying on a combination of intuition, experience and laws which govern the game. Indeed, when a movement is performed in a dynamic environment, under pressure and in response to an unpredictable stimulus[3], the risk of ACL injury is potentially increased. This complex interaction of stimuli indicates that other factors in addition to physical attributes are needed to fully prepare athletes to return to high level competition.

PERCEPTION, DECISION, AND ACTION AS RISK FACTORS FOR ACL INJURY

The actual movement itself is only part of the mechanism; the performer-environment interactions and subsequent decision to execute the movement must also be considered in sport injury etiology. While the physical demands of sports such as soccer have increased quite substantially over recent years (greater number of sprints and increased distance covered in high intensity effort), little is known regarding the increased cognitive demand that may accompany these more intense movements. Most previous work has not factored in the behaviors (i.e., decision making), which lead to the situations in which injuries occur. By failing to appreciate vital contextual information, and simply cataloging the apparent mechanism at the time of injury (e.g., knee valgus and external rotation of the tibia), we may be limiting our ability to understand sport-specific injury mechanisms.

Executing an unanticipated movement presents considerably different challenges to those faced when the athlete is able to predict and plan their next move, whether that be a change of direction or jump-landing task. Such pressure may include a combination of spatiotemporal constraints (e.g., a small area to operate, fast moving ball, and short time between stimulus and response), differing levels of cognitive complexity (e.g., position of teammates, anticipating and reacting to the opposition, and high criticality of the situation) and fatigue (e.g., acute fatigue from preceding play, injury to another limb). These scenarios will impact upon the athlete's ability to execute a movement task effectively and may also predispose them to positions associated with heightened injury risk. During the most intense and demanding moments on the field, athletes may only have milliseconds to scan the surrounding environment and decide upon and execute, an appropriate movement. Indeed, slower baseline cognitive processing speeds (e.g., longer reaction times) are

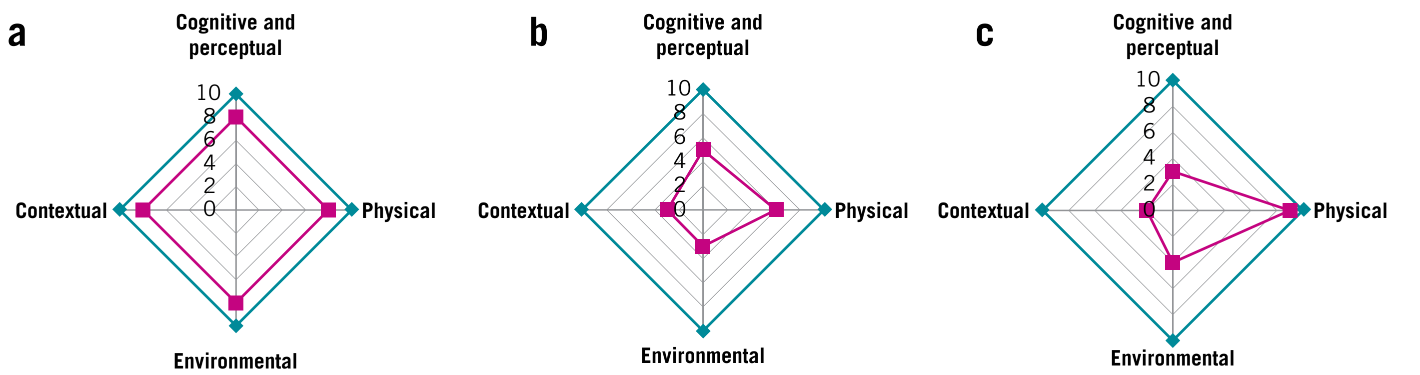

Figure 1: A hypothetical model of the constraints and demands for different football related scenarios of match and training: a) Competitive 90 min 11 a side match; b) Small sided games training; c) High intensity running drill. NOTE: Cognitive and perceptual factors = e.g. number of stimuli, complexity of stimuli. Physical factors = e.g. energetic and mechanical demand. Environmental factors = e.g. match location, weather. Contextual factors = e.g. match importance, situation criticality.

associated with mechanics that may result in greater ACL loading during the execution of unplanned landing and cutting maneuvers[4], highlighting that such time constraints can impact perception, decision and action; and consequently, performance and injury risk.

THE IMPACT OF ACL INJURY ON PLAYER CAPACITY

An ACL injury is no longer considered a 'simple' musculoskeletal pathology with only local mechanical or motor dysfunctions. Together with the psychological trauma and reductions in physical capacity, there is a cascade of likely events across the whole spectrum, including neurological insult to the central nervous system and reductions in the sensorimotor system that makes for a challenging return[5]. Therefore, only reconstructing the mechanical structures of the knee and then sending the athlete back to sport 'when it's time' is likely to produce unsuccessful outcomes[6]. Indeed, signing off an athlete for return to play without having considered their ability to integrate perception, decision making, and action effectively within sport relevant scenarios perhaps leaves us open to the athlete being underprepared and at risk of reinjury.

POSSIBLE MISSING LINKS IN CURRENT PREVENTION STRATEGIES

Many ACL injury risk reduction programs have been developed for soccer players and athletes in other sports[7]. These training programs can be broadly categorized as balance, plyometric, strength, and change of direction training; notably all isolated physical components. Despite the efforts of practitioners and scholars it is reasonable to suggest that some of these programs may not be effective in addressing the necessary realms of sporting performance. Programs typically take the form of either long-duration neuromuscular training or short-duration warm-up programs, and a multi-faceted approach that includes the majority, if not all of these components is the most commonly used. A deficiency in one or more of these physical capacities is often blamed as a contributing factor for ACL injury, despite the difficulties in isolating the individual components. However, the disproportionate focus on physical and technical capacities in isolation might be due to the relative ease of controlling and measuring this type of training, rather than their superior deterministic abilities. There currently seems a bias toward assessment and monitoring of variables which are easy to measure, rather than what is important. For example, screening methods that include visual assessment of control of the knee during a slow, single leg squat or hop are likely very different to movement variability during an unplanned direction change task while fatigued and under high cognitive loads. While the former provides useful information regarding generalized physical capabilities and should not be discounted, the latter is also difficult to control and obtain sufficient data reproducibility. Nonetheless, the apparent mismatch between current assessment protocols and the chaotic scenarios encountered in match play with emerging and constantly changing environmental constraints may in part be a contributing factor to our limited understanding of risk factors for injury.

MISMATCH

Despite the best intentions of training, the overall physical, psychological and emotional demands of a competitive match are a unique event that are unlikely to be fully replicated (Figure 1). At best, it is arguable that most of the specific drills and exercises performed are characterized by simplistic reactive responses as opposed to complex decision making which more closely represents what an athlete may face on the field[8]. Comparing this to unplanned tasks in an actual match, where players need to make many decisions quickly while immersed in a complex and dynamic situation highlights the disparity between preparation and realization of sport-specific training. Regarding athlete preparation, if there was a large mismatch in the amount of high-speed running exposure performed between training and a match, then it would be stressed that the athlete is underprepared, and more training is needed. In a similar regard, an important objective in training is to include situations which require perception-decision-action coupling that closely resembles those of actual match activity. Subsequently, it is unlikely that current planned physically dominant drills adequately challenge the cognitive abilities of players, particularly those competing at the highest level. Using an analogy from the sport of motor racing, the best car on the grid (physical attributes), without a highly skilled driver controlling the dashboard (perception-cognitive), will provide no chance of harnessing the car's full potential, and there is every chance of crashing it!

It is important to acknowledge that for a significant portion of rehabilitation following ACL injury / reconstruction, the athlete is not exposed to the sport-specific stimulus that drives skill acquisition via perception, decision action coupling. The prolonged absence of sport-specific motor skills may result in task-specific detraining. Anecdotally, on return to team training, players have referred to this as a perception of under preparedness, feeling "rusty" or "not up to match pace." Physically, they may be stronger and fitter than preinjury, but a lack of appropriately integrated cognitive load in the rehabilitation process leaves them feeling unable to "read the game" and use their physical capacities effectively. This may result in the player feeling confident that they are ready to return to training, but not to complete the most challenging of tasks, or to return to competition. It is also possible that a returning player will push themselves beyond their usual efforts to remind fellow players and coaches of their ability to make a positive contribution to the team. This combination of blunted decision-making abilities and increased volitional exertion might increase the risk of injury.

TRAINING CONSIDERATIONS

The selection and progression of an exercise (modality, intensity, and duration) is usually determined by the conditioning staff and tends to lean toward progression of the physical aspects. However, another pertinent question should also be asked - is cognitive load progressed appropriately? To illustrate this point, consider an example of a 1 versus 1 drill, often included in the final stages of end-stage rehabilitation before the player enters full training. Although this training drill integrates relevant decision making and may exceed the physical demands encountered in team training, it neglects many other factors. Because of the challenges of an applied environment (e.g., limited human resources), the player will typically perform against a familiar and less trained opponent (rehab coach), offering few basic stimuli, with little accommodation of constraints (e.g., offside, teammates, spatial, and temporal) or context (e.g., in a state of acute fatigue). Further, within normal training, players will have played against the same small pool of opponents on so many occasions that they are likely well attuned to their opponent's movement patterns and style of play. As a result, we should also consider the principles of training variability, specificity and overload when it comes to the cognitive demand.

RECONSTRUCTING COGNITIVE FUNCTION

Preparing a team sport athlete may be as much about training the brain as it is movement technique and physiological adaptation. Perceptual and cognitive load must be viewed with the same level of importance as the physical components of performance that we devote so much of our time towards. Therefore, training should include exercises to modify possible injurious movement patterns (action) and include drills to improve aspects of perception and decision making. It is highly likely that some athletes lack the ability to identify relevant cues (perception) which may cause a cascade towards compromised decision-making, and in turn lead the athlete to perform "emergency maneuvers," being the only solution available to carry out the action.

In a similar regard that good movement technique and appropriate training load are considered important in the gym, the focus should not solely be on reaction and response time, but rather also include accuracy and error rate. Monitoring an athletes' agility success rate during progressively more game like training scenarios may provide practitioners with an enhanced appreciation of the player's readiness to train; this could be a very interesting avenue for future research. Sometimes the effect of motor task difficulty on cognitive performance as an error rate (inappropriate execution of movement in response to a specific stimulus) would be masked with a delay in reaction time. Therefore, simultaneous assessment of reaction time and error rate could provide a broader understanding regarding cognitive performance during more complex undertakings such as dual tasks.

We have recently indicated that the current assessment protocols used to measure change of direction ability for ACL reconstruction patients are likely unsuitable[9]. This notion is underpinned by literature showing differences in competitive vs. non competitive, planned vs. unplanned, fatigued vs. non fatigued,

> ***Clearing an athlete for return to play without having considered their ability to integrate perception, decision making, and action effectively within sport relevant scenarios perhaps leaves us open to the athlete being underprepared and at risk of reinjury.***

as well as the effects of assessment characteristics (e.g. cutting angle, approach velocity, technique, visual disturbances, dual cognitive task, double stimulation). In a similar regard, training that incorporates visual or neurocognitive processing, such as ball tracking or engaging other players, task complexity (reaction and decision making), anticipatory aspects, and cognitive load (dual task) are an important component of the program. The ability to identify when and how to adjust attention can be taught during training by increasing a player's awareness as to what type of information he needs to direct his attention to in different situations. A proposal may be to include some youth academy players when performing selected game-based drills with the returning player(s). This will challenge the player(s) and expose them to stimuli (movements) from an opponent that is less familiar and allowing for a more competitive environment. This would be expected to mutually benefit both the returning player(s) and serve as a learning curve for the youth players' development. Also, because of time pressures to return to competition, the window for progressing toward game-like cognitive load between return to training and full return to competition is often small.

Despite the best intentions, it is unlikely that players will ever be truly prepared to

Table 1

Nº	Training	Objective	Phase
1	*Video Analysis*	*Player reviews relevant clips to increase self-awareness:* • *Guided to evaluate decision making* • *Builds awareness of areas for technical improvement (e.g. landing mechanics or changing direction)* • *Identifies scenarios in which they felt high confidence and low confidence in executing the task (e.g. 1v1 against a particularly fast player, slide*	*Focus in early stages* *Revisited throughout*
2	*Reaction Drills*	*Player begins basic and isolated stimulus/response tasks to relearn perception action coupling:* • *Reactive drills that develop movement association tasks (hand, foot and trunk drills)* • *Stimuli should allow for both compatible (same) and incompatible response(opposite)* • *Focus on quality of movement and response rather than the speed*	*Focus during early stages of conditioning* *Progressive throughout*
3	*Dual Task*	*Player is exposed to simultaneous cognitive and physical tasks to improve dissociation from injury:* • *Encourage players to dissociate from the injury by including increasingly complex cognitive tasks (eg. Cognitive distraction tasks) during physical tasks* • *Perform drills in close proximity to an opponent (fitness/rehab coach) to challenge spatial awareness* • *Include temporal constraints, challenges and contextual interference to encourage better learning*	*Focus in the early stages of functional training*
4	*Individualised Scenarios*	*Player has large influence on addressing individual weaknesses of game related scenarios to develop confidence:* • *Performs scenarios in which they felt high confidence and low confidence in executing the task (multi player scenarios)* • *Increase the level of contextual interference by introducing more players (e.g. youth team players) into the training* • *Include 'worst case scenarios' that offer a combination of cognitive/perceptual, physical, contextual and environmental demands*	*Focus in final stages* *Carries over to team full first team integration*

Table 1: Examples of training tools and methods that may be used in accordance with the different stages of the rehabilitation phases, as per the hypothetical model.

return to performance, until they are faced with that given situation. Realistically, players are likely to only fully demonstrate their physical, mental, emotional and cognitive proficiency when required, rather tending to play within the constraints of the given situation. The impact of actual competition on execution of movement has been shown in an interesting study by Spittle et al.[10] They found basketball players performed more pass decisions during high decision criticality situations (classified by a remaining time of 60 seconds or less and score differentials of 2 points or less) and more shoot decisions during low decision criticality situations (classified by remaining time of 5 minutes or more and score differentials of 5 points or more). Unfortunately, it is unlikely that we will be able to fully replicate these environments since competition performance will be influenced by a myriad of contextual factors such as score line, opposition and period of match. However, our role is to bridge the gap between rehabilitation and performance as best we can by exposing athletes to a wide range of relevant tasks and environments in which they are able to re-define their movement skills in tasks that at least in part, represent their sporting environment.

ATHLETE EDUCATION

Research has demonstrated the effectiveness of using video footage to educate female soccer players on safe techniques for jumping, strength and agility-based activities, resulting in an 88% overall reduction in ACL injury rate in the first year[11]. Recent research has also shown that watching a video of an opposing player running and executing a change of direction can produce an acute improvement in sport-specific response time[12]. An advantage of video training during the rehabilitation phase is that it can provide complementary "off-field" training during the early stages of rehabilitation. This may be particularly useful to promote self-awareness of their movement technique, patterns in their decision-making abilities, situations in which they perform below expectations, and an increased understanding of the rehabilitation program (Table 1). An increased awareness can then be carried forward into the rehabilitation program and may allow for a better transition into the different phases of training.

ATTANING 'BUY IN' TO ENSURE EFFECTIVE IMPLEMENTATION

Education, communication, and coach support are pivotal but 'buy-in' for injury reduction programs from players and coaches remains a problem within many clubs[13]. Some of the main challenges include (a) the perceived benefit of playing is greater than the risk of injury, (b) the desire of players to perform as much training as possible with the team; and (c) the belief that the prescribed exercises are unlikely to be of benefit[13]. Successfully implementing an injury reduction program may largely be dependent on its packaging and delivery rather than its scientific merit. If the coach holds the opinion that it does not include enough "sport-specific" activities, the probability of low compliance may increase by a staggering 81%[14]. Therefore, practitioners needs to explore alternative methods and strategies to reduce this resistance.

To get the buy-in from the coach and player, where possible, injury reduction exercises should be integrated with routine sports practice, rather than being a separate entity[15]. Involving the players and coaches in the design and/or selection of exercises may prove a fruitful endeavor by increasing the perception of ownership. For players to be fully engaged in an injury reduction program, they must feel a degree of empowerment in the exercise selection and the program is specifically tailored to their individual needs[16]. A standardized program also lessens the dialogue between the players and the medical staff[16]. The resultant effect may be a player with greater knowledge about the training process, satisfaction of an individualized approach bespoke to their needs, and overall better buy-in for the rehabilitation and/or training program. Combining this with the experience and knowledge of the fitness and/or rehabilitation specialist makes it possible to adopt a more individualized and athlete led approach.

SUMMARY

There is a disproportionate bias toward ACL injuries in games versus training. Given the greater exposure and assuming players are physically capable of regularly training at or above match intensity, this suggests that contextual factors, which separate games from training, play a large mediating role in ACL injury risk. Therefore, we should always consider the inherent cognitive demands present in team sports and appreciate the complex interplay between physical capacities and decision making, which ultimately determines movement, performance, and injury risk.

Injury reduction and rehabilitation should include a much broader array of drills and practice scenarios with increasing levels of cognitive complexity to ensure adequate exposure and heightened readiness to re-perform. In addition, involving players and coaches in the design and/ or selection of exercises may prove a fruitful endeavor by increasing the perception of ownership and adherence. Perceptual and cognitive load must be viewed in the same light as the physical components of performance that we devote so much of our time towards. A greater number of decision making scenarios and shorter time periods to react to those decisions are some examples that might contribute to ACL injury. Future research into injury mechanism should also consider the contextual factors surrounding the injury to ensure the chaotic complexity of match play is at the forefront of discussion.

Perceptual and cognitive load must be viewed with the same level of importance as the physical components of performance that we devote so much of our time towards.

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FROM CONTROL TO CHAOS TO COMPETITION

BUILDING A PATHWAY FOR RETURN TO PERFORMANCE FOLLOWING ACL RECONSTRUCTION

– *Written by Matt Taberner, Tom Allen, and Emma Constantine, UK and Daniel D Cohen, Colombia*

INTRODUCTION

Despite the enhanced knowledge around rehabilitation and large body of research defining return to sport (RTS) criteria following anterior cruciate ligament (ACL) injuries[1]; RTS following ACL reconstruction (ACLR) is a complex process[2]. No consensus exists regarding the optimal rehabilitation and re-injury risk remains high[3,4]. Is it possible that current rehabilitation approaches fail to fully prepare athletes for the demands of their sport, hindering the success of a return to performance?

It is suggested that safe (i.e. with minimal risk of re-injury) RTS may require up to two years following ACLR[5]. However, risk management is key in the high-pressure environment of professional sport where team success is the goal but must be balanced with protecting the player's health. The balance of risk [to player]: and benefit [to team of having player available to play] potentially represents competing interests which require shared decision-making between performance/medical team, player and coach/club. However, there are limits to the influence of the performance/medical team's objective data, clinical experience and literature evidence[4,5]. Even if this suggests completely safe return requires approximately two years, would this be implemented in team sports?

Sports-specific physical preparation and return retrospective chronic loading (i.e. training loads that players have been used to performing pre-injury) are vital elements of the rehabilitation pathway but are suggested to be overlooked components of RTS criteria[2].

We recently proposed the 'control-chaos continuum' (CCC; Figure 1)[6], an adaptable RTS pathway developed for on-pitch rehabilitation in football. The CCC progresses from high control to high chaos, underpinned by sports-specific conditioning and the concept of returning players to retrospective (pre-injury) chronic running loads. This process can be informed by global positioning systems[7], combined with a gradual increase in qualitative characteristics of in-competition movement providing incremental perceptual and neurocognitive challenges[8].

WHY WE THINK THE CONTROL-CHAOS CONTINUUM FITS END-STAGE REHABILITATION AFTER ACLR

We believe the CCC is an ideal model for on-pitch rehabilitation following ACLR,

	HIGH CONTROL	MODERATE CONTROL	CONTROL>CHAOS	MODERATE CHAOS	HIGH CHAOS
SESSIONS	<0.35GAME LOAD**	<0.35-0.45 GAME LOAD**	<0.40-0.60 GAME LOAD**	~0.55-0.70 GAME LOAD**	>0.70 GAME LOAD**
TYPE	RETURN TO RUNNING PHASE 1 (RTR1)	RETURN TO RUNNING: CONTROLLED CHANGE OF DIRECTION PHASE 2 (RTR2)	INTENSIVE | EXTENSIVE	INTENSIVE | EXTENSIVE	INTENSIVE | EXTENSIVE
CONDITIONING EMPHASIS	THRESHOLD ENDURANCE (80-85% MAX^{HR}) INTENSIVE ENDURANCE (70-80% MAX^{HR})	THRESHOLD ENDURANCE (80-85% MAX^{HR}) INTENSIVE ENDURANCE (70-80% MAX^{HR})	EXTENSIVE TEMPO LEVEL 1 (~55-70% MS) $V0^2$MAX DEVELOPMENT (>85% MAX^{HR}) THRESHOLD ENDURANCE (80-85% MAX^{HR}) INTENSIVE ENDURANCE (70-80% MAX^{HR})	EXTENSIVE TEMPO LEVEL 2 (~65-85% MS) EXTENSIVE TEMPO LEVEL 1 (~55-65% MS) $V0^2$MAX DEVELOPMENT (>85% MAX^{HR}) THRESHOLD ENDURANCE (80-85% MAX^{HR}) INTENSIVE ENDURANCE (70-80% MAX^{HR})	SPEED (>85% MS) EXTENSIVE TEMPO LEVEL 2 (~65-75% MS) $V0^2$MAX DEVELOPMENT (>85% MAX^{HR}) THRESHOLD ENDURANCE (80-85% MAX^{HR}) INTENSIVE ENDURANCE (70-80% MAX^{HR})
DESCRIPTION	LINEAR RUNNING (> FROM ALTER-G - 90% BW) LOW MAGNITUDE ACC/DEC LOW VOLUME EXPLOSIVE DISTANCE LOW MUSCULOSKELETAL IMPACT FORCES END OF STAGE INTRODUCTION TO HSR (INJURY SPECIFIC) EXAMPLES: 3X6,4X6 (3-4X3MINS) 3X8, 4X8 (3-4X4MINS) (1-2MINS PR)	INTRODUCE COD WITH/WITHOUT BALL ($45-180^0$ TURNING) >LINEAR RUNNING SPEEDS (FARTLEK) >MUSCULOSKELETAL IMPACT FORCES/JOINT DEMANDS INTRO SHORT-RANGE TECHNICAL E.G. PASSING EXAMPLE: 3-5X3-4MINS (1-2MINS PR)	COD WITH*/WITHOUT BALL (ALL TURNS) RUNNING SPEEDS (~60-70% MS - HSR) (FARTLEK) LOW VOLUME/INTENSITY P+M/POP >MUSCULOSKELETAL IMPACT FORCES/JOINT DEMANDS >ACC/DEC PREPARATION PROGRESSION OF TECHNICAL SKILLS INTENSIVE: 4-6X1-2MINS (1-2MINS PR) EXTENSIVE: 4-6X4-5MINS (2-3MINS PR) TEMPO/AEROBIC POWER INTERVAL RUNNING (17:13/15:15S) *WITH BALL WILL INCREASE HEART-RATE RESPONSE, AND PLAYER MOTIVATION TO PERFORM DRILLS'	>RUNNING SPEEDS ~(>75% MS) >HSR ACCUMULATED >SPRINT EXPOSURE POSITIONAL P+M/POP (INCLUDING TECHNICAL SKILLS) >ACC/DEC DEMANDS (POSITIONAL) >MUSCULOSKELETAL IMPACT/JOINT DEMANDS >VOLUME/INTENSITY SPEED:5-10S (1:5-1:10) SPEED ENDURANCE: PRODUCTION/MAINTENANCE INTENSIVE: 20-45S/1-3MIN (1-2MINS PR) EXTENSIVE: 4-8MINS (2-3MINS PR)	>RUNNNG SPEEDS (>90% MS) >HSR/SPR ACCUMULATED RTT POSITIONAL SPECIFIC DEMANDS ACC/DEC DEMANDS (POSITIONAL) >MUSCULOSKELETAL IMPACT/JOINT DEMANDS >MATCH-DAY TYPE PREPARATION SPECIFIC P+M/POP (POSITIONAL – TECHNICAL SKILLS) SPEED:5-10S (1:5-1:10) SPEED ENDURANCE: PRODUCTION/MAINTENANCE INTENSIVE: 20-45S/1-3MIN (1-2MINS PR) EXTENSIVE: 4-8MINS (2-3MINS PR)
LOAD EMPHASIS (INJURY SPECIFIC)	TD | <EXPD/<HSR <ACC | <DEC	TD | >EXPD/<HSR >ACC | >DEC	TD | >EXPD/<HSR | TD | >EXPD/>HSR (SPR) >ACC | >DEC | >ACC | >DEC	TD | >EXPD/<HSR | TD | <EXPD/>HSR (SPR) >ACC | >DEC | <ACC | <DEC	TD | >EXPD/<HSR | TD | <EXPD/>HSR (SPR) >ACC | >DEC | <ACC | <DEC
NO. OF SESSIONS	2-4	3-4	3-4	3-5 (DEPENDANT UPON TRAINING METHOD)	3-5 (DEPENDANT UPON TRAINING METHOD)

Figure 1: Return to Sport model: Control-Chaos Continuum. Model adjusted to specific injury diagnosis, estimated healing times, and expected return to training. TD = Total Distance, HSR = High Speed Running (>5.5ms^{-1}), SPR = Sprint Distance (>7ms^{-1}), Exp-D = Explosive Distance (Accelerating/Decelerating from 2-4ms^{-1} <1s, Acc = Accelerations, Dec = Decelerations, Magnitude (Acc/Dec) = rate of change in velocity e.g. 3ms-2 , PR = Passive Recovery, COD = Change of direction, BW = bodyweight, MS = maximal speed, MAXHR = maximal heart-rate, ** = game-load adjusted according to injury specificity/severity.

targeting potential modifiable risk factors for re-injury whilst building running loads and performance to pre-injury levels (or beyond).

Epidemiological evidence in elite football is highly suggestive of an association between fatigue and injury. In relation to acute fatigue, time dependent increases in incidence are evident during match-play[9]. Similarly, accumulation of residual fatigue increases incidence during congested match periods[10]. Acute fatigue is associated with temporary alterations in neuromuscular function including decrements in peak force, rate of force development (RFD), and decision-making ability[11,12]. Notably, soccer-specific activity is associated with a selective reduction in the eccentric strength of the hamstrings[13] – potentially reducing their effectiveness as ACL agonists. Moreover, soccer-specific fatigue in parallel with the decline in hamstring strength, leads to unfavourable changes in knee biomechanics which may heighten injury risk[14]. Therefore, attempting to limit the adverse effects of fatigue is logical from both a performance and injury risk perspective; despite this, recent meta-analyses concluded that there is a lack of evidence demonstrating an association between fatigue and ACL injury risk[15,16].

One of the key objectives of the CCC is to progressively provide adequate energy system conditioning throughout the different phases of rehabilitation. The manipulation of exercise : rest ratios, ensures the required stimulus is placed on the cardiovascular system to improve both general work capacity and target energy system conditioning for the sport inclusive of positional demands, aiding the player to return to pre-injury levels of performance (or beyond). Furthermore, the CCC aims to reduce soft tissue injury risk during ACL rehabilitation through careful player management, taking into consideration retrospective running loads and neuromuscular measures to define players response to loading. Appropriate progression is also applied, ensuring increments are not too rapid (i.e. running speeds/volumes), to avoid exceeding the capacity of the musculoskeletal system to adapt.

ACL injuries have recently been suggested to be neurophysiological injuries[17], with apparent neurocognitive deficits following ACLR. Rehabilitation should therefore integrate training of the neurocognitive system in a sport relevant format, to facilitate transfer of training. The construct of the CCC is based upon a constraints-led approach, with task and environmental constraints manipulated to influence movement variability[18]. In the high control phase, we maintain constraints to limit movement variability and cognitive demands to reduce re-injury risk or setbacks associated with excessive high-speed running (HSR) or unexpected changes of direction[6]. This phase provides a safely delivered base of metabolic and tissue/neuromuscular (NM) conditioning for progression of conditioning/running loads. As these constraints are reduced, we gradually increase situational awareness, sensory integration, motor control, co-ordination and NM demands. They are also required to perceive and respond to increasingly complex, unpredictable situations including movement of other players, opponents and interaction with the ball. Technical actions are also progressively incorporated including passing/crossing, shooting, jump/landing and tackling to ensure adequate training of sport-specific skills (Figure 2).

Once the player enters the sport-specific phases, we emphasise periodisation to condition in a format resembling the NM and physiological demands of team training. Fitness development is structured to provide overload in game components

PHASE	PASSING/CROSSING		SHOOTING		JUMP/HEADING		TACKLING	
HIGH CONTROL	N/A: ALLOWANCE OF SMALL TECHNICAL SKILLS INCLUDING "KEEP-UPS" AND TOUCHES BETWEEN 'FEET'							
MODERATE CONTROL	SHORT RANGE	LOW	N/A		STATIC	LOW	STATIC	LOW
CONTROL>CHAOS	SHORT/ MID RANGE	MODERATE-LOW (SESSION SPECIFIC)	SHORT RANGE	LOW	STATIC/ MOVEMENT	LOW-LOW	STATIC/ MOVEMENT	LOW-LOW
MODERATE CHAOS	SHORT/MID/ LONG RANGE	MODERATE-MODERATE-LOW (SESSION SPECIFIC)	SHORT/MID RANGE	MODERATE-LOW (POSITIONAL SPECIFIC)	MOVEMENT/ CONTEXT	MODERATE-LOW (POSITIONAL SPECIFIC)	STATIC/ MOVEMENT	MODERATE-LOW
HIGH CHAOS	SHORT/MID/ LONG RANGE	HIGH/ MODERATE (SESSION SPECIFIC)	SHORT/MID/ LONG RANGE	MODERATE-HIGH (POSITIONAL SPECIFIC)	CONTEXT	MODERATE-HIGH (POSTIONAL SPECIFIC)	MOVEMENT	MODERATE-HIGH (POSITIONAL SPECIFIC)
RETURN TO TRAIN (NON-CONTACT AND CONTACT)	SHORT/MID/ LONG RANGE	HIGH/ MODERATE (SESSION + POSITION SPECIFIC)	SHORT/MID/ LONG RANGE	MODERATE-HIGH (SESSION + POSITION SPECIFIC)	CONTEXT	MODERATE-HIGH (SESSION + POSITION SPECIFIC)	CONTEXT	MODERATE-HIGH (SESSION + POSITION SPECIFIC)
RETURN TO TRAIN (FULL INTEGRATION)	SHORT/MID/ LONG RANGE	SESSION SPECIFIC	SHORT/MID/ LONG RANGE	SESSION + POSITION SPECIFIC	CONTEXT	SESSION + POSITION SPECIFIC	CONTEXT	SESSION + POSITION SPECIFIC

Figure 2: Pathway for progression of technical actions during rehabilitation (control-chaos continuum) and transition back to the team training environment (return to training phases). Model adjusted to specific injury diagnosis, estimated tissue healing times, and expected rehabilitation and return to training durations. Intensity of passing/crossing/shooting - Short = 5-10m, Mid = 10-15m, Long = 15m+, Low, Moderate, High =no of efforts; refers to number of technical actions performed, relative to the number performed by the individual in the normal / current team training model and their game traits/position i.e. number of passing efforts different to number of tackles. Static = in-place e.g. block tackle, Movement = technical action preceded by movement e.g. running take-off for a header, Context = how these actions would be performed in training/match-play e.g. centre forward attacking a cross for a header at goal.

Table 1

Injury	Considerations for RTS Load Planning	Neuromuscular Strength/Power Diagnostics
*ACL Graft type emphasis/ considerations *patella tendon #hamstring tendon*	*Appropriate weekly planning between sessions in early stages Progression of running volumes (total distance, explosive distance, HSR, sprint distance) Progression of running speeds (>70% Maximal Speed) and running speed with chaos# Progression of acceleration/deceleration efforts (no. of efforts)* Progression of acceleration/deceleration magnitudes (e.g. 3 to 5ms^{-2})* Progression of acceleration/deceleration density i.e. maximal intensity periods* (e.g. max no. of decelerations efforts (>3ms^{-2}) in 2-minute period) Progression of technical actions – passing/crossing, shooting, jump/landing actions, tackling (type/ volume) Session/drill modification during RTT (NC and C phases) Appropriate integration of 'recovery' during RTT (NC and C phases Appropriate monitoring/progression of external/ internal load during RTT-RTC-RTPerf phases Appropriate progression of competitive match minutes during RTC-RTPerf phases*	*DL CMJ: ecc*, con, landing force/impulse asymmetries (FP) SL CMJ: jump height, power, impulse asymmetries DL/SL drop jump: RSI (FP) Iso squat/mid-thigh pull: PF, RFD (FP) Dynamic split squat force/impulse asymmetries (FP) Iso, con/ecc* quadriceps: PT, RFD, SE (IKD) Iso soleus/gastrocnemius: PF, RFD (FP) Iso posterior chain PF, RFD, SE (FP)# Ecc hamstring: PF (NHE)# 10-5 hop test: RSI, CT (FP) Triple hop test: distance (asymmetry) Iso hip abductor/adductor: PF (GroinBar™)*

Table 1: ACL injury-specific load planning considerations and neuromuscular strength/power diagnostics for phase progression during return to sport (RTS). HSR = High-speed running (>5.5ms^{-1}), COD = Change of direction, ACL = Anterior Cruciate Ligament, iso = isometric, ecc = eccentric, con = concentric, PT = peak torque, PF = peak force, RFD = rate of force development, IKD = isokinetic dynamometry, RSI = reactive strength index, DL = double Leg, SL = single leg, DJ = drop jump, NHE = nordic hamstring exercise, SE = strength-endurance, FP = force platform, CT = contact time, RTT = return to train, NC = non-contact, C = contact, RTC = return to competition, RTPerf = return to performance, no. of = number of.

using 'intensive' and 'extensive' football practice environments[19]. Intensive football aims to overload the musculoskeletal system and specific energy systems through accelerations, decelerations, and changes of direction within restricted areas (e.g. 10×15m). Extensive football reflects typical positional match demands using larger areas to allow higher speeds and distances.

Periodising the rehabilitation model to mirror the demands of the training model is a key aspect of the CCC model and as the methodology and training approach of each coach varies, it is important to quantify and monitor team training indicators under a new coaching regime.

If the player's chronic retrospective running load data was under a previous management (more likely in long-term injuries such as an ACLR), there may be changes in intensity, volume and duration under the new regime which must be accommodated for. The player may also be expected to play in a different position, leading to different competitive load demands. This may necessitate adjustments to the rehabilitation plan to ensure appropriate conditioning, potentially above pre-injury chronic training load and/or different style of training loads to ensure adequate preparation for new and varying demands.

PLANNING END-STAGE REHABILITATION; FROM CONTROL, CHAOS AND BEYOND

Formulating a rehabilitation plan involves communication with the inter-disciplinary sports performance and medical team and the coaching staff to obtain as much information as possible regarding the individual player, whilst keeping the player informed and involved in the process. The players retrospective chronic training and concurrent (training plus match) running load should be obtained, alongside training indicators and expectations under the coaching team (number of training days, sequence of training days, training duration, training type, etc.). Additionally, previous injury history, details of his/her current injury, positional demands (and playing style), objective neuromuscular profile (strength and power diagnostics) and trends in this data prior to and since injury, nutritional status, and potential healing times i.e. graft maturation should also be considered. This information, alongside the training considerations (including gym-based strength and conditioning) should inform decision making, estimates of the required duration of pitch-based rehabilitation, and the required level of running load that the player needs to return to. In our experience, outdoor physical preparation for an ACLR injury should be around 10-14 weeks. However, this is entirely dependent upon each individual case, considering that progression is based principally on objective criteria and informed by strength and power diagnostics (Table 1) to support clinical reasoning and aid decision-making[6].

Simple clinical tests such as the triple hop (for distance) may serve value[20], whilst persistent post-ACLR kinetic and kinematic asymmetries in female athletes have been highlighted using the drop jump[21]. However, the dual force platform bilateral CMJ is a core diagnostic tool, as it is more common for players to have historical (benchmark) CMJ data. Increased lower limb kinetic asymmetries in specific eccentric and concentric variables and in the landing phase are reported in this test after return to competition (RTC) following lower limb injuries in elite players[22], and post-ACL in other populations[23]. These involved limb deficits may lead to potential compensatory movement strategies and unusually asymmetrical loading patterns.

CONTROL-CHAOS CONTINUUM

High Control

Aims: Return to running with high control over running speeds/loads indicative of low musculoskeletal impact forces and build player confidence.

The goal during this phase is to gradually increase linear running volume at lower speeds, with limited HSR (<60% Maximal speed (MS)). Task constraints can be maintained using speed = distance/time as indicator of the target speed, albeit with speed changes implicit in accelerating and decelerating at the start/end of each effort. By integrating different periods of active recovery between running bouts the development of the required energy system is emphasised. During this phase sports-specific tasks and ball based technical actions are limited (Figures 1 and 2). We suggest running volumes <0.35 game load with minimal HSR. HSR threshold is determined by individuals maximal speed (MS) i.e. high MS >10ms^{-1} or low MS ~7ms^{-1} (possibly in the case of some female athletes), then adjustment is made to apply relative rather than absolute speed zones. Minimal knee swelling and pain (<2/10 numerical rating scale (NRS)) indicates that the involved limb is coping with imposed demands. As a foundation for the next phase we suggest that controlled acceleration/deceleration drills (Table 2) are incorporated to prepare the player for the increased force production and acceptance demands to build upon physical qualities developed in gym-based conditioning.

Moderate Control

Aims: Introduce change of direction (COD) with and without ball, reduce control (somewhat controlled chaos), progression of HSR load.

In this phase, we progressively integrate COD, reducing the level of control and restrictions on movement variability. Acceleration/deceleration demands increase with increments in the intensity and volume of directional changes; reducing task constraint and progressively increasing explosive distance. Progressively, we incorporate running mechanics,

Table 2

Drill Focus	*Drill progressions*
Running Mechanics	*Walking A's, A-skips, running A's* *Walking B's, B-Skips and running B's* *Straight-leg bounds, straight leg bounds into acceleration*
Acceleration Preparation	*Falling starts, partner falling starts, falling MB throw starts, split stance starts, split Kneeling starts* *Jump-back starts, sideways split stance starts, sideways kneeling starts, cross-over step* *NB. Additional resistance can be applied to certain drills if required*
Deceleration Preparation	*In-place deceleration: drop squat, drop squat 'catch', drop split squat, drop split squat 'catch'* *Acceleration to: squat stance deceleration, sideways deceleration, split stance deceleration, staggered stance deceleration*
Movement Transition	*Back-pedal into acceleration, diagonal back-pedal into acceleration, acceleration > backways 'jockey'* *Directional changes: 0-45°, 45-60°, 60-180°, sequence of directional changes* *Cutting: speed cuts, power cuts, sequence of speed/power cuts* *Combination of acceleration/deceleration preparation drills i.e. Falling start into 10m acceleration into split stance deceleration* *Addition of auditory/spatial/reactive cues to movement transition, directional changes, cutting drills* *Sports-specific context: passing speed/direction dictates athlete movement strategy (positional acceleration/speed conditioning)*

Table 2: Drill focus and sample drill progressions to be used within pre-training preparation to link gym-based and on-pitch conditioning and promote the development of sports-specific starting-strength (rate of force development), movement quality and control. NB. Emphasis should be made to overload involved limb as appropriate on split stance/split kneeling drills i.e. 2sets/1set, MB = medicine ball, 45° = 45-degree directional change.

> ***The 'control chaos continuum' is an adaptable pathway, progressing from high control to high chaos, underpinned by sports-specific conditioning and the concept of returning players to retrospective (pre-injury) chronic running loads characteristic of in-competition movement providing incremental perceptual and neurocognitive challenges.***

acceleration/deceleration and COD drills into warm-ups prior to the conditioning element of the session (Table 2). We progress these drills by controlling speed, acceleration/deceleration magnitudes, acceleration start (e.g. falling, split stance, split kneeling) and deceleration end positions (e.g. squat stance, split stance) to help address starting-strength (RFD) and force reduction deficits. Drills are designed to provide specific progressive overload of deceleration capabilities on the involved limb under controlled conditions. Within the conditioning element of the session, most directional changes involve the ball, progressively increasing explosive distance alongside linear HSR (60-70% MS). We progress running load relative to game load (~0.35-0.45) according to the individual rehabilitation plan. Routine physiotherapy communication is essential to ensure the knee is coping with the imposed load; minimal knee swelling, and lack of pain are criteria for progression.

Control to chaos
Aims: Introduce a sport-specific weekly training structure to overload game-specific demands reflecting a transition from control to chaos (inclusion of a limited number of movements with unanticipated actions).

The periodisation of the weekly rehabilitation plan now switches to a football-specific training weekly structure. We continue to use the warm-up to progress development of athletic qualities (Table 2), with emphasis on the specific demands of the session i.e. extensive; preparation for running at higher speeds and increased magnitude of accelerations/decelerations. Within intensive sessions, drills include more reactive passing and movement alongside position-specific acceleration/decelerations to replicate explosive movements. Drill prescription within extensive football sessions progressively incorporates running at higher speeds (>65-85% MS) with work: rest ratios manipulated to target the required energy systems, where the emphasis is towards aerobic qualities i.e. Vo_2max development (time >85% Max^{HR}).

Moderate chaos
Aims: Increase HSR, sports-specific COD and reactive movements under moderate chaos.

In this phase, HSR loads increase progressively under both controlled and chaotic conditions. Extensive sessions target HSR (>75% MS) including directional changes, with progressive increments in sprint distance, relative to game load (~0.55-0.70; according to planned sessional load progression). Increasingly position-specific pass and move and pattern of play drills are used to progress technical skills. For example, short/mid-range passing and crossing, whilst interaction with other individuals challenge visual perception and spatial awareness. Other technical skills are also incorporated, such as position-specific jump-land activities. Adding reactive elements to positional speed drills aims to challenge the player by increasing movement variability and exposure to conditions of higher risk within restricted areas i.e. reaching to an unexpected, mis-directed or bad pass. Conditioning continues to emphasise aerobic qualities, and HSR load progression (tolerance of intensity driven increases in ground reaction forces) allows introduction of speed-endurance conditioning.

High chaos
Aims: Return the player to, or just above chronic retrospective weekly training indicators using drills designed to challenge the player in worst-case (high-risk) scenarios.

In the final phase before return to training, we emphasise position-specific conditioning and retrospective weekly volumes. We integrate position-specific speed/speed-endurance drills – whereby player movement speed is dictated by the speed/direction of pass, achieving peak speed (>90% MS) relative to retrospective volumes (number of efforts). Conditioning of both speed and speed-endurance qualities now become the focus as well as integration of technical actions in position-specific contexts i.e. tackling in 1 vs 1 situations or drills ending with a shooting opportunity in position-specific areas. Training duration should also be considered, and dependent upon the training methodology i.e. long technical sessions or physical drills combined with decision-making at the end of a session. Alongside achieving target chronic training loads and number of/volume of technical actions, strength and power diagnostics form the final part of RTS criteria to ensure the player is physically prepared whilst communication with the player helps keep them involved in the shared decision-making process and ensures all parties

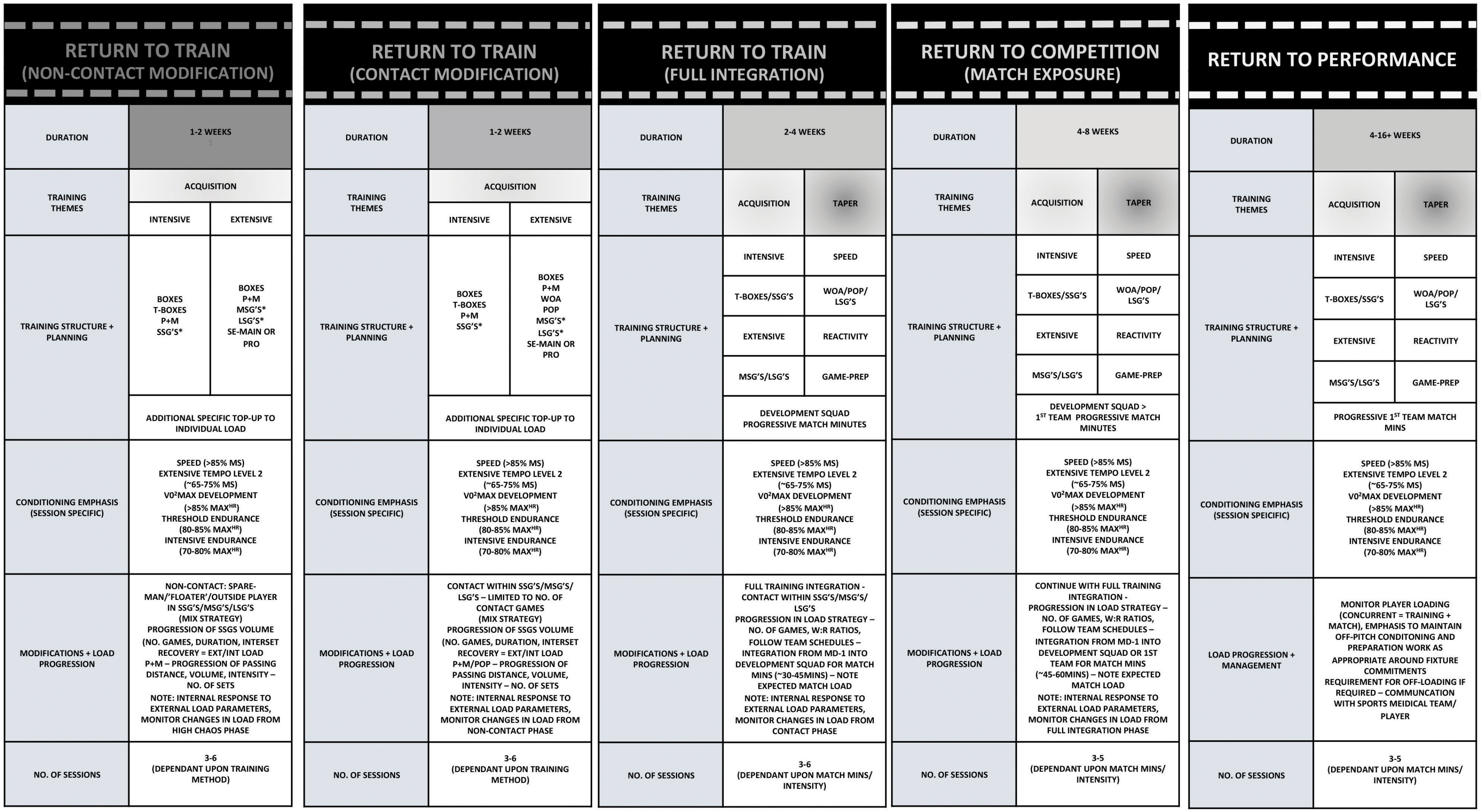

Figure 3: ACL-specific Return to Performance (RTPerf) pathway - adjunct to Control-Chaos Continuum to help ensure progressive transition from rehabilitation into the team training model/competitive match minutes. Model can be adjusted to specific needs of the injury/individual. MS = maximal speed, MAX^{HR} = maximal heart-rate, ** = gameload adjusted according to specifics and severity of injury. P+M = pass and move, WOA = waves of attack, POP = pattern of play, SSS's = small sides games, MSG's = medium sized games, LSG's = large sided games, T-Boxes = transition boxes, SE = speed-endurance, Main = maintenance, Pro = production, Ext = external, Int = internal, No. = number of, W:R = work:rest, mins = minutes.

are confident that the player is ready for progression.

BEYOND RETURN TO SPORT: MAKING STRIDES TOWARDS RETURN TO PERFORMANCE

While successful rehabilitation includes achieving both planned chronic running loads and passing RTS criteria, the journey may not be fully complete. As we mentioned earlier, the decision when to return to competition is a risk management exercise and sometimes players can return before attaining pre-injury levels. Additionally, reaching target pre-injury chronic running loads and strength/power criteria etc. are clearly different to being back to pre-injury levels of competitive match-play (e.g. technical, tactical, physical, mental performance). The return to performance transition process is a continuum of pitch-based rehabilitation, safe resumption of team training and gradual introduction to competitive match-play[2]. However, due to the long duration of absence from training and an inability to truly replicate the training (and match) environment in the rehabilitation scenario, we propose an adjunct to the CCC; The Return to Performance (RTPerf) pathway (Figure 3). This framework fits within the RTS continuum[24] and is specifically for players returning to training/competition following ACLR due to the persistent deficits in explosive and decelerative neuromuscular (RFD) and neurocognitive performance[25,26] and biomechanical control[27]. The RTPerf framework separates the return to training (RTT) phase into three subphases; non-contact, contact, full integration, followed by a transition back to competition.

Players often experience a 'trafficking' effect when reintegrated to training with a high cognitive load and 'little space and time' to manoeuvre. This phenomenon is likely due to the long period of absence of intense player interaction. neurocognitive readaptation is required to become re-accustomed to player interaction, especially under game-based training conditions.

RETURN TO TRAINING; NON-CONTACT

Aims: Re-introduction to team training (non-contact), use of 'modified' acquisition days (training to overload game formats; intensive/extensive football incorporating technical/tactical elements) to minimise


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player trafficking, monitor running load progression.

In this phase the player is re-integrated into non-contact team training. On the main team acquisition days[19] (Figure 4), training is modified to reduce the experience of 'trafficking' but ensure player interaction to promote neurocognitive system conditioning under game-specific conditions. The unpredictable team environment is the only real-life stimulus with match level demands of rapid information processing and responding to the situation-specific visual-spatial cues and is crucial to the RTPerf pathway. The emergence of virtual reality technology in elite sport rehabilitation reflects the interest in replicating these situational-specific demands while maintaining neuromuscular control and recognition that brain dynamics is an important, but untapped area[8]. Specific session modification is implemented primarily in game-based session elements where 'trafficking' is highest. For example, the player may act as link on the outside of the small sided games and then progress to a 'floater' in small sided games (e.g. 4v4+1). A similar format is followed in medium to large sided games where the 'floater' option is the most effective way to integrate with minimal contact. In such conditions, it is essential to monitor HSR loads, as required outputs may not be achieved with football-specific activity/sessions only. Maintenance or required progression in HSR can be achieved through additional aerobic power i.e. 15:15s intervals or speed-endurance conditioning (preferably position-specific drills). Importantly, during this phase the internal response (time >85% maximal heart-rate and heart-rate exertion) is comparable to running loads achieved during the CCC-high chaos phase. An elevated internal response is expected due to interaction with players in the team training environment. If subjective fatigue increases after two modified acquisition days, a recovery day is advised before rejoining the team match-day minus one session (MD-1; reactivity). On match-day, the player can either join

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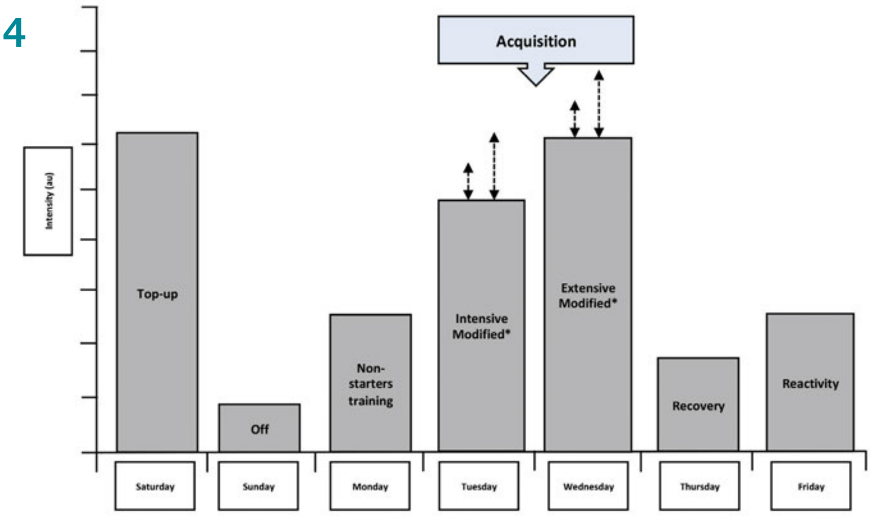

Figure 4: Potential Weekly Planning Template (Return to Training; non-contact and contact). Arrows represent load increments in week to week individual intensive and extension training sessions to build chronic running loads (Increments are increases in running loads; magnitude of increment dependent on 1) player's chronic (pre-injury) loads 2) current injury. Intensive = Intensive Football, Extensive = Extensive Football, Off = Day off, Intensity = arbitrary unit (au), Modified* = modified session/drills.

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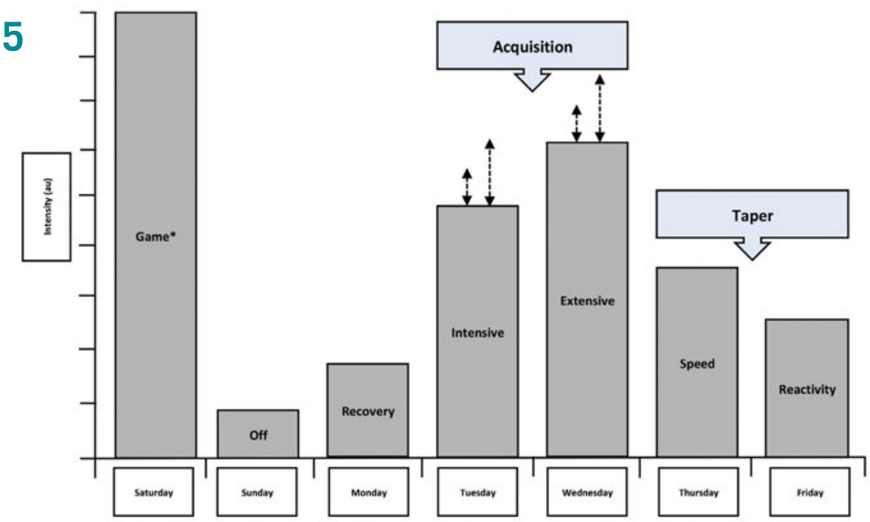


Figure 5: Sample Planning Template (Return to Training – Full Integration, Return to Competition and Return to Performance phases). Arrows represent load increments in week to week individual intensive and extensive sessions to build chronic running loads. Increments are increases in running loads; magnitude of increment dependent on 1) player's chronic (pre-injury) loads 2) current injury. Intensive = Intensive Football, Extensive = Extensive Football, Off = Day off, Recovery = Recovery day, Intensity = arbitrary unit (au), Game* = progression of competitive match minutes, Recovery or Non-starters training* = recovery or training determined by number of competitive match minutes/match minutes running load output and response to load (subjective, selected S&C diagnostics, medical assessments).

players not involved in the match-day squad alongside additional top-up conditioning or have an individualised session related to achieving performance targets required for running load progression/stability.

RETURN TO TRAINING; CONTACT

Aims: Continue re-integration to team training under contact conditions, modified acquisition days to minimise trafficking, monitor running load progression.

In this phase the player is progressively integrated into team training and exposed to contact. The previous phase weekly training structure applies, with modification on acquisition days (Figure 4). Within game-based conditions, the player may alternate between a 'floater' to becoming fully integrated into games e.g. 4v4+2 to 5v5. This allows gradual exposure to full training in controlled doses, allowing the player to become accustomed to player interaction in restricted areas, training fast reactive abilities, true sport-specific agility and high-level decision making. Communication with the coaching staff is also key to help ensure that technical skills requiring practice can be refined in-session i.e. pass and move drill with increasing passing distance and touch number restrictions. Internal response to running loads is still monitored; time >85% Max^{HR} and HRE relative to running load metrics ratio in comparison to the high chaos and RTT – non-contact phases. Recovery can be scheduled if appropriate, or a reduced match-day minus two type session such as team warm-up, boxes, pass and move (moderate sized area) and finish – restricting session intensity/volume. As in the previous phase, the player should join with the team on MD-1 and be involved with the players not selected on match-day and on a match-day minus 5 (non-starters training; Figure 4).

RETURN TO TRAINING; FULL INTEGRATION

Aims: Resume full team training, implement a minimum of two acquisition days and two taper days. Monitor running loads i.e. changes in intensive/extensive session loads, internal response, and week to week changes. Introduction to behind closed doors/development squad match minutes.

In this final RTT phase the player is fully integrated into team training. The team's specific training structure will apply here, where two acquisition days are followed by two tapering days leading into match-day (Figure 5). Within the two acquisition days, the continued progression of energy system development in game-based elements of session can be manipulated through alterations in work: rest periods whilst set and repetition parameters of specific drills can be progressed to provide a new training stimulus (e.g. standard sets, wave loading, descending/ascending pyramids or mixed game formats). These parameters are influenced by technical/tactical coaching alongside the competitive playing schedule. If the sports medical, performance, and coaching team as well as the player him/

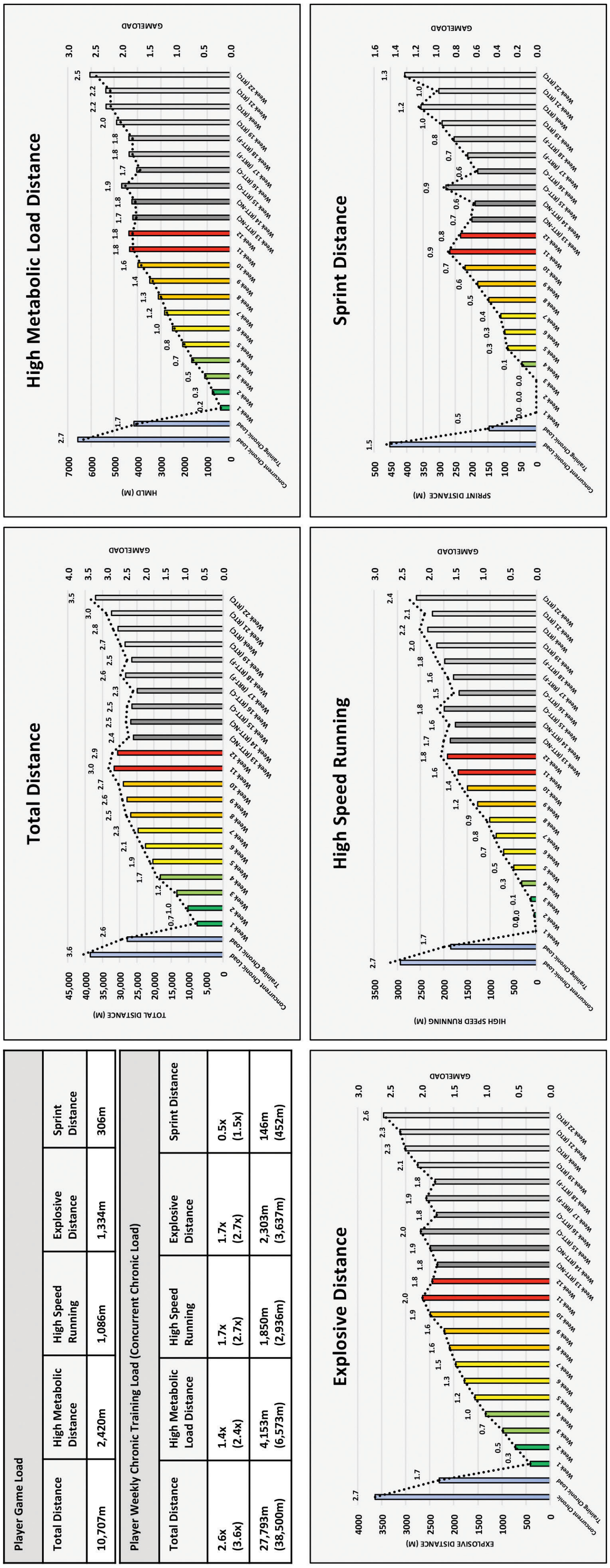
herself feels they are ready, a behind closed doors game could be arranged or, commonly the player follows the development squad training schedule in the two days leading into match-day. Match minutes are normally limited to less than thirty as part of a step-wise progression for RTC. If the shared-decision is not in favour of competitive match minutes, then the same format as the two previous phases is repeated.

RETURN TO COMPETITION; MATCH EXPOSURE

Aims: Continue integration to full team training, progression of competitive match minutes (as appropriate), monitoring of running loads/response, regular inter-disciplinary discussion and shared-decision making on competitive involvement.

In this subphase, the player is integrated with the team and preparation is now focused on a progressive increase in competitive match minutes (Figure 5). This phase represents a substantial marker for the player as they are now faced with their biggest psychological challenge; coping with the intense physical and mental demands of professional football. A considered progression of match minutes is implemented, dependent on any development squad minutes accumulated in the previous phase. We suggest starting off with ~20-30 minutes as a substitute or starting the first 45 minutes.

Training load information should form a starting point for discussion with sports medical/performance team to create a planned match minutes strategy for the forthcoming games schedule in collaboration with the coaching staff and the player. We have presented an idealised scenario in which player care is paramount and in which the medical and fitness/performance staff communicate with each other and the coach which does not always align with the reality of the elite environment[28]. Coaches may be willing to take a higher risk than the support staff. The player's voice may be critical in such circumstances, as experienced professionals know their bodies, and the last thing they want is return to play and get another injury[29]; hence shared decision-making is critical. Availability of other players in the same position, management opinions, tactical decisions and/or in-game circumstances such as injuries to other players can result in the player not



Player Game Load				
Total Distance	High Metabolic Distance	High Speed Running	Explosive Distance	Sprint Distance
10,707m	2,420m	1,086m	1,334m	306m

Player Weekly Chronic Training Load (Concurrent Chronic Load)				
Total Distance	High Metabolic Load Distance	High Speed Running	Explosive Distance	Sprint Distance
2.6x (3.6x)	1.4x (2.4x)	1.7x (2.7x)	1.7x (2.7x)	0.5x (1.5x)
27,793m (38,500m)	4,153m (6,573m)	1,850m (2,936m)	2,303m (3,637m)	146m (452m)

Figure 6: Example of progression in Return to Chronic Running loads following ACLR using the Control-Chaos Continuum and Return to Performance (RTPerf) pathway. Data representative of full-back game load i.e. physical demands of game (mean) and respective training and concurrent (training + match) absolute and relative load (game-load i.e. 2x = 2 games). TD = Total Distance, HSR = High Speed Running (>5.5ms^{-1}), SPR = Sprint Distance (>7ms^{-1}), Exp-D = Explosive Distance (Accelerating/Decelerating from 2-4ms^{-1} <1s). Green = High control (low intensity) moving towards High Chaos (high intensity). Grey shades = Return to Performance Continuum; Darkest grey = Return to Training: non-contact (RTT-NC), dark grey = Return to Training: contact (RTT-C), Mid-grey = Return to Training: Full Integration (RTT-F), Light Grey = Return to Competition: match exposure (RTC) – the phase leading into a RTPe.

achieving match minutes targets or playing more minutes than planned. One must plan for a worst-case scenario and adapt plans accordingly to changing circumstances. If the player does not play, appropriate post-match top-up conditioning planned in line with running load targets and the upcoming training/fixture schedule is an option. If the player plays more minutes than expected, medical checks in the acute post-match/proceeding days followed by appropriate player management i.e. extra recovery (off-loaded), or modified training is recommended. Although early reintegration increases risk of re-injury, having key players available benefits the team30. Information (i.e. subjective, running loads and response) should therefore be collated in order to estimate risk associated with full return.

Running loads are monitored to try and ensure planned progression and avoid unnecessary 'spikes' (increments or decrements in load). If responses (i.e. perceived exertion, subjective ratings, neuromuscular profile) to load compared to the individual's norms suggest an abnormality, then a reduction in load may be required, albeit while attempting to somewhat maintain load 'stability' (i.e. minor week-to-week fluctuations). At this stage, concurrent running loads should now be approaching pre-injury outputs, dependent upon match involvement and training indicators, as demonstrated in our example of a full-back (Figure 6). If a key player is returning with the possibility of more rapid RTC (immediately playing >60mins), during the RTT subphases we recommend practitioners provide a more aggressive (albeit safe) overload stimulus to specific running loads metrics i.e. exposing the player to HSR demands rather than the typical progression of match minutes to achieve concurrent running load.

RETURN TO PERFORMANCE

Aims: The player is meeting required training demands, regularly involved in competitive match minutes, confident in their level of performance, monitoring concurrent running loads/response, continue development of physical qualities.

Judgement on whether RTPe status has been achieved is made after the RTC phase and depends upon match exposure and the period of adaptation to the imposed competition load. No definitive length of time is suggested for this period due to variable responses and likely disruption of medical/performance staff plans (described above). During this phase, the player is becoming accustomed to the normal training/competition routine and accumulating full matches, during which time we recommend close attention to concurrent running loads and load response through NM performance monitoring. Off-pitch conditioning/pre-training preparation should be maintained, as an on-going part of development of physical qualities.

Player management around fixture schedules i.e. multiple fixtures in the same week, may represent a challenge. A reduction in training load (number of sessions/intensity of sessions) can assist with management alongside building up to these periods where game load is high, ensuring the training stimulus (volume/intensity) is adequate to condition to meet these expected physical outputs. Factors to consider in defining progress towards RTPerf include; equal or exceeding pre-injury typical match outputs, typical performance traits (i.e. physical, technical, tactical qualities) visible to coaching staff and frequent team selection. Load-response monitoring of selected strength and power diagnostics such as CMJs is performed on a standard day of week leading into match-day, both bilateral "fatigue-markers" and in a returning player, attention to individual limb responses and trends, particularly if abnormally high interlimb deficits remain at RTC.

SUMMARY

Sports-specific preparation and return to chronic loading is suggested to be overlooked in RTS criteria in the complex process of rehabilitation from ACLR[2]. The CCC is an adaptable pathway with which to formulate an on-pitch rehabilitation plan, returning the player to the required running loads whilst integrating sport-specific conditioning and technical skills.[6] Due to the long duration of absence from training and inability to truly replicate the training (and match) environment in the rehabilitation scenario following ACLR we propose an adjunct to the CCC. The RTPerf pathway fits within the RTS continuum[24] to ensure a logical return to the team training environment, competitive matches and setting a pathway towards a RTPerf.

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OUSMANE DEMBÉLÉ
BARCELONA'S RISING STAR!

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Masour Ousmane Dembélé is considered one of the emerging talents in world football due to his exciting and skillful performances. He is an attacking player whose career began at Rennes prior to joining Dortmund in 2016. After only one year, he then made a record breaking transfer to Barcelona. In his first season he won the league and cup double. Dembélé also plays for the French national team, making his senior international debut in 2016 and was part of the 2018 World Cup winning squad.

In 2019 and 2020 he visited Aspetar as part of his rehabilitation following a series of hamstring injuries. In this interview, Dembélé opens up to discuss his experience in different countries, what he looks for in the club's medical staff, coping with injuries when they happen, the importance of prevention programmes, and effective strategies he uses in his off-field preparation to be able to complete in the modern game.

OUSMANE DEMBÉLÉ

Full name:	**Masour Ousmane Dembélé**
Date of birth:	**15 May 1997 (age 22)**
Place of birth:	**Vernon, France**
Playing position:	**Forward**
Current team:	**Barcelona**
Number:	**11**

CAREER HIGHLIGHTS

2018 **ORDERS**
Chevalier of the Légion d'honneur

2018 **FRANCE NATIONAL TEAM**
FIFA World Cup

2017- **BARCELONA**
La Liga: 2017–18, 2018–19
Copa del Rey: 2017–18
Supercopa de España: 2018

2016-17 **BORUSSIA DORTMUND**
DFB-Pokal, (Man of the Match - Cup Final)
UEFA Champions League Breakthrough XI: 2016
Bundesliga Rookie of the Season: 2016–17
Bundesliga Team of the Season: 2016–17

2015-16 **RENNES**
UNFP Ligue 1 Young Player of the Year: 2015–16
UNFP Ligue 1 Player of the Month: March 2016

This is your second visit to Aspetar, have you had an enjoyable and worthwhile experience?
Yes, I am very satisfied with my time here. I have worked very hard and progressed well with my rehabilitation. There is still some way to go before I can return to play but I am getting closer every day.

That's great to hear. When did you start playing football?
I began playing football with friends in my local neighbourhood in Evreux, France. We would mess around a lot and play 1v1, 2v2 games. I loved football from the beginning and it quickly became my passion.

At what age did you began specialising in football and subsequently play your first professional match?

I became very serious at 13 years old. This is when I started attending the Rennes FC centre of excellence. It was a big adjustment for me and my family due to the 250km distance from our home town. In order to attend, we all moved in Rennes to be closer to the club. My routine then became school in the day and training in the evening. This was a big change as I was still very young.

After graduating from the youth team, I made my first team debut aged 18 years against Angers who are in the French 1st division. However, I only stayed at Rennes for a further 6 months before moving to Germany to play for Borussia Dortmund.

> ***There is still some way to go before I can return to play***

Did you also play other sports during your childhood?
No I just played football, it was my dream to be a professional football player and I was focused on that since the beginning. Also, being at the Rennes FC centre of excellence made it difficult to play other sports due to the time commitment and I also did not want to over train.

After your move to Dortmund – did you notice differences in their training methods and the way they approached the game? If yes, how did you adapt to this?
Yes, they are very different! In Germany, the training is very tough and the approach is quite strict. I really enjoyed my time in the German championship and the style of play was very attacking which was great. It was a very pleasurable year I spent there before moving to Barcelona.

Was it a tough progression to move from Rennes, to Dortmund and then Barcelona all in a relatively short period of time?
Yes, it was a big challenge to move between 3 countries and clubs in a short space of time but also very exciting. Each club has slightly different philosophies with respect to training approaches, workload requirements and style of play. For example, at Barcelona we place a lot of emphasis on technical work and small side games, whereas at Rennes and Dortmund, a greater amount of time was spent on physical preparation. It has been great experience for me to be exposed to such a diverse range of methodologies so young in my career as I believe this will aid in my development.

You have recently had a hamstring injury, the first serious injury of your career. Have you found this period difficult?
Obviously it is always disappointing and frustrating to be injured; however, I was optimistic as I knew that if I work hard then I will be back on the pitch quickly. I have been very focused during my rehab and can't wait to play again at the highest level.

Is it difficult for someone of your age to be an elite footballer in the modern age and someone who is constantly in the spotlight?
I am young yes, and my record transfer to Barcelona naturally brings some pressure, but to be honest it wasn't a problem for me. I have always dreamed of playing at the highest level and for a top club like Barcelona. Therefore, I have constantly been preparing myself for the pressure and I feel it gives me even more motivation to succeed.

> ***I would encourage young people to work hard as that is essential if you want to succeed but also not to forget about their studies.***

Ousmane Dembele in action. Barcelona, 2018.

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What advice would you give to young boys and girls dreaming of playing at the highest level?
I would encourage young people to work hard as that is essential if you want to succeed but also not to forget about their studies as you never know what can happen in life.

As a top professional football player, what qualities do you look for in the medical staff at the club?
First and foremost, to be experienced and knowledgeable which will ensure they can provide the first class treatment, rehabilitation and reconditioning. It is also important to build good relationships and try to understand the players needs. This shows that they care and helps build confidence and importantly, re-assurance. At Barcelona we have 3 doctors who I am in constant contact with and they have been especially helpful during the period of my recent injuries.

In light of your recent hamstring injuries, do you believe it is important to incorporate on-going injury prevention work into your regular routine?
Yes, I think it is very important and is now an integral part of my weekly training regime to ensure I give myself the best possible chance of staying fit, healthy and able to perform at the highest level. In the modern game, you have to be physically prepared and this is not only the responsibility of the club but also you as the player to ensure you remain professional in your approach.

Dembele vies with Unai Nunez during the Spanish league match between Athletic Club Bilbao and FC Barcelona in August 2019.

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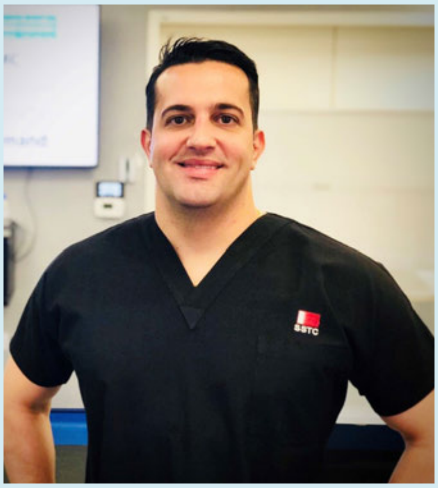
Is there anything else we haven't asked that you would like to mention for our readers?
Yes, I was surprised you didn't ask me about best practices for how to live your daily life and off-field preparation!

As well as physical preparation, you also have to pay attention to your nutrition and recovery. At Barcelona, the advice and guidance we receive is first class. I also think I am more aware now of what the right things are for my body. I now understand that I can't just eat anything I want or stay up late to play computer games and expect to perform at my best. I am much stricter in my approach these days. Specifically, with the help of the club I tailor my nutrition appropriately, focus on sleep to aid recovery and stick to a routine which ensures I am always ready to train or play.

Nebojsa Popovic M.D. Ph.D
Interview taken on 18th January 2020.

Dembele during his recovery in Aspetar – Qatar Orthopaedic and Sports Medicine Hospital, Doha, 2019.

ASPETAR FELLOWSHIP PROGRAMME



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How did you hear about Aspetar Fellowship Program?
I first visited Aspire Zone Foundation during a camp with the Brazilian National Team in 2006 and 2007. Aspetar was on the verge of opening its doors at the time. Ever since, I was determined to visit Qatar again and to work at Aspetar. In 2016, I visited Aspetar as part of its International Observational Program within the Surgery Department for one week. When it came to an end, I was invited by the team to join their Orthopaedic Fellowship Program for one year. I went back home, discussed with my family, finished my master's degree in Knee Surgery and decided to take on this immense challenge.

What are the fellowship activities at Aspetar?
We start the week with our surgical meeting every Sunday. The surgical team discuss all the cases operated the week before, and the cases we have that week. In the mornings, I attend the operative room to assist our surgeons in their cases, in addition to the visiting surgeons during their visits to Aspetar. In the afternoons, I attend clinics to examine walk-ins, post-operative patients and urgent reviews. Along with the surgeons, we organize monthly educational and research activities in our Cadaveric Lab, including anatomy sessions, training on surgical techniques and developing new innovative techniques. Furthermore, we conduct pre and post-operative rounds for the inpatients in the ward, research activities, lectures and journal clubs, on calls and emergency operations. To conclude, in addition to the above-mentioned, fellows also support Aspetar's Sports Physicians during the coverage of international sports events hosted in Qatar and abroad when required.

What can Aspetar provide to doctors that are looking to improve their experience in Sports Medicine?
Aspetar is a unique place in the world, and the work atmosphere here is amazing. We have a state-of-the-art facility that provides our patients with excellency in Sports Medicine and Orthopaedics. The first impression that everyone has when arriving to Aspetar is how exceptional the facility and services are. Our focus is to provide athletes with the best medical service in order to improve their performance. At Aspetar, all healthcare providers: surgeons, sports physicians, physiotherapists, sports scientists, nutritionists, phycologists, nurses etc. are all working together to bring athletes back to their best conditions, so they can go back to play faster and better. Aspetar's Visiting Surgeons Program brings the most renowned specialists from all over the world to treat our patients. International highly-recognized surgeons are available to diagnose and operate on patients that require special complex surgeries. Our relationship with these specialists increases not only our expertise and knowledge, but also the network and connections in the field of Sports Medicine.

What is your main achievement as a Fellow in the last two years?
It is impossible to say only one thing. Surely, there is no bigger achievement than seeing your patient around the hospital, and they come to you and say thank you. This is priceless and makes all the hard work worth it. Since my first day, I have a lot of good memories working at Aspetar. At that time, I had all the support from the staff, specially my teammates from the Surgery Department and Scrub Nurse team. In two years, I can't mention all the good moments I've experienced during the fellowship program, but these are my Top 5:

1. Few weeks ago, I have reached 1.000 surgeries attending in the Operating Theatre. Personally, this number made me very happy and proud because it is an impressive number for a fellow. I assisted in surgeries in all the various pathologies: knee, foot, ankle, hand, wrist, elbow, shoulder, groin, and soft tissue procedures. Few places in the world can provide this huge number of surgeries during a fellowship program.
2. It was amazing to be part of the medical staff in the IAAF Athletics World Championship. I could see how Aspetar has built a very strong medical team working together.
3. I had an impressive experience representing the Surgical Department at the Qatar Health 2020 Conference here in Doha.
4. I conducted a presentation supported by Aspetar at the Isokinetic Conference at Camp Nou Stadium in Barcelona, and a poster presentation at Wembley Stadium in London.
5. I can't forget to mention all the friendships I gained here. The doctors, the physiotherapists, the nurses, the receptionists and the secretaries, everyone is special.

What are your comments and tips about the fellowship program at Aspetar to the next candidates willing to come? How can they apply for the next vacancies?

Aspetar is a real step up in my career. I am sure it was the best decision I made. Here I focused on my main area of interest, caring for the athletic population. I have developed personally in terms of decision-making, knowledge and expertise. If anyone is thinking about joining as a fellow, they will never regret it. I am sure they will enjoy their time here, especially through all the sportive environment that only Aspetar can offer. It is very pleasant to be part of the Aspetar's Family.

All certified doctors with their specialization board diploma can apply for the fellowship. They can choose to be a Sports Medicine or Sports Surgery fellow. We have just increased the number of fellow vacancies to two sports physicians and three sports surgeons. The fellowship program is for a one-year period, and the hospital will support the selected candidates with all the government documentations. Once per year, we open for applications on Aspetar's website. It is open for all nationalities, everybody is welcomed.

What about Qatar? What are your impression of the life people have here?

Qatar is an amazing country. Modern while sustaining its traditions and culture. It is a diverse place (only at Aspetar you can find people from more than 80 nationalities). Qatar is developing quite rapidly, especially in preparation for the FIFA World Cup 2022. Qatar hosts dozens of sports events during the year that is open for the world's population to attend, in different sports such as Football, Tennis, MotoGP, Triathlon series, Marathon, Swimming, Athletics, Gymnastics, etc. It is the perfect spot for sports lovers. Qatar offers very good life quality, safety, education, entertainment, museums, malls, nightlife, nice restaurants, you can find everything here. In my opinion, it is the perfect place for families. After work, as a sports guy, usually I do some sports activities, go to the gym and practice Brazilian jiu-jitsu. We also have one football night with colleagues from the hospital every week.

What do you want for the future? What are your plans?

I am very happy living in Qatar and working at Aspetar with my teammates and friends. I have totally adapted to the lifestyle. I will see the opportunities that will arise after the end of the Fellowship Program. Actually, I am working together with Dr. Khalid Al Khelaifi and Dr. Pieter D'Hooghe in a way to have a continuous improvement for the fellowship program, increasing its activities, cadaver lab sessions and surgery facilities to receive new fellows. We have great plans and I would like to see it all on track for success in the coming years.

I am very excited that I have the chance to enjoy the FIFA World Cup here in Qatar, I am sure it will be amazing. Inshallah, I will be here to see these special moments in the gulf region. It will be historical.

INDUSTRY NEWS

– Written by Nathan Riding PhD, Qatar

Practical solutions to promote healthy sleep outlined by the IOC

Recovery

Having a role in recovery at the cellular, network, and endocrine system levels, the importance of sleep is clear. While exercise has been shown to improve sleep quality and quantity, paradoxically a near 80% of athlete's report getting less than the revered 8 hours. A consensus statement last year from the IOC and published in the *British Journal of Sports Medicine* provided some advice on combating the issue. They suggest that the sports medicine team can promote healthy sleep by firstly ensuring coaches schedule training around sleep and circadian rhythms. Circadian dysregulation can be common among athletes that frequently cross time zones for competition, and both time bright light exposure and melatonin may be suitable among some athletes depending on their specific chorotype. Promoting sleep health education and encouraging healthy sleep as part of the training protocol are two further suggestions from the IOC group. Sleep deprivation impairs athletic performance across the sporting spectrum however due to the psychological and physiological demands such as late night training and competition, associated muscle soreness and states of hyper-arousal, elite sport can pose a significant challenge to quality sleep. This can be tracked by monitoring sleep, with the Athlete Sleep Screening Questionnaire specifically created to determine which athletes suffer from clinically significant sleep problems and who would benefit from preventative measures.

Extended cardiac rehabilitation shown to improve patient outcomes?

Exercise Medicine

As survival rates following a heart attack continue to improve, more and more people are living with heart disease. One of the key components to care following a coronary event is cardiac rehabilitation. Shown to exert benefits on a range of coronary risk factors, exercise capacity and psychological factors, in addition to overall cardiac morbidity and mortality, more than 80% of countries worldwide offer the programme in some form. Adhere is however low, data from the UK showing that just 50% of referred patients enrol and that only short-lasting beneficial effects are elicited after 6 weeks of outpatient cardiac rehabilitation. With this in mind a team from Austria began implementing a unique additional 6-12-month programme following the completion of a traditional 4-6-week programme. The researchers then prospectively compared the outcomes of 4,771 patients who underwent just the first 4-6-week phase versus 5,192 completing the newly implemented extended rehabilitation. Promisingly, patients within the first group significantly improved their lipid profile, blood pressure, and psychological well-being, while exercise capacity rose by 14% when compared to the onset of the programme. The 12-month programme elicited further improvements among their cholesterol scores and an additional 10% increase in exercise capacity. The study highlights the importance of continued education and supervision following a coronary event, with the findings notably indicative of a 10% improvement in 12-month survival.

Preseason training associated with lower in-season injury burdens

Sports Medicine

"As you head for home, you crawl back to your car and try not to fall asleep in the supermarket queue as you do the food shop". The words reported in the *Guardian* by professional footballer Mark Roberts demonstrate the changing nature of a footballer's preseason routine, where intense sessions up to 3 times per day are the norm; and indeed the correlation between increased preseason aerobic fitness and injury has been documented. Setting out to determine whether there is a link between number of pre-season sessions and injury risk was the Football Research Group from Sweden. Using a large cohort of 244 combined team seasons from the UEFA elite club injury study data set they examined the association between session number and various injury outcomes. Although unable to report the composition of preseasons beyond session number, and lacking in-season load measures, they identified that more preseason team training sessions were significantly associated with training attendance, match availability and lower injury burden for the whole season. In another context, for every 10 extra sessions injury burden decreased by 22 days per 1,000 hours of exposure suggesting that more preseason training sessions may help players to remain somewhat healthier during the competitive season.

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Finish town offering free gym membership for the over 65's

Exercise Medicine

The Finnish town of Kurikka may be a quaint settlement in the rural west of Finland surrounded by luscious green countryside, but sitting at number 5 of its tripadvisor top things to do list is Kroppani Kuntokeskus...the local gym. It is for this that the town has received international attention, as it has recently started an initiative offering free gym usage for the over 65's. Speaking to the *BBC* The mayor of Kurikka, Anna-Kaisa Pusa stated that "there has been a lot of discussion about preventive healthcare, and how to support people to take care of themselves, but little action". With the aim of improving the health of her residents the Mayor hopes people who take up the offer will be healthier leading to the council saving money in the long run due to lower social care costs. The results are already clear with the *BBC* report claiming users have said they are in need of less pain medication and that their mental health has improved

© Sun Valley Group of Schools/Flickr.com (cropped)

Children under 12 to be banned from heading footballs

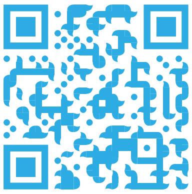
Sports Medicine

On the back of results published in the *New England Journal of Medicine* the English and Scottish FA's have moved to ban heading of the ball in training among young football players up to the age of 12, while limitations will be placed on the weight of footballs and frequency of heading all the way up to under 18. Although new research suggests heading is rare in youth football, the landmark findings that led to these FA rulings had identified that mortality from neurodegenerative disease was higher among former male professionals than controls. Headed by Dr Stewart, the study group from Glasgow, Scotland, retrospectively analysed the medical records of 7,676 former football players against 23,028 matched controls and compared the data over an average follow up of 18 years. Overall mortality was lower among the former professionals including from ischemic heart disease and lung cancer. Neurodegenerative disease as the primary cause of mortality among former footballers was 1.5% and 2.2% when included as a contributory cause. This differed from the presentation among controls where prevalence lay at 0.5 and 1% respectively, leading to a subhazard ratio of 3.45. Although the authors concede that death certificates are subjective to error they noted that medication typically used for Alzheimers and dementia was also prescribed more frequently among the footballers. While the authors state the findings need to be confirmed among prospective studies it has not stopped the football associations taking action

IN NUMBERS

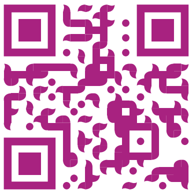
79€ Pre-participation screening in Italy identified a range of diseases in 2.0% of apparently healthy athletes at an average cost of €79 per athlete.

15 Weeks: According to the latest research, recent injury is the greatest risk factor for the four major muscle strains, with increased risk persisting for 15 weeks after return to play.



Free access to all content

Aspetar website



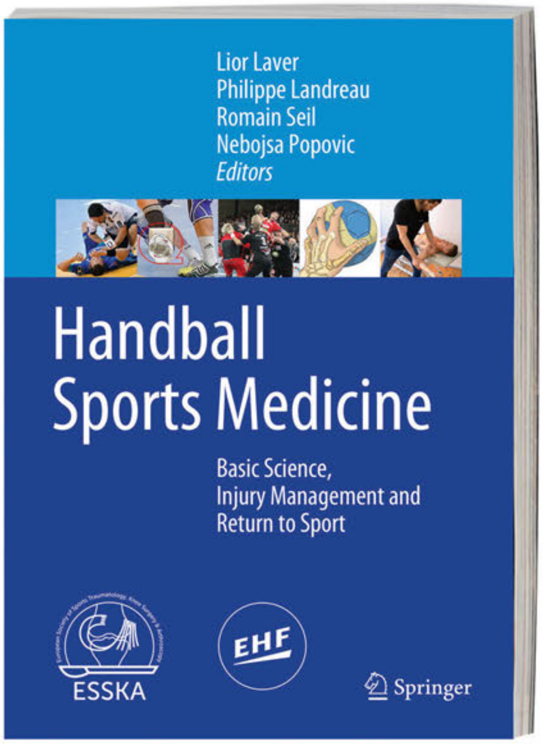
AZF website

Get in touch with our team

European Society of Sports Traumatology, Knee Surgery & Arthroscopy

ESSKA

HANDBALL SPORTS MEDICINE
Basic Science, Injury Management and Return to Sport



This book is designed to help **improve the medical care of athletes** engaged in team handball all over the world.

It provides concise practical information on the nature of frequently encountered injuries, the management of these injuries, injury prevention, and rehabilitation following treatment.

Other specific sections also focus on physiologic, endocrinologic, biomechanical, and nutritional aspects; psychological issues, as well as special considerations in particular groups of players.

The medical needs of a handball team are explained as well as recommendations on preparticipation assessment and screening.

All editors and authors are leaders in their field. Their excellent teamwork ensures that the book, published by ESSKA and with affiliation to the European Handball Federation (EHF), will represent a superb, comprehensive educational resource.

It will meet the needs of both handball medical caregivers and handball personnel, providing readily accessible answers to a wide range of medical questions and facilitating effective collaboration among the various professionals involved in team handball.

The book will be available for purchase from Springer (www.springer.com) and at a discount for ESSKA members.

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