Module 4. A framework for Kinetics in rehabilitation and RTS

Daniel Cohen & Matt Taberner

In the Kinetics in ACL injury, rehabilitation, and RTS module, we introduced the evidence and practice base around the use of the DL-CMJ in rehabilitation, with particular reference to data from athletes assessed across the return to sport pathway following ACL reconstruction. The learner should now be familiar with DL-CMJ asymmetry metrics of interest - those which differentiate injured and uninjured athletes and those which persist well after return to sport - based on group mean data at selected time points. In this module, we go beyond this cross-sectional data and describe both trends within groups and in individual athletes. We refer to both published and unpublished group data and case studies in athletes and draw on the author's extensive experience in implementing and interpreting data from DL-CMJ and other strength & power diagnostic assessments in elite sports.

This module will further expand the learner's knowledge base and will provide a conceptual framework and toolbox to assist practitioners in making decisions on the implementation of S&P diagnostic assessments during rehabilitation-return to sport (R-RTS). This includes developing an understanding of the behaviour of not only asymmetries but also other performance and kinetic variables during R-RTS which is critical to the interpretation of derived data and to the enhanced insights on athlete status and progress gained with these assessments.

However, before addressing the kinetic framework and toolbox in detail in section 2 of this module, we describe the rehabilitation-return to sport (R-RTS) process and its subcomponents. A global understanding of the key elements to consider in this pathway - such as load progression - underpins a clearer understanding of the value kinetics have in informing and supporting decision-making within R-RTS.

4.1 Return to Sport

In 2002, the first consensus statement on return to play (RTP) was issued as part of a collaboration between six major professional organizations in the United States of America, which included the American College of Sports Medicine and the American Academy of Orthopaedic Surgeons (Herring, 2002). The objective of this statement was to provide a decision process for determining when an injured or ill athlete could return to practice or competition. The statement highlighted that RTP should be and should integrate expertise from various sub-disciplines across the sports medicine and performance team to optimize the rehabilitation of the injured athlete. Collectively, these organizations expressed that the 'rehabilitation network' should coordinate a development plan to restore function of the injured body part, and restore and promote musculoskeletal and cardiovascular function, whilst incorporating both sport-specific assessment and training to promote restoration of sport-specific skills.

Since this initial statement, sport and exercise medicine has made considerable progress. Decision-making models have become athlete-centred, with the athlete now an active stakeholder in the RTP decision-making process alongside key members of the interdisciplinary team (King et al., 2019). In 2015, a new consensus statement provided an update on the RTP process, providing clarity around the terminology used on this topic (Ardern et al., 2016). Although RTP had previously been the most commonly used term given to resumption of sports participation, 'play' is mostly only applicable to team-based sports and hence has limited cross-over to other sports. Consequently, return to sport (RTS) is now used to describe an athlete returning to sports participation across all sports.

Return to sport continuum

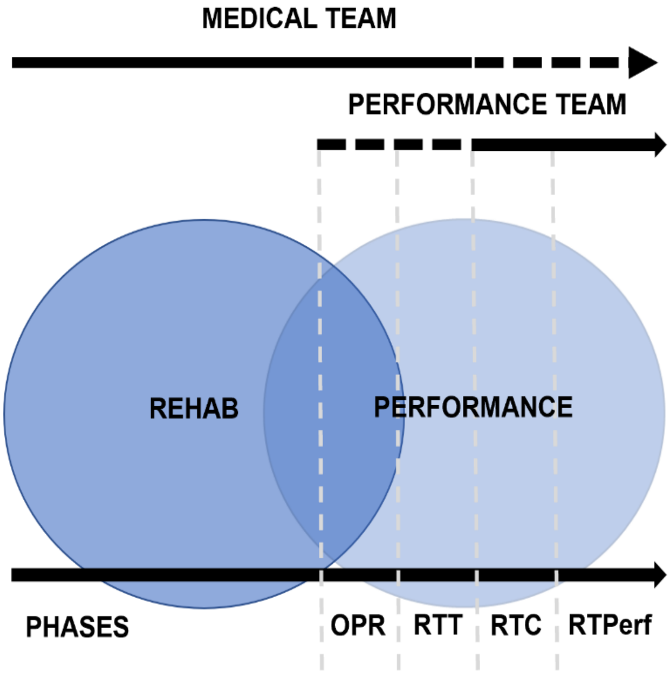
RTS after an injury is a complex process. To make informed decisions, the minimal considerations are the type of sport and the level of participation that the athlete is returning to (Ardern et al., 2016). The decision-making team should collaborate to define RTS success, especially as success can be viewed in different contexts depending on the orientation of the stakeholder. The 2015 consensus highlighted that the RTS decision is not simply a decision made at the end of the athlete's recovery, but should be viewed on a continuum that begins at the onset of injury and continues throughout the recovery, rehabilitation and RTS of the athlete (Ardern et al., 2016). The RTS continuum (figure 1) emphasizes graded, a criterion-based progression that is aligned alongside the individualized goals of the RTS process. Within the return to participation phase, the athlete is within the rehabilitation phase and operating below a lower level defined by the RTS goals. The RTS phase highlights the athlete has returned to their sport, but may not be at the desired level of performance. Finally, the return to performance phase extends the RTS process and is emphasized when the athlete has returned and is performing at or above their pre-injury levels (Ardern et al., 2016).

Figure 1: The return to sport continuum

Source: Ardern et al 2016.

Although the RTS continuum provides clarification over the RTS process, it may fail to recognize the updated 'functional' recovery process – the overlap between clinical rehabilitation and RTS. This phase typically takes place 'on-pitch' or 'on-court' and bridges the gap between the rehabilitation and sports training (Buckthorpe et al., 2019). An amalgamation of the updated functional recovery process and the RTS continuum has been suggested to provide a more complex model, to describe the 'whole' functional recovery process (figure 2) (Buckthorpe et al., 2019).

Figure 2. 'Whole' Functional Recovery Process



From Recommendations for hamstring injury prevention in elite football: translating research into practice, by M. Buckthorpe et al., 2019, *British journal of sports medicine*, *53*(7), 449–456. https://doi.org/10.1136/bjsports-2018-099616

Note. Rehab = Rehabilitation, OPR = On-pitch Rehabilitation, RTT = Return to Training, RTC = Return to Competition, RTPerf = Return to Performance

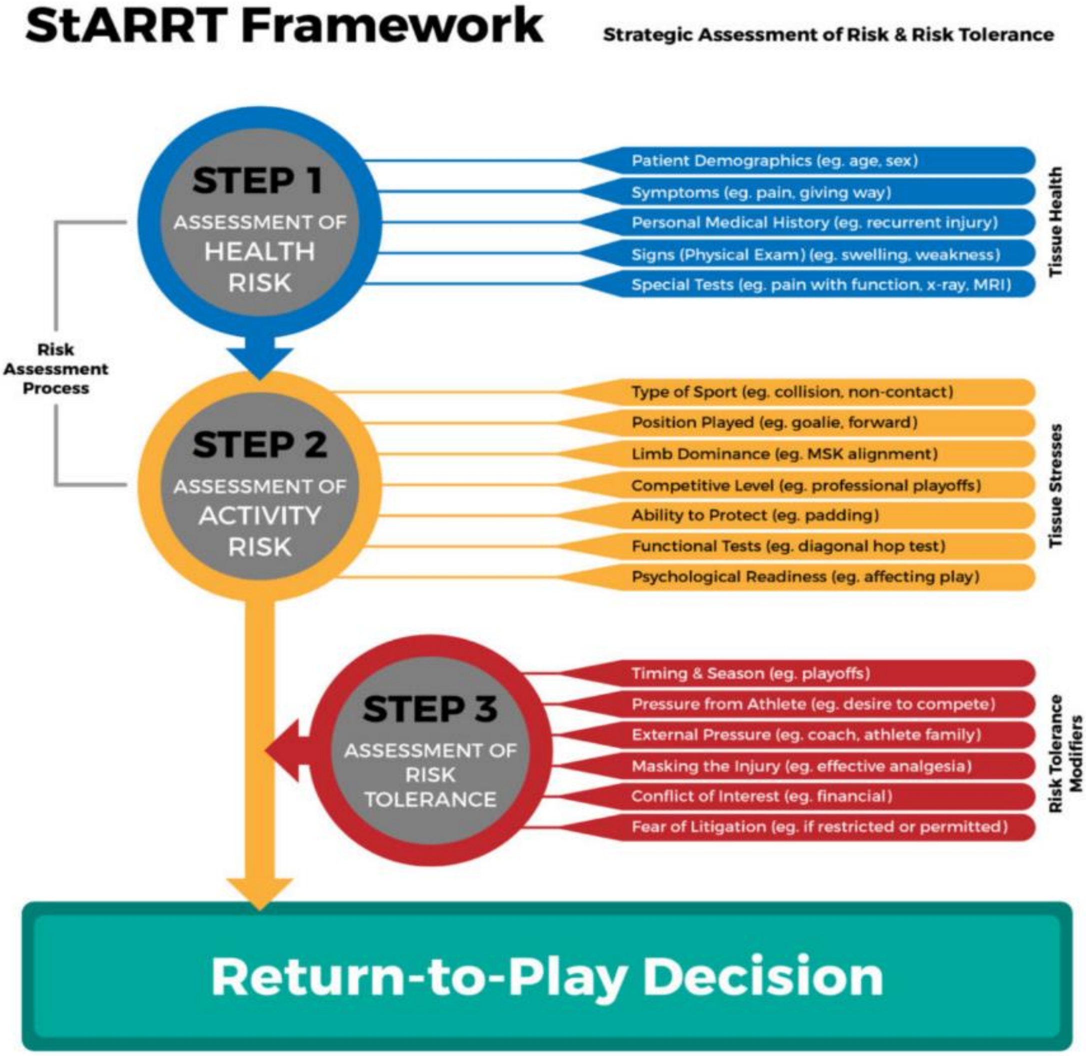
Within this updated model, the RTS phase was proposed to include: a return to training (RTT) and a return to competition (RTC), before a return to performance (RTPerf), with the length of each phase dictated by the type and context of the specific injury. With this added detail in mind, the end stage management of the rehabilitation process is likely outside the remit of most medical oriented staff and required specialist skills and expertise in handling an athlete's journey towards a RTPerf.

Models to understand return to sport

Several theoretical models have been developed to help practitioners understand the complexities associated with the RTS process, whilst also helping to ensure consistency and transparency in the decision-making process. The first of these models is the Strategic Assessment of Risk and Risk Tolerance (StARRT) framework (figure 3) (Shrier, 2015). The model is proposed to help estimate the risk associated with RTS, and the factors that affect what would be considered an acceptable risk considering the specific context. The three-step model consists of: 1) tissue health, like information relevant to the amount of stress the tissue can absorb before injury, 2) tissue stresses, as in information relevant to expected additive stress on the tissue, and 3) risk tolerance modifiers, such as contextual factors that influence the RTS decision. Based upon the model, athletes should be cleared for RTS when the risk assessment (steps one and two) is below the acceptable risk tolerance threshold, which should consider both the sport and the level of participation that the athlete is returning to (Ardern et al., 2016). Closer inspection of the StARRT framework (figure 4), specifically within step three, fails to recognize the importance of the amount of training performed by the athlete, which is potentially one of the most important considerations relating to imposed tissue stress (Blanch and Gabbett, 2016). Furthermore, within the risk tolerance modifiers tier, consideration regarding the training status of the player and type/severity of injury may also be important, as this may influence the amount of training performed, i.e., modification to reduce imposed load to provide a gradual RTS - a new way of viewing RTS (Ardern et al., 2016).

A second model that has been proposed to understand the complexities associated with RTS is the Biopsychosocial model (Engel, 1977; Ardern et al., 2013). Following injury, the model aims to provide stakeholders involved in the RTS process with a framework to consider physical factors like muscle strength, psychological factors such as motivation, and social factors like recovery expectations and how these interact to influence performance. The model highlighted the importance of psychological factors and how these might influence treatment/exercise prescription outcomes. From a rehabilitation perspective, the successful progression of a prospective treatment or exercise programme could serve as a precursor, to promote self-efficacy and readiness to return to activity. The interaction between these factors warrants further investigation during the RTS process, as structured progression has the potential to improve a player's psychological state.

Figure 3: Strategic Assessment of Risk and Risk Tolerance (StARRT) framework



Source: Strategic Assessment of Risk and Risk Tolerance (StARRT) framework for return-to-play decision-making, by I. Shrier, 2015, *British journal of sports medicine*, *49*(20), 1311–1315. https://doi.org/10.1136/bjsports-2014-094569

Adaptation and progression are integral elements of rehabilitation and RTS (Ardern et al., 2016). Banister et al. (1991) first defined an athlete's training status as the difference between positive (fitness state), and negative (fatigue influences); which termed an athlete's training-stress balance. This concept has since been quantified; fitness represented as 'workload' over a period of time (3-6 weeks) i.e., chronic workload, and fatigue represented by 'workload' performed in a shorter time frame, acute workload (1 week) (Hulin et al., 2014; Gabbett, 2016). The acute chronic workload ratio (ACWR) has been proposed as a means to indicate the athlete's risk of injury and level of preparation to perform and has been suggested to be a useful tool during rehabilitation (Blanch and Gabbett, 2016; Ardern et al., 2016). Furthermore, an increased injury risk has been highlighted when the ACWR is >1.5 (Blanch and Gabbett, 2016). Despite the consensus statement on RTS suggesting the ACWR might be a useful tool when an athlete is transitioning through the RTS continuum, recent evidence has highlighted potential flaws within the model (Lolli et al., 2018; Impellizzeri et al., 2019). Despite the potential flaws of the model from a mathematical perspective, the concepts from which the ACWR model is derived from, highlight important aspects for load management during the RTS process, especially the importance of progressive and systematic increments in load to help develop a player's physical capacity (Gabbett, 2016; Blanch & Gabbett, 2016).

Progressing rehabilitation after injury

Despite the recognition within the literature surrounding the importance of reconditioning (Ardern et al., 2016; Blanch and Gabbett, 2016), limited evidence is available to describe and guide practitioners during the on-pitch element of the RTS process. Progressing rehabilitation after an injury is a complex challenge. Formulating a rehabilitation plan involves communication with the interdisciplinary performance or medical team and the coaching staff to obtain as much information as possible regarding the individual player, whilst importantly keeping the player informed and involved in the process – essential in a considerations-based approach towards RTS. The player's retrospective chronic training and concurrent (training plus match) running loads should be obtained (GPS data), alongside training indicators and expectations under the coaching team (number of training days, sequence of training days, training duration, training type, etc.), which may differ from pre-injury demands, especially if under a new coaching team. Additionally, previous injury history, details of his/her current injury, positional demands (and playing style), objective neuromuscular profile (S&P diagnostic assessments) and trends in this data before and since injury alongside potential healing times. This information, alongside the training considerations (including gym-based strength and conditioning), should inform decision-making, estimates of the required duration of on-pitch rehabilitation and the required level of running loads, that the player needs to return to.

The 'control-chaos continuum' was proposed as an adaptable framework developed to guide the on-pitch rehabilitation process in elite football. The 'CCC' moves from high control to high chaos interlinking GPS running load variables, while progressively incorporating greater perceptual and reactive neurocognitive challenges (Taberner et al., 2019). Despite being developed from practitioner experience in the English Premier League, the concepts from which the framework was constructed also have the potential for application across other team sports including rugby, Australian rules football, basketball, and American football. The early phases of the 'CCC' are comprised of general training - limiting movement variability by applying task and environmental constraints upon the athlete to shape the environment to the required outcomes. These early phases of the continuum may be described as having two layers of control, high control over running speeds during the return to linear running and control over directional change load alongside progression of running speeds and integration of technical skills. Physical qualities important to the sport are targeted within the constraints of the injury, building a foundation towards RTS load targets. Thus, improving athlete confidence is one of the main objectives of the controlled phases as progress is being made in the athlete's RTS journey. The transition to later phases of the continuum allows the practitioner to express their creative ability and game understanding as they incorporate 'chaos' in an athlete-centred approach. Rehabilitation now moves from a base of general training towards increasing levels of specificity. From a planning perspective, a sport-specific periodization structure progresses to a club-specific structure and the unique load demands inherent to the game model of the coach leading the preparation of players for competition. Session structure should progressively mimic the composition of team training on acquisition days, targeting the physical qualities important to the athlete's sport and position. However, it must be recognized that there is substantial inter-individual variability in physical outputs and qualities among athletes in the same position, which may reflect the game model used. Multiple acquisition blocks within a micro-cycle enable RTS load targets to be achieved, exposing the athlete to increments in volume, intensity and stimuli that reflect the demands of the athlete's position, sport and injury-specific considerations. A session content level or drill design should incorporate stimuli requiring appropriate neurocognitive challenges, spatial awareness and technical skill content related to the game model that mimic the demands of competition.

Quantification of load

GPS is based upon satellite-based navigational technology originally devised for military purposes to enable three-dimensional tracking over land, sea, or air (Cummins et al., 2013). Recent developments in technology have permitted the use of portable GPS units across a wider variety of settings, including elite sports (Cummins et al., 2013). GPS is now commonplace across team sports, particularly in elite football, to provide sports scientists and coaches with comprehensive and real-time analysis during both training and match-play and in the process investigate applied research questions (Cummins et al., 2013; Malone et al., 2017; Malone et al., 2019). Data obtained by GPS may be a useful tool to benchmark performance levels, quantify on-pitch rehabilitation and set sport-specific targets during the RTS process (Ardern et al., 2016). Despite this promising proposition, much work is still to be done to determine the relevance of specific metrics during the RTS process. The external load cannot be quantified by a single GPS metric (Malone et al., 2019). As such, practitioners should consider the desired training outcome and the demands of the sport when selecting appropriate metrics to be tracked (Impellizzeri et al., 2019). Furthermore, due to the complexity of load monitoring, multiple metrics should be used in conjunction rather than in isolation to quantify the demands of activity (Vanrenterghem et al., 2017).

Despite the potential of GPS as a tool to quantify running loads during on-pitch rehabilitation, it is important to separate the 'signal' from the 'noise' to inform decision-making over a longitudinal period (Malone et al., 2019). Practitioners are advised to conduct their own in-house reliability and validity assessments on the specific GPS units and the metrics obtained within their own environments to establish the potential sources of error (Malone et al., 2019) and to establish confidence in their data to inform decision-making. Nonetheless, commercially available GPS units have been shown to be both reliable and valid for the quantification of distances, football-specific activity, and peak speed (Beato et al., 2016, 2018; Beato and de Keijzer, 2019). In contrast, metrics such as accelerations and decelerations should be interpreted with caution, as these have been reported to show the highest variability, reducing potential confidence in their use within decision-making (Buchheit et al., 2014). Inter-unit reliability has been reported to be good (<2%) for commonly reported GPS metrics in elite football such as total distance and high-speed running (HSR) (Akenhead and Nassis, 2016; Thornton et al., 2019), further supporting the validity of these metrics in running load measurement. As rehabilitation monitoring can occur over longitudinal periods i.e., long-term injury, it is important that a player is assigned a specific unit to maintain confidence in respective data to ensure meaningful interpretation (Jennings et al., 2010). Data collected, as in raw traces of velocity and acceleration, should also be inspected for potential irregularities generated by the devices, which may occur as a result of sudden satellite loss causing delayed detection of locomotion (Malone et al., 2017). Within the rehabilitation setting, decision-making is a crucial element of on-pitch reconditioning and with advancements in sports technology, GPS data is as well now available in real time. Data collected in real-time shows excellent agreement with post-event downloaded data, providing practitioners with confidence when making decisions (Johnston et al. 2019). This presents an opportunity for real-time decision-making, allowing practitioners to make adjustments in planned loading within sessions, reducing the potential for 'spikes' and may help to reduce re-injury risk.

GPS has been commonly used as a tool to quantify the running load demands of elite sports in a team setting (Cummins et al., 2013). Despite being limited to case reports, GPS has also been highlighted as a valuable tool to provide objectivity during on-pitch rehabilitation. Murphy and Rennie (2018) utilized GPS to provide feedback on progression in HSR and peak speeds relating to players' match demands following HSI. Morgan et al. (2018) also used these GPS metrics alongside total distance during the on-pitch rehabilitation process following a quadriceps muscle injury. Morgan et al. (2018) highlighted the value of considering pre-injury training GPS data alongside data obtained from match-play to ensure targeted loads during RTS. The use of GPS data was also reported by Weiler et al. (2015) in the rehabilitation of a player during the non-operative management of an ACL injury. Although limited detail was provided, GPS was used specifically during the early return to running phase to ensure running speed was below 50% of the player's maximal speed (pre-injury data), to build player confidence and to provide a measure of control in the early phase of on-pitch activity.

The use of GPS as a tool in the rehabilitation setting has been more intensively studied in elite rugby union compared to elite football, which could be possibly related to the sanctioning of GPS units with competitive match-play earlier than in association football. Coughlan et al.

(2011) used GPS to quantify game demands in elite rugby union and with match demands used as a foundation for the planning on-pitch rehabilitation running load. The importance of using game video footage with GPS data should not be underestimated to understand the contextual elements related to the physical demands of sports. GPS, therefore, presents an objective tool to individualize rehabilitation, using relative match intensities to develop sport-specific running programmes based on players' positional demands. In agreement with Blanch and Gabbett (2016), the authors suggested that the use of GPS data may be imperative to understand the amount of training that the athlete has performed during rehabilitation, to ensure adequate preparation for the demands of the sport. Additionally, the quantification of progression throughout on-pitch rehabilitation removes the subjectivity associated with the traditional RTS process and provides both encouragement and reassurance to the returning player to attain pre-determined goals (Coughlan et al., 2011) linking to the biopsychosocial model (Engel, 1977; Ardern et al., 2013). Further re-assurance is provided through the achievement of other objective data like S&P diagnostics throughout rehabilitation, which has the potential to provide an indirect influence on player confidence and highlight progression in their RTS journey, an often-neglected part of RTS.

Whilst GPS may be beneficial to measure running load demands during on-pitch rehabilitation, it may be limited in its ability to measure the activities undertaken by players in static-based activities (Reid et al., 2013). Despite this potential issue to quantify static-based tasks, GPS-derived metrics have been established to quantify the demands related to frequent bouts of accelerated and decelerated running in football (Osgnach et al., 2010; Di Prampero and Osgnach, 2018). The potential use of these metrics has, however, been questioned due to their variability despite their potential to provide new insights into the mechanics and energetics related to the football-based activity (Buchheit et al., 2014b, 2015; Hoppe et al., 2017). Such metrics might be able to provide objective information regarding the demands of football activity within restricted spaces, a major component within the tactical periodization paradigm, that will be discussed in due course within this literature review.

Despite the use of GPS data to quantify the running load progression during rehabilitation, limited attention has been placed on the quantification of technical actions such as passing, crossing, and shooting in rehabilitation, which may present a potential risk of re-injury due to the associated musculoskeletal demands (Watanabe et al., 2018). Typically, in the team setting, notational analysis using video tracking multiple camera systems (VTS) is utilized to measure the technical actions within match-play (Barris and Button, 2008). However, the reliability of notational analysis has been questioned due to large variations between observers when tagging key actions (Duthie et al., 2003). Within the rehabilitation setting, where normally the process involves minimal staff working with the player in an on-pitch capacity, issues related to inter-variability between observers are not a major issue. Although the use of VTS to quantify technical actions may be a possible tool during rehabilitation to monitor the volume of these activities, there is currently no sports technology available to quantify the magnitude of these actions, and as such is a possible area where sports technology could in the future enhance rehabilitation processes within elite sport.

Load management

Although load monitoring is commonplace within the team-setting (Akenhead and Nassis, 2015), the concepts of load management and the development of chronic load should not be overlooked during the RTS process. As previously mentioned, Blanch and Gabbett (2016) proposed that how much the athlete has trained before RTS should be a critical aspect of the RTS decision. A survey of club teams and coaches across elite rugby union first highlighted that player's returning to competitive match-play early following injury face a heightened risk of re-injury (Beardmore et al., 2005), whilst another study from elite rugby union reported that 50% of recurring HSI's occur within one month after initial injury (Brooks et al., 2011). These findings were further supported by Orchard and Best (2002) who highlighted that most muscle injury recurrences occur within the first week of RTS, and the risk of re-injury may remain for several weeks. More recently, Finch et al. (2017) highlighted that alongside potential injury recurrence, the risk of sustaining new injury may also be greater in the acute period post RTS. The risk of re-injury or a new injury following RTS, presents a huge obstacle for success within elite sport, especially where player availability has been shown to be an important factor by allowing the manager or coach to select their strongest possible team (Hägglund et al., 2013; Carling et al., 2015). Bengtsson et al. (2019) highlighted in a cohort study of elite male football players higher injury rates in the first competitive match after RTS compared to the average seasonal match injury rate. It was also reported that injury rate was lower when players completed more training sessions prior to a return to competitive match-play. These findings potentially heighten the importance of completing enough training prior to RTS and developing chronic load during rehabilitation, using benchmark (pre-injury) data against which to assess players' and the provision of objective evidence to support players RTS (Ardern et al., 2016; Fuller and Walker, 2006).

Stares et al. (2018) further emphasized the importance of monitoring training loads during the RTS process in a study of Australian rules football players, demonstrating high running loads during rehabilitation protect against subsequent muscle injury. Despite the protective element against injury, it is important to note the on-pitch reconditioning phase was extended to develop chronic load before RTS. In elite football, extending a player's rehabilitation may not always be feasible given contextual factors or pressure from the management, but decision-making must balance early player availability with the potential risk of re-injury (McCall et al., 2017). Nonetheless, the concept of extended on-pitch reconditioning to prepare players training load demands akin to the demands experienced during team training, should not be overlooked nor should allow more team training sessions prior to a return to competitive match-play to reduce re-injury risk, especially in those players returning from long-term injury (>28 days) (Hägglund et al., 2005). Regarding short-term injuries with minimal time frame (1 to 10 days), less importance is given to chronic load aspects in the RTS decision, with emphasis placed upon certain metrics related to musculoskeletal demands placed on the specific injury type, contextual factors, and feelings of the player.

Although developing chronic load during on-pitch rehabilitation is important (Gabbett et al., 2016), consideration for how running load is progressed within rehabilitation may be overlooked. Previous studies in professional football and across other team sports, have highlighted that ‘spikes’ in load; defined as sudden increments in load are associated with increased injury risk (Ehrmann et al., 2016; Hulin et al., 2014; 2016; Malone et al., 2017). Several studies have demonstrated greater injury rates with high external training loads measured using GPS (Gabbett and Ullah, 2012; Colby et al., 2014; Bowen et al., 2017). However, the benefits of training, to improve physical qualities and the associated increments in running loads, may help to increase resilience and potentially offer protective benefits (Gabbett, 2016). Carefully planned programming, leading to the development of chronic running loads, may increase athlete durability. However, ‘spikes’ in running loads created in efforts to achieve chronic load targets too rapidly may result in high injury risk (Gabbett, 2016). Furthermore, from a practical perspective ‘spikes’ in week-to-week load may considerably increase the risk of injury, whilst exposure to extreme running loads, which surpass the load capacity of the athlete may also increase injury risk (Blanch and Gabbett, 2016). Despite the recommendations from a team-setting, these concepts present important considerations for the development of chronic load during rehabilitation. Logically, in the process of developing chronic running loads, athletic qualities can be developed such as aerobic capacity, which are relevant to both the sport and the players position and are vital to ensure adequate preparation for the demands of the game (Blanch and Gabbett, 2016).

The ‘Control-Chaos Continuum’ and Strength & Power Diagnostics

Regular strength and power diagnostic testing throughout RTS can provide the player and staff with positive, objective feedback on components of physical performance and build their confidence in the process. For example, following severe knee injuries such as ACLR, isometric and dynamic squat, isometric and isokinetic concentric/eccentric knee extension and submaximal bilateral countermovement (CMJ) can be implemented relatively early in the rehabilitation process. The information from these tests can be used to determine the player’s neuromuscular status and their progression in selected variables relevant to the test prior to entry to the on-pitch stage of the RTS process.

Regular strength and power (S&P) diagnostics such as DL-CMJ kinetics are an important feature throughout the ‘CCC - in addition to the standard use in the period assessment of status and chronic progress through R-RTS, this data also supports practitioners' decision-making around the phase and load progression (Taberner et al., 2020a). Note that the use of the term “S&P diagnostics” in R-RTS does not refer to the diagnosis of the injury, instead it denotes the detailed profiling of an athlete's strength and power or neuromuscular qualities, commonly applied to the healthy athlete. Diagnostics characterizes the underlying subcomponents of functional performance, including the neuromuscular characteristics of specific phases within jump-based tasks and time-related measures such as RFD within isometric strength assessments. Specific S&P diagnostics will be selected based on the type of injury and required loading demands within the sport (Glasgow et al., 2015). However, core assessments such as the DL-CMJ may be incorporated during R-RTS, as a global measure of neuromuscular performance (Taberner et al., 2020b).

As highlighted elsewhere in the certificate, functional tests such as the single leg hop for distance and other hop tests have historically been used as part of a risk evaluation and criteria for an athlete’s readiness for RTS (Ardern et al., 2016; Zambaldi et al., 2017; Burgi et al., 2019) via a limb symmetry index (LSI) with an LSI of 90% deemed acceptable (Burgi et al., 2019). Functional tests, however, typically, only provide output variables such as distance and height (Reid et al., 2007; Lauder et al., 2015). While reasonable clinical tools for the general population returning to normal activities or recreational sports following ACL reconstruction, for a number of reasons, this may not be adequate in high-performance and elite sports. Fundamental limitations in the context of ACL RTS for which these functional tests are principally applied include the “normalization” of output variables does not equate to a recovery of function at the knee and significant kinetic and biomechanical deficits identified may be present in the athlete with SLHD symmetry (Kotsifaki et al., 2020; Wren et al., 2017).

In addition, most functional testing assesses closed skill tasks whilst sport requires open skills with reactive elements alongside decision-making and sometimes in a fatigued state (Ardern et al., 2016). Functional tests and the parameters provided should therefore be the minimal level of information to support RTS decisions (Ardern et al., 2016). However, the jump-land kinetics along with isometric assessments available in most contemporary high-performance settings allow the consideration of multiple neuromuscular qualities across the force-velocity spectrum that reflect or contribute to maximal strength, reactive strength, rate of force development (RFD) and power - that relate to the demands of the athlete’s sport and position and ensure a comprehensive analysis of status (Maestroni et al., 2019). These assessments not only capture how force is produced but also how it is reduced - during deceleration (i.e. in the downward phase of the jump) and impact (landing), important aspects of function given both are linked to certain mechanisms of injury (Hewett et al., 2010; Oberhofer et al., 2017). Since persistent deficits in these capacities have been highlighted in jump-based tasks following RTS (Paterno et al., 2007; Cohen et al., 2014; Jordan et al., 2015; Hart et al., 2019; Read et al., 2021), basing RTS decisions on performance outcome-based variables alone may not provide an overall assessment of an athlete’s performance status.

Informing training prescription

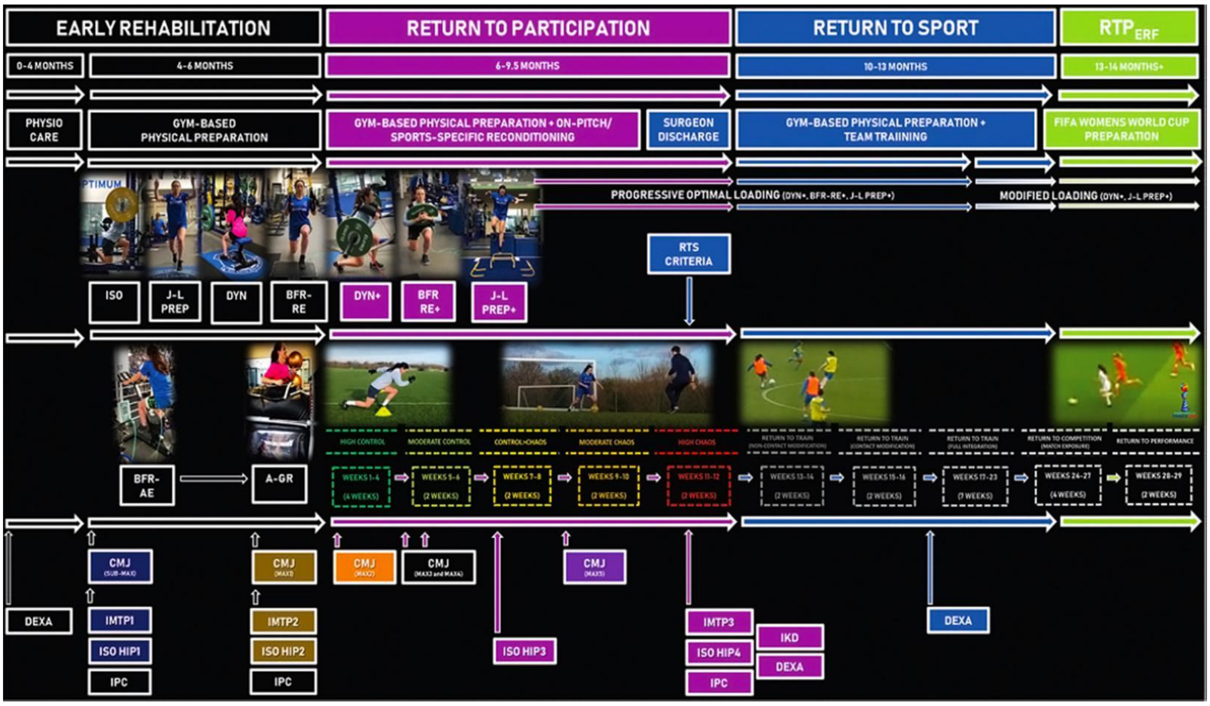
However, it is important to underline that the added value of S&P diagnostics-kinetics over functional tests is not only due to concerns with the precision or accuracy of the latter with respect to quantifying recovery of knee function post-ACL (Kotsifaki., et al, 2020) and to associations between "passing" these tests and re-injury risk (King et al., 2021). The value of S&P diagnostics in R-RTS also relates to how putting neuromuscular performance "under the microscope" with these assessments enhances insights into neuromuscular qualities or potentially regions within the range of motion driving/underlying ("localising") deficits in higher level outputs such as - jump height (in CMJ or DJ), or contraction (CMJ) or contact time (DJ). Localising these deficits can inform more specific and optimal loads and conditioning types and by the same token more precisely quantifies the effectiveness of these stimuli in driving the desired adaptations. Objectively and frequently monitoring the response to the loading stimulus applied during rehabilitation, can enhance the individualisation and potentially the efficiency of the rehab training prescription by allowing the practitioner to modify or "fine-tune" the loading stimulus. Therefore, while jump-land (and other dynamic) kinetics and isometric tests are classically applied periodically to quantify the neuromuscular status and chronic progress relative to 'benchmark' data to quantify progress, they may also be used more frequently to quantify shorter-term adaptations to loading. Within the context of the CCC R-RTS continuum, S&P diagnostics have the potential to support clinical reasoning around progression decisions.

The double-leg countermovement jump (CMJ) provides an assessment of triple extension performance output and strategy, indicative of the contribution of each limb in the actions of accelerating, decelerating, and landing at high velocity (Cohen et al., 2020). It is suggested that marked asymmetry for example in eccentric deceleration RFD may indicate a preference to break stride in on-pitch deceleration tasks using the uninjured leg, a potential avoidance strategy driven by a lack of confidence and capacity in loading the injured limb (Cohen et al., 2020). Identification of such deficits informs the loading strategy, as modifications to the optimal loading programme can be implemented to address such deficits whilst informing the on-pitch rehabilitation programme, such as restricting running volume. For example, following a hamstring strain injury (HSI), measurement of isometric peak force (McCall et al., 2015a; Read et al., 2019) and RFD (Taberner & Cohen, 2019) has the potential to support an on-pitch return to running and subsequent progression throughout on-pitch rehabilitation.

Informing phase progression decision-making

Differences between injury, position-specific running load demands and in player response to these demands mean that on-pitch rehabilitation cannot be a 'one-size fits all' approach. The large inter-individual variability in progress in neuromuscular qualities, underlines the importance of quantifying individual response to reconditioning alongside reference to healthy 'benchmark' data, if available. This contributes to more informed decision-making processes around conditioning prescription and phase progression based not only on expected, but also actual progression in specific neuromuscular qualities in a timely enough manner to modify prescription appropriately. This information, combined with achievement of on-pitch running load targets both across and within phases of the 'CCC' and beyond RTS, reduces the dependence on expected / predicted responses and healing time frames by providing an extra layer of objective information helping to support clinical reasoning and used to inform progression. Criteria considered in progression decisions include the achievement of running load targets and technical skill components, absence of pain/swelling (i.e., <2/10 numerical rating scale) and joint effusion, respectively - absence of pain being the most commonly reported criteria (Dunlop et al., 2020). Additional considerations also include player confidence to perform the required tasks (verbal communication based on perception of confidence scale, i.e., 0-10) and their subjective feedback (session rate of perceived exertion, i.e., 1-10 x training duration) (Allen et al., 2021).

Figure 4: An overview of the return to performance (RTPerf) of an elite female football player following ACL reconstruction (ACLR) with the timing of CMJ and other S&P diagnostic assessments



Source: Taberner et al., 2020

Short-term LRM in R-RTS

S & P diagnostics are also a means to quantify shorter-term (acute & residual) neuromuscular responses to increments in load or introduction of specific types, volumes and intensities of off- and on-pitch conditioning in transitions across or within phases. Implementing tests in this context is distinct from the periodic assessment of status that is more universally applied (which on the contrary should be performed under recovered conditions if feasible), to determine chronic adaptations. Instead, these tests aim to identify trends that might be indicative of maladaptive responses / abnormally slow recovery / excessive mechanical loading. In the R-RTS context this aims to obtain an indication of the player's overall and injured or uninjured limb fatigue via the residual response to the demands of on (or off) -pitch rehabilitation - in the former, examined in conjunction GPS quantified on-pitch load data. While there is substantial evidence supporting this approach in the LRM of healthy athletes (as discussed in the load response monitoring toolbox module), its application in R-RTS athletes has only been described in the literature in a case study in an elite female footballer (Taberner et al., 2020a), has not been described in the literature.

In summary, in addition to the objective evaluation of neuromuscular performance status – i.e., asymmetries and performance at periodic timepoints in rehab and at RTS - S & P kinetics inform on the early response to load during gym-based physical preparation, contribute to decision-making processes surrounding the initiation of return to on-pitch activities and to progression decisions within and between phases of the CCC by quantifying load-response to on- and off-pitch progressive loading. providing which can inform decision-making processes across the continuum – through the rehab and RTS pathway and beyond– through return to performance and competition. In section 2, we elaborate on the concepts described above, with particular reference to the rehabilitation of the elite footballer.

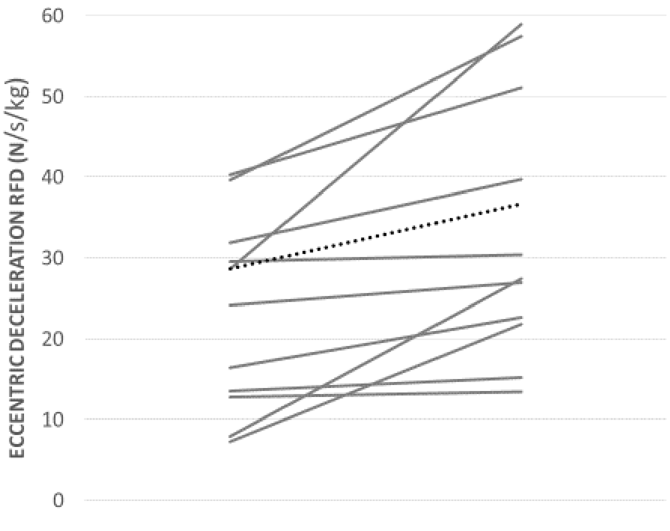
4.2 The Kinetic Framework & Toolbox

The framework refers to the concepts and paradigms that can help guide and inform the delivery and use of S&P diagnostics and the derived data during rehabilitation.

Interindividual variability in progress through R-RTS

While there are expected timelines for return following a given injury, it is well-recognised that these can vary substantially. Irrespective of this variability, in professional sports there is also pressure to accelerate this return in the players most valuable to a team. Critical to the value of integrating kinetics in R-RTS is its capacity to quantify and inform on individuals' neuromuscular recovery/progress - one component of recovery. While "time is a healer", evidence suggests that following ACL-R, a lack of association is reported between time since surgery and deficits (Myer et al., 2012). Published evidence shows large interindividual variability in ILA metrics across rehab time points based on standard deviations and confidence intervals reported in the serial cross-sectional study of Read et al (2021) and Miles et al (2019), and the SGP-ACL (shown in the Kinetics in ACL injury, rehab and RTS module). Variability in response or trajectory of metrics and % ILA during rehab is evident even in an apparently homogenous group - this is illustrated in figure 5 which shows individual trends in the involved limb values in DL-CMJ assessments at two-time points during rehab following ACL-R, in professional footballers (SGP-ACL).

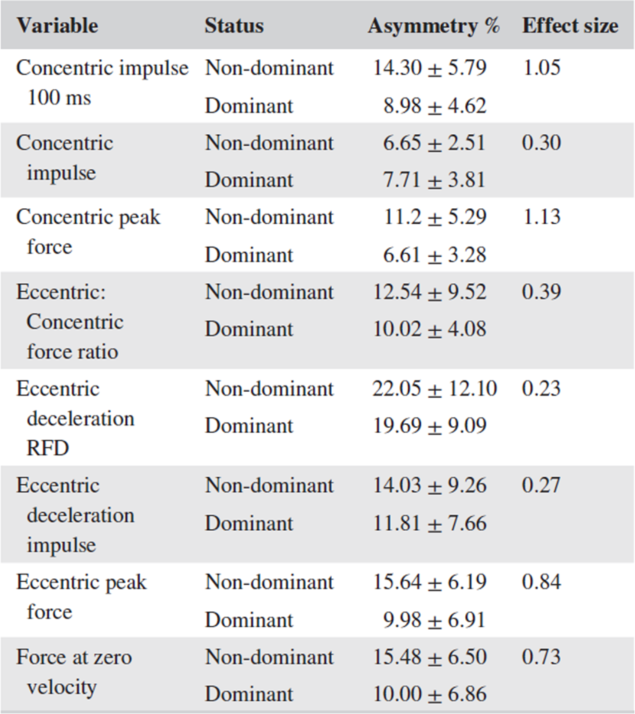
Figure 5: Changes in Injured Limb Eccentric Deceleration RFD in Professional Footballers in Rehab Following ACL-R



Each line is an individual player's (n=11) absolute eccentric deceleration RFD/kg in the injured limb, obtained in DL-CMJ assessments at two time points during rehab. Dashed line is the mean value for the group - mean increase was significant (p=0.02)
Source: Authors own elaboration (SGP-ACL)

The work of Hart et al., in healthy professional footballers with prior severe lower limb injury (i.e., residual asymmetries post-RTC) suggests that one of the determinants of the magnitude of ILA % post-injury is whether this occurred in the dominant or non-dominant limb; significantly higher values were noted for specific variables if the dominant limb was injured (see table 1). This aligns with anecdotal observations in athletes for whom benchmark (preinjury) data is available, that the preinjury ILA profile of the athlete – direction and magnitude have a strong influence on values they express in rehab. Large differences are evident for example in concentric impulse-100 and concentric peak force (ES > 0.8) but only small differences in concentric impulse or eccentric deceleration RFD (ES < 0.5).

Table 1: Countermovement jump asymmetry % (mean ± SD) in Healthy Professional Footballers with Dominant (N = 11) versus Nondominant (N = 6) Prior Severe Lower Limb Injury



Variable	Status	Asymmetry %	Effect size
Concentric impulse 100 ms	Non-dominant	14.30 ± 5.79	1.05
	Dominant	8.98 ± 4.62	
Concentric impulse	Non-dominant	6.65 ± 2.51	0.30
	Dominant	7.71 ± 3.81	
Concentric peak force	Non-dominant	11.2 ± 5.29	1.13
	Dominant	6.61 ± 3.28	
Eccentric: Concentric force ratio	Non-dominant	12.54 ± 9.52	0.39
	Dominant	10.02 ± 4.08	
Eccentric deceleration RFD	Non-dominant	22.05 ± 12.10	0.23
	Dominant	19.69 ± 9.09	
Eccentric deceleration impulse	Non-dominant	14.03 ± 9.26	0.27
	Dominant	11.81 ± 7.66	
Eccentric peak force	Non-dominant	15.64 ± 6.19	0.84
	Dominant	9.98 ± 6.91	
Force at zero velocity	Non-dominant	15.48 ± 6.50	0.73
	Dominant	10.00 ± 6.86	

DL-CMJ absolute ILA% in healthy players who had either suffered from a dominant limb or non-dominant severe lower limb injury in the previous 12 months.

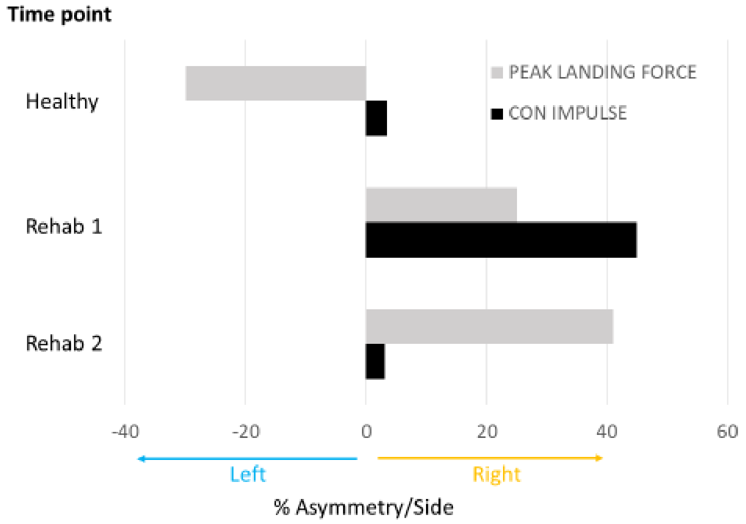
Source: Hart et al., 2019

Given the emphasis of LRM in R-RTS being on assessing and understanding progress in the individual response to reconditioning, it is of interest to further understand which factors influence the trajectory of neuromuscular progress through rehab. There is evidence that genetic factors via single nucleotide polymorphisms (SNP) (variations in DNA sequence) influence the length of recovery from, and severity of, soft tissue injury. For example, in an analysis of 73 elite footballers, Pruna et al., (2013) found that amongst players with ligament injury, return from injury was significantly shorter (mean 24.7days) in those with the ELN AG genotype than those with the ELN GG (mean 37.5 days) or AA (mean 83.2 days) genotypes. There are also studies in healthy athletes showing that SNP influences the degree of susceptibility to exercise-induced muscle damage (Baumert et al., 2016). Therefore, there are non-modifiable factors that modulate the effect of the injury itself and the athlete's response to the reconditioning exercise embedded in rehab - that will influence the rate of recovery. The phenomenon of responders and non-responders to chronic exercise is also described in healthy individuals (Pickering & Kiely., 2019). In healthy athletes, physical capacity qualities such as strength and power can modify the interindividual variation in the recovery profile / residual response to the demands of competition (Johnston et al., 2015; Norris et al., 2019), and may also contribute to variability during R-RTS.

Pain measures, inflammation and scans may inform on the rate of healing and acute response to loading, kinetics provide granular objective measures of the neuromuscular response during this process. The potential to quantify the variability described and provide detailed insights as to the individual response to reconditioning to then better inform more targeted, efficient and individualised "precision" training prescription is at the core of the value proposition for the integrating of the force platform and other S&P diagnostics into R-RTS. Indeed, it is suggested that inadequate individualisation and an over-reliance on traditional time-based criteria for rehabilitation progression and RTS is contributing factor to the substantial number of players who do not return to sport after a severe injury such as ACLR, or who return and re-injure the same or a different tissue (Taberner et al, 2022). The corollary-enhancing individualisation across the pathway has the potential to positively influence outcomes.

A comprehensive analysis of kinetic ILA's also reveals divergent trends in different metrics across rehab within athletes, as shown in figure 6. The left knee injury has driven large increases in right limb ILA in both metrics (with pre-injury values available for the player). It also shows that between two DL-CMJ assessments performed 6 weeks apart during rehab, there was an improvement (reduction) in concentric impulse ILA %. However, peak landing force ILA % increased - suggestive of an increased landing impact force avoidance strategy - despite the positive response in the force production (upward/concentric) phase.

Figure 6: Trends in concentric impulse and peak landing force asymmetry in DL-CMJ during rehabilitation following a knee injury and healthy pre-injury values: a case study in elite footballer



CON=Concentric; Asymmetry % and direction (bar to left = left asymmetry, bar to right = right asymmetry) for DL-CMJ assessments performed at 3-time points: Healthy=athlete's healthy preinjury "benchmark" assessment; Rehab 1= Assessment at first clearance to perform jump during rehab; Rehab 2= Assessment performed 6 weeks after rehab 1, prior to the transition to increased high-speed change of direction

Source: Authors' own elaboration

Bilateral Performance and "Alternative" Kinetic Metrics

Which metrics to monitor?

What metrics should I look at? The eternal question - is whether to monitor the healthy or injured athlete. In the Kinetics in ACL injury, rehab and RTS module we focused on ILAs in the DL-CMJ and identified those that most differentiated the injured and non-injured athlete during rehab and post. We also presented data which demonstrated that within the same injury, ILA response varied according to graft type, and highlighted how metric choice may vary in injury subpopulations. This is the type of information that further contributes to the enhanced individualisation of monitoring of the response of identified injury-specific deficits to reconditioning. It also underlines the value of ongoing comprehensive ILA analysis to create precision monitoring "signatures" across other injury types and subtypes. This data is presented in the Kinetics in ACL injury, rehab and RTS module but a summary of the asymmetry metrics in each phase with the largest effect size difference between injured (assessed during rehab) and non-injured players is given in table 2.

Table 2: Selected DL-CMJ Asymmetries in professional footballers 5 months post ACLR (n=39) v Controls (n=24).

Metric	Control	ACL	P value	Effect size
Downward (Eccentric) phase				
Deceleration RFD	9.6 (8.9)	28.8 (17.1)	<0.001***	1.32
Eccentric RFD	13.4 (11.5)	22.8 (13.3)	0.01**	0.75
Force @ Velocity	10.3 (8.8)	18.4 (10.6)	0.003***	0.81
Upward (Concentric) Phase				
Impulse	5.9 (4.2)	18.3 (8.8)	<0.001***	1.67
Force@PeakPower	4.2 (2.9)	17.9 (8.9)	<0.001***	1.89
Landing Phase				
Impulse 70 ms	14.5 (8.7)	36.7 (22.8)	<0.001***	1.18

Peak Force	10.0 (6.5)	25.7 (16.9)	<0.001***	1.13

Source: Authors own (SGP-ACL)

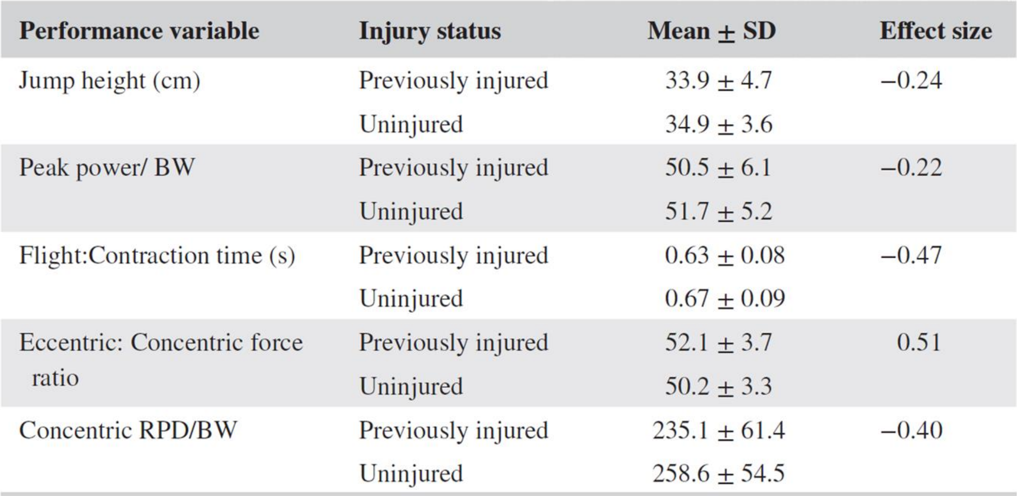
Kinetic asymmetries and classic performance outputs (jump height, concentric peak power) are still the common “go-to” bilateral metrics reported when monitoring players during rehabilitation (Read et al., 2021; Costley et al., 2023; Cohen et al., 2020; SGP-ACL). We also indicated above that other metrics should be considered and incorporated into progress reports in R-RTS. This includes the “alternative”, CMJ kinetic variables, now well established as variables with greater sensitivity to residual fatigue, positive adaptations to loading and effects of specific unloading and recommended in load response monitoring (LRM) of the healthy athlete. In addition, these variables and others that describe movement technique during the jump provide context which improves the classification of values and changes seen in ILA. These may help explain and better understand a trend, or it may alter its interpretation. Examples of this are shown below, but first, let’s examine the bilateral CMJ-kinetics.

Alternative Bilateral Metrics in R-RTS

These metrics may also help to identify the origin of a deficit in an output such as jump height in the CMJ or jump height and contact time in the DJ, along with waveform inspection. Neuromuscular status or qualities that are inferred from the kinetic metrics derived may or may not reveal a divergent trend to that of performance outputs, but they provide phase and sub-phase or force, velocity, time, and displacement insights that are likely to improve the practitioners insight ability to localise – in terms of phase body position or neuromuscular quality the driver or determinants of deficient functional outputs, potentially informing a shift in emphasis or focus in training prescription than was planned.

Consider the table below from Hart et all’s (2019) comparison of the DL-CMJ bilateral variables in healthy professional footballers with or without prior severe injury. Although differences are not significant, differences between the groups are more pronounced (larger effect sizes) for CMJ-kinetic variables that represent either time constrained performance (FT: CT or Con RPD-100) or indicative of altered force production strategy (Eccentric: Concentric force ratio) than differences in the typical reported metrics - jump height and concentric peak power.

Table 3: Bilateral countermovement jump variables in Healthy Professional Footballers with (N = 17) or without (N = 17) Prior Severe Lower Limb Injury



Performance variable	Injury status	Mean ± SD	Effect size
Jump height (cm)	Previously injured	33.9 ± 4.7	−0.24
	Uninjured	34.9 ± 3.6	
Peak power/ BW	Previously injured	50.5 ± 6.1	−0.22
	Uninjured	51.7 ± 5.2	
Flight:Contraction time (s)	Previously injured	0.63 ± 0.08	−0.47
	Uninjured	0.67 ± 0.09	
Eccentric: Concentric force ratio	Previously injured	52.1 ± 3.7	0.51
	Uninjured	50.2 ± 3.3	
Concentric RPD/BW	Previously injured	235.1 ± 61.4	−0.40
	Uninjured	258.6 ± 54.5	

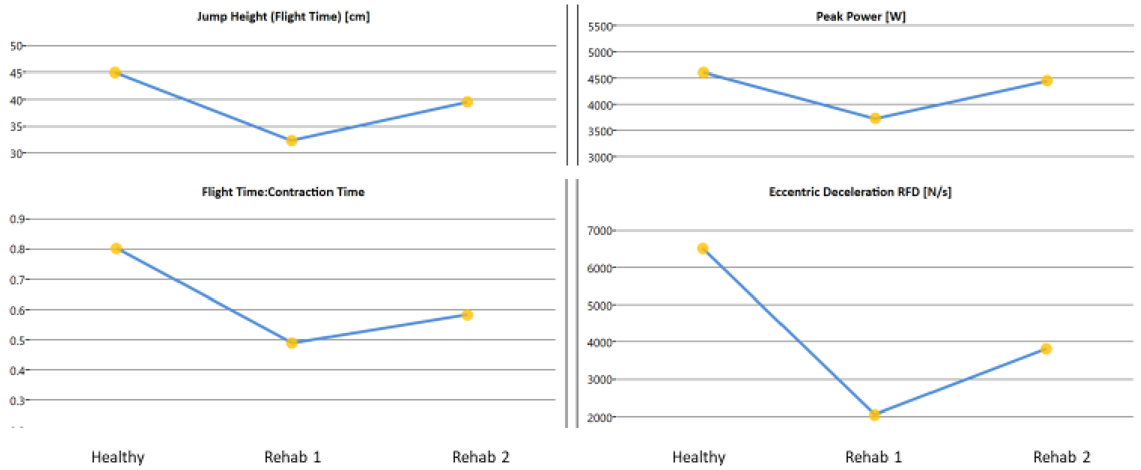
BW=body weight; RPD=rate of power development. Effect size classification < 0.2=trivial; 0.2 - 0.5 = small; 0.5 - 0.8 = moderate

Source: Hart et al., 2019

While the lack of significance may be partly due to the relatively small sample of 17 in each group, it is also likely due to real interindividual variability in response. Overall, this data suggests that while there is a tendency for the CMJ-kinetic variables to be less recovered / more affected by prior injury the deficits may not be large or they are not consistent across all rehab outcomes. Read et al., 2021 did not report bilateral CMJ kinetic variables but did highlight that in professional players, at over 9 months post ACLR surgery in addition to elevated DL-CMJ ILA’s mean jump height was significantly lower (30.7 cm SD: 4.6) than in non-injured counterparts (34.5 cm SD: 4.0).

Anecdotally - we observe that there are athletes for whom jump height is slower to recover following injury than CMJ-kinetics and others for whom examining jump height and concentric peak power alone will give a misleading impression of progress and recovery. As seen in figure 7 below, status relative to the athlete’s healthy benchmark, and trajectories of recovery may differ in these metrics – as they do in healthy athlete LRM.

Figure 7: Trends in “typical” versus “alternative” bilateral metrics and healthy pre-injury value during rehabilitation following knee injury: case study in an elite male footballer

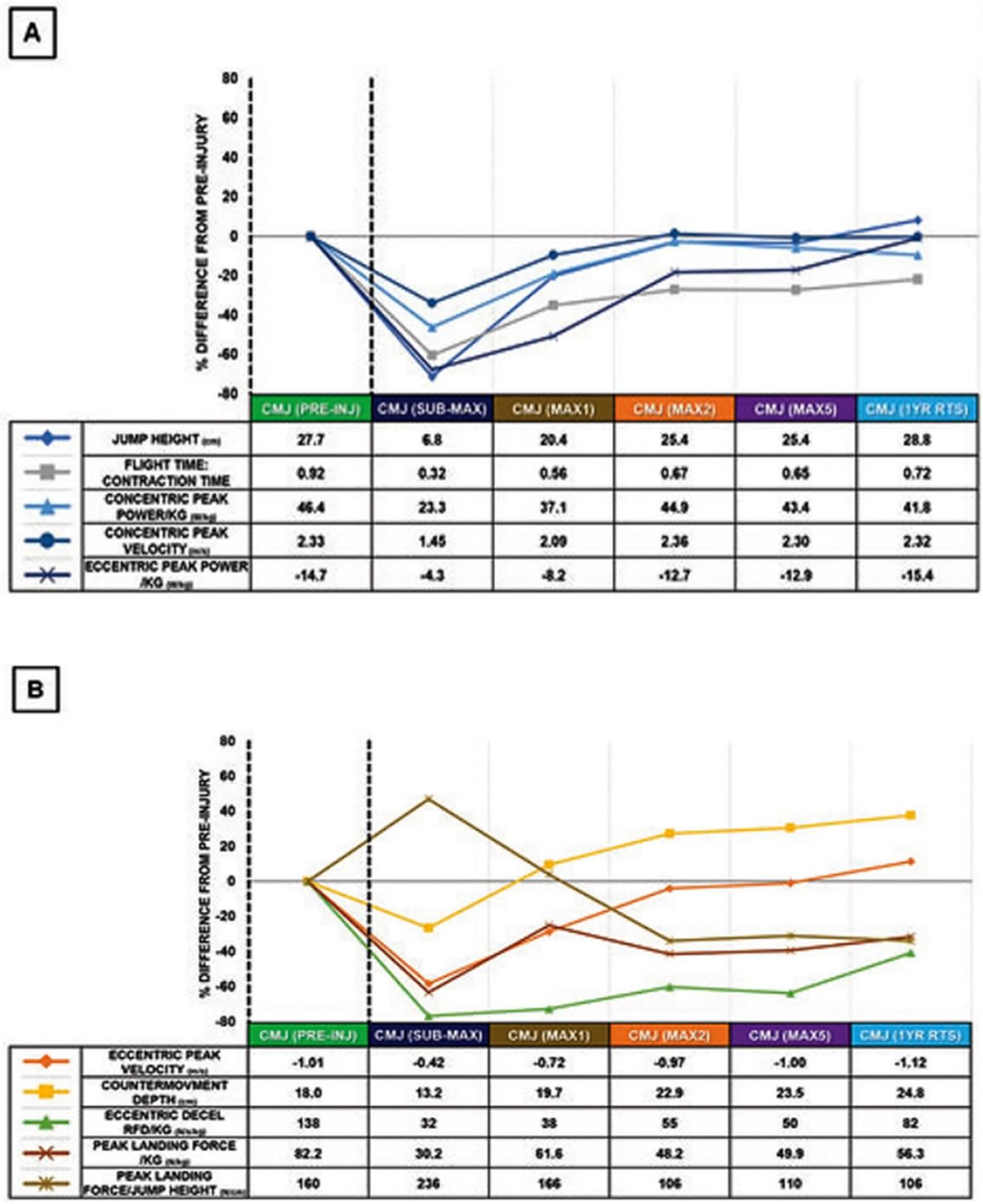


Mean of 3 trials of DL-CMJ performed at three time points: Healthy=athlete’s healthy preinjury “benchmark” assessment; Rehab 1= 1st clearance to perform jump during rehab; Rehab 2= Approximately 6 weeks after rehab 1, prior to transition to increased high-speed change of direction

Deficits in jump height and concentric peak power (i.e., relative to healthy benchmark values) were -12 and -4% respectively, whereas corresponding deficits in FT: CT and eccentric deceleration RFD were 27% and 41%, respectively. In this case, the CMJ-kinetics identified deficits / divergent progress in neuromuscular qualities not expressed in typical outputs such as jump height and concentric peak power.

In figure 8 below, shows the DL-CMJ data of an elite female player pre-injury, at several time points during rehab and post-return (Taberner et al., 2020). Metrics within the tests display a wide range of magnitudes of deficit relative to preinjury are evident at 1st (sub max) assessment, and varying trajectories of recovery thereafter. Trends at each assessment are considered in conjunction with other force and impulse metrics - with total, involved-uninvolved and ILA % (e.g. figure 10 below) - and in the context of load demands of the prior and subsequent phase (as discussed above). Note that certain metrics did not revert to preinjury values even after 1-year post-RTS; FT: CT, CM depth, Eccentric Deceleration RFD, absolute and jump height relative to Peak Landing Force. The relevance of this is discussed below.

Figure 8: DL-CMJ Bilateral Metrics During Rehab Following ACL-R - Trends in Selected Relative to Pre-injury Values: Case Study Elite Female Footballer



		CMJ (PRE-INJ)	CMJ (SUB-MAX)	CMJ (MAX1)	CMJ (MAX2)	CMJ (MAX5)	CMJ (1YR RTS)
◆	JUMP HEIGHT (cm)	27.7	6.8	20.4	25.4	25.4	28.8
■	FLIGHT TIME: CONTRACTION TIME	0.92	0.32	0.56	0.67	0.65	0.72
▲	CONCENTRIC PEAK POWER/KG (W/kg)	46.4	23.3	37.1	44.9	43.4	41.8
●	CONCENTRIC PEAK VELOCITY (m/s)	2.33	1.45	2.09	2.36	2.30	2.32
✕	ECCENTRIC PEAK POWER /KG (W/kg)	-14.7	-4.3	-8.2	-12.7	-12.9	-15.4

		CMJ (PRE-INJ)	CMJ (SUB-MAX)	CMJ (MAX1)	CMJ (MAX2)	CMJ (MAX5)	CMJ (1YR RTS)
◆	ECCENTRIC PEAK VELOCITY (m/s)	-1.01	-0.42	-0.72	-0.97	-1.00	-1.12
■	COUNTERMOVMENT DEPTH (cm)	18.0	13.2	19.7	22.9	23.5	24.8
▲	ECCENTRIC DECEL RFD/KG (N/s/kg)	138	32	38	55	50	82
✕	PEAK LANDING FORCE /KG (N/kg)	82.2	30.2	61.6	48.2	49.9	56.3
✱	PEAK LANDING FORCE/JUMP HEIGHT (N/cm)	160	236	166	106	110	106

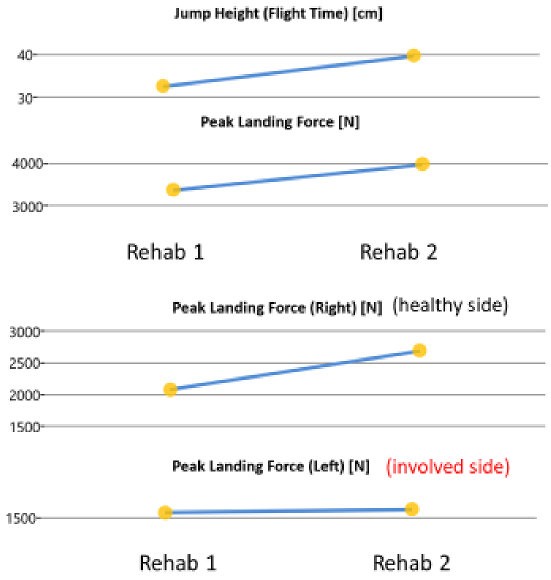
Mean of 3 trials of DL-CMJ. TIme points of pre-injury were 2 months prior to injury (in-season), submaximal and maximal tests performed approximately monthly from 4 months post-ACLR.

Source: Taberner et al., 2020

Individual limb outputs “versus” ILA

In DL-CMJ (and other DL test) monitoring, the trends in individual limbs’ absolute values for force, RFD and impulse are often overlooked with the product of this data - asymmetry (ILA) % focused on. In R-RTS, once 2 timepoints are available (i.e., in longitudinal monitoring) the raw data from which asymmetries are calculated - involved and uninvolved limb values - should also be considered, in **conjunction with** total (involved + uninvolved) values and ILA % asymmetry. Examining the separate involved and uninvolved limb trends, in the context of total values provides additional insights beyond the ILA asymmetry trend alone. Consider the data in figure 9 below, showing trends in absolute peak landing force values - total, involved and uninvolved limb - between two the time points of rehab during which peak landing force asymmetry increased from 25% to 41% - in the player shown above in figure 6. Jump height trends are also displayed since an increase would, via an increase in landing velocity, be expected to also increase landing (impact) force. This data explains the asymmetry trends - showing that despite the substantial increase in total landing peak force, the involved limb shows stable values. This suggests that capacity, willingness to load the involved limb on landing has not progressed and the uninvolved limb has to “attenuate” all of the additional load.

Figure 9: Trends in jump height, total and individual limb peak landing force during rehabilitation following knee injury: a case study in elite male footballer



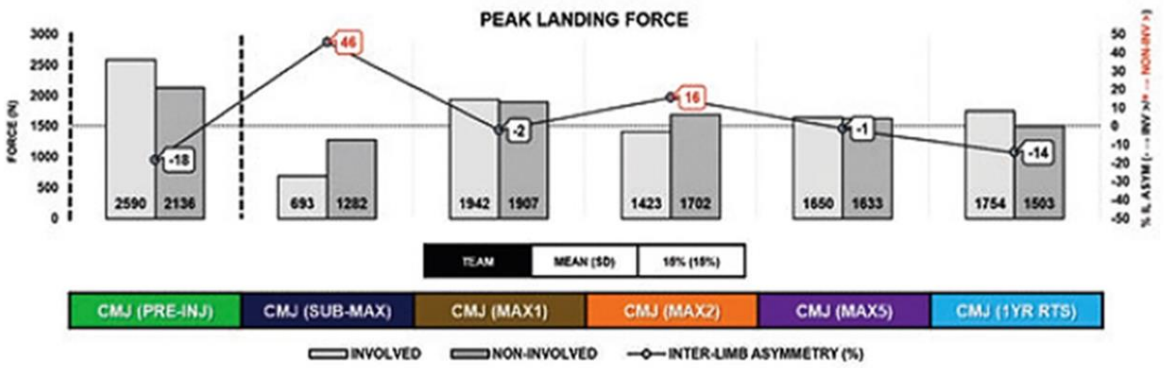
Mean values of 3 trials of DL-CMJ assessments performed at two timepoints during rehab approximately 6 weeks apart.

Source: Authors own elaboration

In the case shown in figure 9, examining individual limb and total values for the metric plus a determinant - jump height - provides context and understanding but wouldn't change the conclusion reached by observing an increase in asymmetry from 25-41%. However, in other cases, the additional information does alter the interpretation of an asymmetry trend, particularly when considering eccentric/downward phase ILAs.

Contrast the trend in figure 9 with that seen below in a female player between a sub-max test in which her jump height was 6.8 cm and her first max test in which she jumped 20.4 cm and peak landing forces increased from c.2000 to 4000 N. In her case, in the sub-max test, she showed a large avoidance strategy (46% asymmetry) but in the max test her involved limb peak landing had increased by more than 100% to (693 to 1492) and the asymmetry was now 2% (favouring the involved side). Increase in absolute and relative load attenuation and reduced avoidance - all indicating progress.

Figure 10: DL-CMJ peak landing force ILA% and involved and uninvolved limb values pre-injury, during rehab and 1-year post return to competition: Case study elite female footballer.



Absolute values for each limb show within each bar (light grey=involved (left), dark grey = uninvolved (right). Call-out boxes show ILA % and direction (-ve = left dominance, +ve = right dominance). Team = mean (SD) for absolute ILA% based on preseason assessment.

Source: Taberner et al., 2020

In R-RTS, one of the most important contextual factors that may alter your interpretation of trends in variables and in asymmetries is the athlete's status and subsequent changes in the centre of mass (COM) displacement (height) and velocity. This may be seen in the landing phase as shown in figure 9, but more often during the eccentric/downward phase of the jump. From the CMJ COM-displacement-time curve, we can obtain COM-position and estimate COM-position changes at key events such as the maximum countermovement depth (CM depth) at the end of the eccentric/downward phase. COM position aligns with peak knee flexion (Sahrom et al., 2021) and therefore we can obtain an indirect (or "proxy") indicator of knee flexion even though vGRF-derived COM is not joint-specific. However, a change in CM depth might be due to an increase in trunk flexion at the end of the downward phase with no change in knee flexion, or to a change at the knee.

In the context of rehab, COM displacement (and velocity) during the downward phase can provide the practitioner with some objective characterisation of injury-induced changes in the athlete’s willingness, confidence and capacity to rapidly load in eccentric knee flexion and go into knee ROM, and of the response and recovery of deficits in these through the pathway (Taberner et al, 2020; Cohen et al, 2020). Conversely, less CM depth may be due to deliberate restraint to avoid pain in deeper knee flexion. The female player in figure 8B shows a reduced CM depth (5 cm less CM depth in her first (submaximal) DL-CMJ assessment than in her preinjury test early in rehab, due to her limiting knee flexion - as can be observed in figure 8B in the female player.

Decreased eccentric peak velocity (EPV) is consistently observed after an injury. For example, the player in figure 8 had a preinjury EPV of 1.01 m/s, and 0.72 in her first maximal DL-CMJ, while in the sub-max test it was 0.42.

It is not uncommon during rehab to observe a trend that is both counterintuitive and on face value indicative of poor progress; an athlete displays a very low eccentric asymmetry in an early rehab assessment, and in an assessment, after a period of conditioning the magnitude of asymmetry increases substantially. An example of this is shown in table 4, in which a player’s eccentric deceleration RFD ILA % increases from 14% to 28%, a trend which appears paradoxical in terms of the progress observed in jump height for example. However, the large (> 20%) increase in EPV, itself a positive marker of increased willingness and confidence to descend rapidly, creates a large increase in the deceleration demand at the end of the downward/eccentric phase before reversing direction. However, unlike the example given above in figure 9, in which the increase in jump height has contributed to an overall increase in loading demands and the involved limb not assumed any of the additional loadings, in the present case the involved does show a more than 10% increase in eccentric deceleration RFD but the large increase in asymmetry is due to a much larger relative increase on the uninvolved side. Therefore, by taking into consideration not only %ILA but also individual limb data, EPV, as well as the other bilateral metrics, the insights become more complete. One that demonstrates progress rather than regression - albeit with a need to ensure that the involved limb receives an adequate deceleration development stimulus.

Table 4: Trends in Asymmetry %, Involved and Uninvolved Limb Absolute Values and Bilateral Metrics During Rehab Post-ACLR: Case Study Male Professional Footballer

	Involved and Non-Involved Limb & ILA %						**Bilateral**		
Time	**Eccentric Deceleration RFD**			**Concentric Impulse**			**EPV (m/s)**	**JH (cm)**	**CT (ms)**
	Inv N/s	Uninv N/s	ILA %	Inv N.s	Uninv N.s	ILA %			
1	2063	2344	14	285	382	13	1.26	34	926
2	2457	3499	28	304	340	11	1.53	44	821

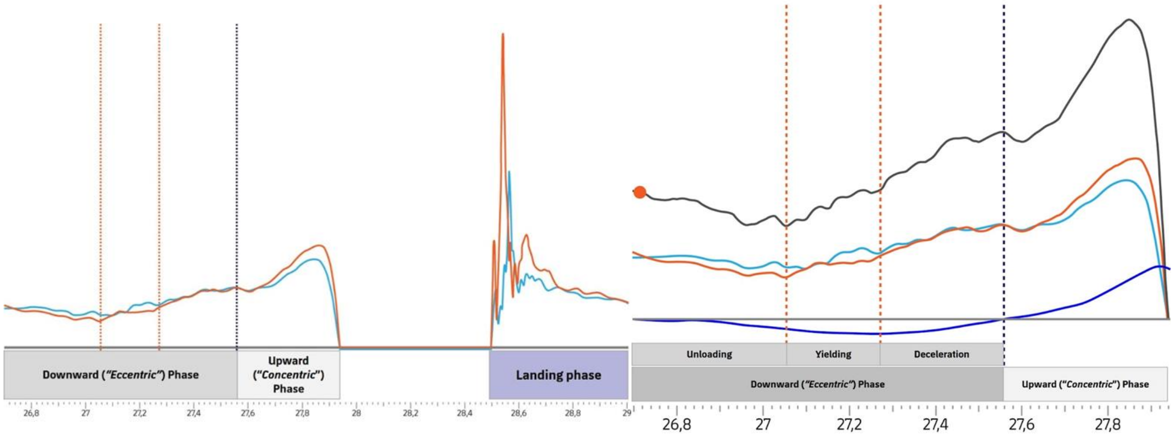
Inv=Involved limb; Uninv=Uninvolved; EPV=Eccentric Peak Velocity; JH=Jump height; CT=Contraction time. Time 1 and 2=1st and 2nd assessment.

Source: Adapted from Cohen et al., 2020

The left panel of figure 11 below shows the left and right force-time curves in a professional footballer during rehab following a left-side ACLR. On visual inspection, there is unexpectedly low asymmetry evident and indeed ILA values for this trial were 2.7% in eccentric deceleration impulse and approximately 8% in eccentric deceleration / eccentric RFD, which are far below mean values for those metrics at that time point (see table 2 above). Larger asymmetries are evident in the concentric (force @ concentric peak power ILA% =19.1) and landing phases (peak landing force ILA= 45.3%). It is evident from visually inspecting the force-time curves, that unweighting is limited and the slope of the rise in force from the start of the yielding phase is very shallow, and adding the velocity-time curve a low EPV value (0.78 m/s) is also evident.

Figure 11: Force-time and Velocity-time Curve in Post-ACLR Professional Footballer with Low Eccentric (Downward) Phase Kinetic Asymmetries.

A: Left and right force-time curves **B: Plus total vGRF, velocity-time**



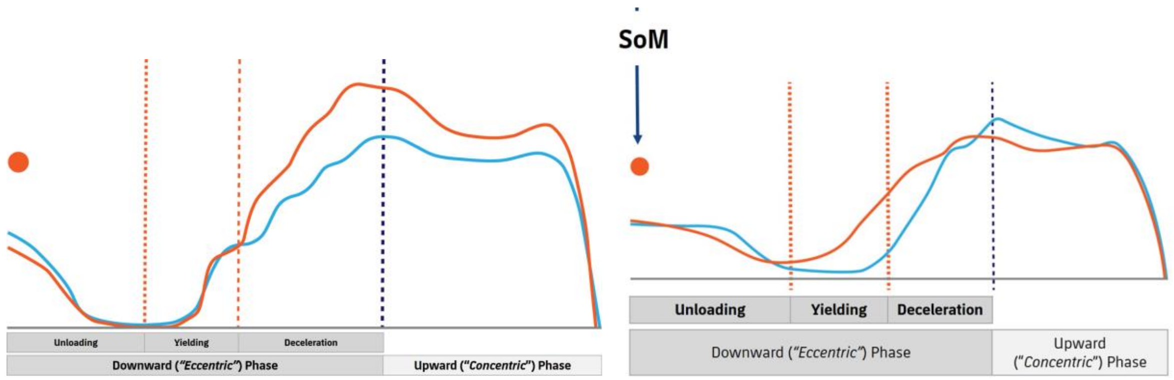
Light blue line=involved limb; Orange=uninvolved; Black=total vGRF; Dark blue=Velocity

Source: Authors own elaboration (SGP-ACL)

This strategy might explain the exceptionally low eccentric asymmetries - the deceleration demand has been self-limited via a large reduction in negative (downward phase) deceleration.

Another aspect of visual inspection in the interpretation of data relates to the use of eccentric deceleration versus eccentric RFD ILA %. As shown in figure 12, the latter (more commonly reported) is calculated as the slope of force (force change/time change) from the start of the deceleration phase to the end of the downward phase while the latter begins the slope calculation at the start of the yielding phase (also ending at the end of the downward phase). Figure 12 shows two types of eccentric/downward phase asymmetry patterns, that can be identified on visual inspection of the left and right force-time curves and which will also impact the two ILA% variables mentioned. These two patterns should be recognised as for example ILA can be fully characterised within the downward using eccentric deceleration RFD in the A panel pattern and deceleration impulse would give very similar values. In the B panel pattern, the impulse and RFD ILA magnitude and direction are paradoxical (impulse higher values on the side, RFD higher on the opposite) because a different strategy is evident whereby high rates of loading are avoided on the right during the more demanding deceleration by having an earlier and lower rate, beginning in the yielding phase.

Figure 12: Left and right force-time Curves showing common eccentric (downward) phase patterns



A: EDRFD ILA pattern **B: E-RFD (yielding) ILA pattern**

SoM=start of movement; Orange line=Right limb, Blue=left limb.

Source: Authors own elaboration

Additional considerations in interpreting trends in the injured athlete

As mentioned above, our interpretation of a trend is often based on and biased by our interpretation of trends in that variable in the context of the healthy athlete LRM (and associated evidence base). There are caveats / additional factors to consider when interpreting trends in them, in an injured athlete. In reference to the elite female player, as discussed (and shown in Figures 8A and B above) her FT: CT and CM depth remained below preinjury values at RTS and in an assessment following a successful return to competition. In healthy players, a decreased FT: CT is considered to be indicative of residual neuromuscular fatigue following competition (Cormack et al., 2008), and associated with reduced high-speed running performance (Cormack et al., 2013), and an increase, a positive adaptation to loading and improvement in SSC function (Lonergan et al., 2021). However, the player achieved a new maximal speed after returning after ACLR and the increased CM depth underlying the extended contraction time component of FT: CT appears to be a chronic alteration in CMJ strategy. It also represents a reduction in stiffness during the downward phase of the jump, also displayed in her landing force trends; reduced absolute peak and peak relative to jump height (figure 8B). Therefore, a trend that would be interpreted as a negative adaptation in the healthy athlete, paradoxically, appears to represent a positive one in the context of rehab. It should be noted that this may be specific to the female athlete - for whom higher landing forces and landing stiffness (in the DJ) have been associated with an increased risk of ACL re-injury. Furthermore, Collings et al (2022) found that in female footballers, higher DL-CMJ concentric peak force (total not ILA%) was associated with increased prospective risk of ACL (combined 1st and reinjury). In contrast, stiffness and higher forces were associated with a lower risk of ACL reinjury in male athletes (King et al.,2021).

The single-leg countermovement jump

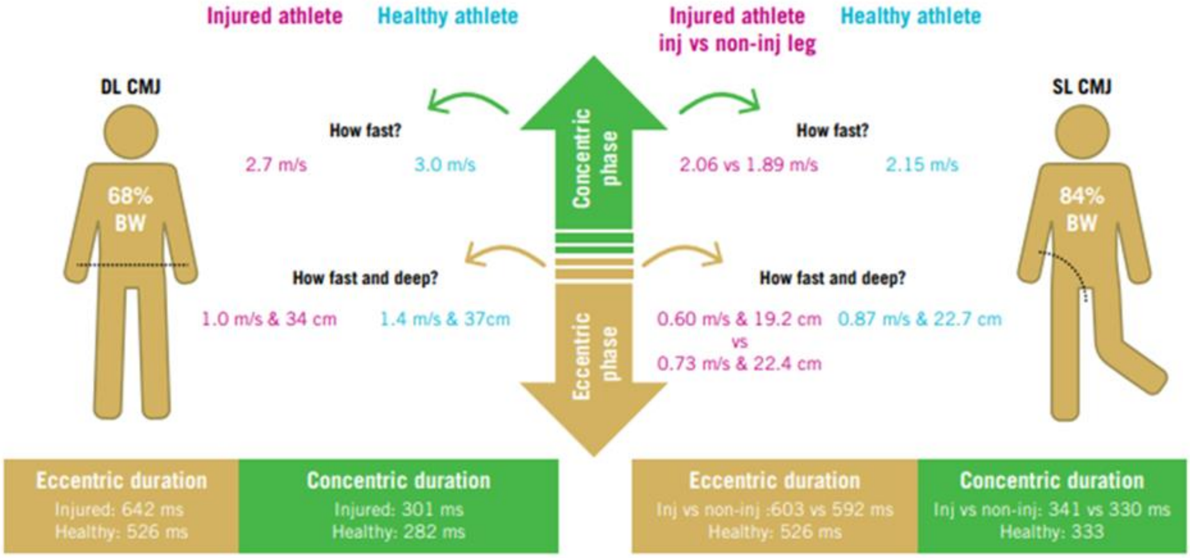
It is clear throughout the certificate that the DL-CMJ has become the core test in high-performance settings with force platforms. It has been highlighted in several places that the single-leg (countermovement) jump SL-CMJ test can also provide valuable information. It has however received less attention in this certificate, which is in accordance with the more limited research conducted on SL-CMJ assessment on force platforms examining potential information gain provided by kinetics in the test over that provided by jump height alone - a key focus of the certificate. It is also far less commonly used within high-performance settings in LRM.

However, if (dual) force platforms are not available, asymmetry cannot be determined simultaneously with other COM performance and kinetic metrics and ILA % and should be determined using single limb assessments – whether using the CL-CMJ, SL-DJ or hop tests. However, if force platforms are available, and DL-CMJ ILA% is being obtained, a question that often arises does the SL-CMJ ILA% adds value or should be used instead of the DL-CMJ data.

Fundamentally, incorporating additional assessments is justified on the basis that they provide enhanced insights, that better define injury status and more accurately classify readiness to return, reveal neuromuscular deficits/lack of progress in neuromuscular qualities and can detect and localise positive and negative responses to specific loading, to better inform training prescription.

Both SL and DL-CMJs are dynamic triple extension assessments, but as shown in figure 13 compared to the single-limb jump tests, the DL-CMJ has a higher velocity, particularly during the downward phase in healthy and post-ACLR athletes (Cohen et al., 2020). As highlighted above, the challenge associated with decelerating body mass at higher downward phase (eccentric peak) velocity in the DL-CMJ creates demands which reveal ILA / deficits that may not manifest with lower velocity demands - suggesting it is an important feature of the assessment (and DJ or drop-land assessments which create extrinsic deceleration demands in impact). The DL-CMJ also involves substantially greater countermovement depth than the SL-CMJ reflecting greater knee flexion during the movement. This may explain why SL-CMJ jump height ILA % did not differ following bone-to-bone patella graft versus hamstring grafts (shown in the kinetics in ACL injury, rehab & RTS module) whereas significant differences in the deeper flexion and faster DL-CMJ.

Figure 13: Selected kinetic differences between DL and SL-CMJ in healthy and (ACLR) injured athletes



BW= body weight. Healthy = Healthy elite professional footballers assessed in preason. Injured = Professional footballers assessed during rehabilitation following ACLR.

Source: Cohen et al., 2020, p.5

The DL-CMJ, therefore, provides a greater challenge to the athlete's high-velocity deceleration and load attenuation capacities while relative to the DL-CMJ, the SL-CMJ is further towards the strength end of the force-velocity curve, and particularly so with respect to downward (eccentric phase). The SL-CMJ is also a less "reactive" test - while involving the stretch-shortening cycle, in practice, it is often performed with a small, slow countermovement and often with a pause at the end of a short downward phase - a rapid exchange between downward and upward phase is not consistently obtained and requires more coaching than for the DL-CMJ.

In the kinetics in ACL injury, rehab & RTS module we showed that even jump height and concentric impulse asymmetries (theoretically the most closely aligned ILA) only moderately correlated at the group level in post-ACLR footballers. A number of studies on healthy athletes (Miras-Moreno et al., 2021; Bishop et al., 2022) have also shown a lack of agreement in ILA in different jump tests at a mean and individual level - both in magnitude and direction - highlighting the "task specific" nature of ILA. Given the differing load and velocity characteristics of these assessments, the lack of agreement is perhaps not surprising and also the basis for inclusion on the basis that they provide information about the status and progress of differing neuromuscular qualities (Cohen et al., 2020). Apart from the kinetic characteristics and demands, the DL versus SL stance delimits different options or avoidance strategies for the athlete to reduce loading on an injured joint during and post-R-RTS (Roos et al., 2014; Baumgart et al., 2017; Chan & Sigward, 2019).

Asymmetries in DL v SL CMJ

As highlighted in the kinetics in ACL injury, rehab & RTS module, differences in left and right limb outputs and the resultant ILA % based on the DL-CMJ (or other DL-jump assessment) have been referred to as "compensatory strategies" (Baumgart et al., 2017) as well as asymmetries (Jordan et al., 2015; Read et al., 2021; Costley et al., 2023). Another perspective, argued by Benjanuvatra et al. (2013) is that asymmetries determined in the DL jump tests do not reflect "true asymmetries" and that due to the potential for interlimb compensatory strategies in these assessments, asymmetries must be measured using single leg tests that isolate the limb and allow the measurement of the limb's true force production capabilities. In injured individuals, significant interjoint compensations have been described in the single leg hop test which may mask knee function deficits and undermine the validity of ILA % in distance as a measure of knee function and overestimating degree of recovery (Wren et al., 2018; Kotsifaki et al., 2022a). In contrast, ILA% in performance outputs in the SL-CMJ (jump height) and SL-DJ (jump height and RSI) have been highlighted as more valid and sensitive measures of knee function in male athletes post-ACLR (Kotsifaki et al.,2022b). Therefore, SL tests per se do not appear to be universally superior in identifying and quantifying deficits - the specific demands of the test and potential for compensations to influence outputs needs also to be considered.

Isokinetic correlations

Studies report significant moderate (r=0.52-0.52) (Fischer et al., 2017) to good correlations (r = 0.73-0.79) (Ohji et al., 2021) between SL-CMJ height and isokinetic concentric peak torque across different speeds. Petschnig et al. (1998) reported SL CMJ height and isokinetic quadriceps concentric peak torque (Con-PT) (15/sec) ILA and the association between in patients at two post-ACLR time points (3 v 13 months). SLJ height showed a moderate (r = 0.51) significant correlation at 13 but not at 3 months – this correlation was similar to that found between Con-PT and single and triple hop for distance. While there were significant asymmetries in both con-PT and SL-CMJ at both timepoints, they were larger in the SL CMJ at both time points and at 13 months post-ACLR. They concluded that as the SLJ ILA was 25.1% in comparison with 12.8% in isokinetic peak torque, the jump was more revealing of underlying neuromuscular deficits. They suggested that the greater sensitivity of the SL-CMJ compared to IKD-PT might relate to balance and stabilisation requirements of the test, and the impairment of these qualities post surgically, in addition to the deficits in strength.

SL-CMJ: Limitations/disadvantages

Indeed, there are also practitioners and researchers who rigorously exclude the SL-CMJ from test batteries due to concerns related to the variability of test execution and reliability of kinetics derived from the test.

There are also a number of ways in which jump height in the SL-CMJ can be achieved using techniques which contribute to jump height but do not reflect knee joint output. While the SL-CMJ, performed with hands on hips or using dowel limits a variable contribution of the upper body, the position and movement of the passive limb is a source of variability in the task execution - Sado et al. (2020) reporting a significant contribution of the free hip to force production. When providing their rationale for use of the DL-CMJ to measure force asymmetries Impellizeri et al (2007) highlighted that the balance and stabilisation requirements of the test made the SLJ a less accurate / more contaminated measure of strength post-ACLR than the DL-CMJ. The instability prior to the initiation of the downward phase and tendency of athletes to start in a slightly flexed position and beginning with a very slow descent, also challenges kinetic analysis - for example start of movement detection and in turn calculation of phase durations - thereby making detailed analysis of the movement difficult.

SLJ values – residual asymmetry

While Baumgart et al. (2017) reported persistent SJ-CMJ ILA in jump height (11.5%) in a mixed cohort a mean of 31 months post ACLR. As the only study to compare functional outcomes of SL and DL-CMJ ILA's and one of the few to present SL-CMJ kinetics, they also present some additional pertinent findings. As highlighted in the kinetics in ACL injury, rehab & RTS module they observed that while higher asymmetry % in several of the DL-CMJ kinetic ILAs evaluated were associated with poorer self-report function, a higher SL-CMJ jump height ILA% was not. They also found no significant interlimb differences in impulse or peak vGRF, while there were 16.4% and 10.3% asymmetries respectively in the equivalent DL-CMJ ILA's. Importantly however they did note that poorer knee function was associated with a higher % in one SLJ kinetic ILA - force @ zero velocity. This suggests that as for the DL-CMJ, there is SL-CMJ kinetics that is more revealing of residual deficits - an area that warrants further research. Based on the SGP-ACL data and observations, we suggest that in the SL-CMJ, in addition to ILA % (and absolute values) in jump height and force @ zero velocity, trends in CM depth and velocity should also be examined to discern altered strategies. Also, as highlighted by Cohen et al., 2020, peak landing force, adjusted for jump height (to account for the likely greater height and therefore landing velocity on the uninvolved side) is a metric that is indicative of a stiffer landing and associated with reduced knee flexion (Ithurburn et al., 2019). Reductions in this metric would be interpreted as a positive trend, as the jump height adjusted peak landing force in the DL-CMJ (as shown in the player in figure 8B).

Taken together, the SL-CMJ jump height may serve as a good proxy for peak concentric quadriceps strength and this simple metric and easily obtainable shown to be a more valid indicator of knee function than horizontal hop performance and ILA%. The DL-CMJ provides detailed cross-phase and particularly willingness, capacity and strategies related to high-velocity deceleration and opportunity to manifest and inform on a combination of capacity + compensatory strategies related to loading attenuation on landing from a substantially greater height than in the SL-CMJ. The kinetic detail from the DL-CMJ complemented with the higher strength demands and isolated performance and ILA% and proxy kinematics highlighted will generate extensive insights on status and progress. Furthermore, discrepancies between ILA in the SL v DL test - can guide the practitioner to an emphasis on single or double leg exercises as deficits in activation and interlimb compensatory strategies are observed post-ligament (Chan & Sigward, 2019; Roos et al., 2014) and muscle injury (Bourne et al., 2016) during bilateral exercises.

Early and frequent enough assessments also allow the quantification of the absolute and relative (i.e., to the involved) response of the uninvolved limb to sports-specific and gym-based conditioning. Divergent responses may reflect altered load distribution (avoidance) strategies/inhibition (Roos et al. 2014) and provide a proxy indicator of the degree of stimulus during these activities (Taberner et al., 2020). Kinetic and kinematic asymmetries in a change of direction tasks are reported (King et al., 2018), and avoidance patterns in running (Kotsifaki et al.,2022a) following ACLR.

Limitation of LSI calculation in single limb tests

In high-performance sports, physical performance tests are at a minimum likely to be completed in the preseason and provide some form of benchmark data for reference in case of injury - which in these settings should be considered as a minimum duty of care (Cohen & Kennedy, 2021). In professional leagues, a player without at least a preseason force platform DL-CMJ test is rapidly becoming the exception rather than the rule. Test batteries may or may not include single jump or hop tests to provide, in addition to the DL-CMJ derived asymmetries/compensation strategies, a form of characterising slower speed strength, and capacity ILA% (as discussed above). In youth sport settings with poorer resources, that make the availability of force platform technology less ubiquitous, and suggests that in these settings single leg jump height which can be obtained with various lower cost means should be considered a minimum standard of care.

As highlighted above, particularly in figure 7, benchmark data can substantially change the interpretation of an athlete's status with respect to bilateral CMJ kinetics. We also highlighted the potential for misclassification of DL-CMJ ILA% data. With respect to asymmetries calculated from single limb strength & power diagnostic test data without preinjury benchmarks, the practitioner depends on the limb symmetry index to classify status and progress. This means using data from the contralateral healthy limb also obtained during rehab. At least in long-term injuries which involve some period of immobilisation, the LSI should be interpreted in the context that due to a significant reduction in sports-specific load and gym-based conditioning, there is likely to have been substantial deconditioning of the uninvolved limb. There is limited published data describing detailed pre-injury data for subsequently injured athletes with which to determine the magnitude of the decline of neuromuscular performance based on data collected just prior to the injury. However, Wellsandt et al., 2017 took an alternative approach in which they compared the limb symmetry index (LSI %) determined using the uninvolved limb performance obtained in an assessment during rehab 6 months post ACLR with an index calculated using an uninvolved limb test performed after the injury, but before surgery ("EPIC %"). Their results illustrate the potential for the inflation and misclassification of individual progress using the 6 months LSI approach.

They found significant differences between the % asymmetry calculated using LSI data versus EPIC data; the only difference between the two calculations being only that the LSI uses the value obtained in the uninvolved limb at 6 months and the EPIC uses the post-injury, pre-surgery, value. Furthermore, EPIC classified a significantly lower proportion of patients as meeting the 90% criteria for RTS. Most importantly, follow-up of patients demonstrated that this misclassification of readiness to return had clinical consequences; 8 / 11 who suffered a 2nd ACL injury (either ipsi- or contra-lateral) had passed the LSI criteria at 6 months post ACLR. Of those 8, only 2 met the (also 90%) EPIC criteria.

While the study involved IKD and hop tests, and did not involve vertical jump tests, it fundamentally shows that deconditioning in the uninvolved limb results in a significant underestimation of asymmetry and inflates LSI which overestimates the degree of recovery of the ACL-R limb. It also suggests that if the practitioner does not have healthy preinjury IKD data for an athlete who sustains an ACL injury but can access the device to periodically examine during rehab, a pre-surgery assessment could add tremendous value, in terms of better estimating their ILA. Given its association with concentric extensor isokinetic strength, assessment of the single-leg vertical jump (SLJ) at such a time point might also improve the accuracy of later calculations and classification of SLJ ILA%.

As described previously, (Cohen et al., 2020) the authors ascribe to potentially including both within a baseline/benchmark screen. Understanding the insights tests can provide as well as their advantages/practical limitations are at the core of decision-making around their use. The DL-CMJ but not the SL-CMJ would then be performed regularly as part of in-season LRM in the healthy athlete, but in the event of a knee injury – ligament or tendon – both assessments would again be performed, the DL-CMJ performed as a core test throughout the rehab pathway, and the SLJ potentially implemented again at less frequent intervals. Potentially to denote the possibility that the SL-DJ is performed instead of the SLVJ, and the DJ, at least in the preseason. In terms of risk of re-rupture of ACL, at least in male athletes, as prospective evidence indicates deficits in the test (and DL-DJ, while CMJ was not examined) were associated with an elevated risk of contralateral ACL injury (King et al., 2021). However, there were trivial and non-significant differences with respect to SL-CMJ or hop test LSI.

References

Akenhead, R., & Nassis, G. P. (2016). Training Load and Player Monitoring in High-Level Football: Current Practice and Perceptions. *International journal of sports physiology and performance*, *11*(5), 587–593. https://doi.org/10.1123/ijspp.2015-0331

Ardern, C. L., Taylor, N. F., Feller, J. A., & Webster, K. E. (2013). A systematic review of the psychological factors associated with returning to sport following injury. *British journal of sports medicine*, *47*(17), 1120–1126. https://doi.org/10.1136/bjsports-2012-091203

Ardern, C. L., Glasgow, P., Schneiders, A., Witvrouw, E., Clarsen, B., Cools, A., Gojanovic, B., Griffin, S., Khan, K. M., Moksnes, H., Mutch, S. A., Phillips, N., Reurink, G., Sadler, R., Silbernagel, K. G., Thorborg, K., Wangensteen, A., Wilk, K. E., & Bizzini, M. (2016). 2016 Consensus statement on return to sport from the First World Congress in Sports Physical Therapy, Bern. *British journal of sports medicine*, *50*(14), 853–864. https://doi.org/10.1136/bjsports-2016-096278

Barris, S., & Button, C. (2008). A review of vision-based motion analysis in sport. *Sports medicine (Auckland, N.Z.)*, *38*(12), 1025–1043. https://doi.org/10.2165/00007256-200838120-00006

Baumert P, Lake MJ, Stewart CE, Drust B, Erskine RM. (2016) Genetic variation and exercise-induced muscle damage: implications for athletic performance, injury and ageing. Eur J Appl Physiol. 2 Sep;116(9):1595-625. doi: 10.1007/s00421-016-3411-1.

Beardmore, A. L., Handcock, P. J., & Rehrer, N. J. (2005). Return-to-play after injury: practices in New Zealand rugby union. *Physical Therapy in Sport, 6*(1), 24-30, https://doi.org/10.1016/j.ptsp.2004.04.002

Beato, M., Devereux, G., & Stiff, A. (2018). Validity and Reliability of Global Positioning System Units (STATSports Viper) for Measuring Distance and Peak Speed in Sports. *Journal of strength and conditioning research*, *32*(10), 2831–2837. https://doi.org/10.1519/JSC.0000000000002778

Beato, M., De Keijzer, K. L., Leskauskas, Z., Allen, W. J., Dello Iacono, A., & McErlain-Naylor, S. A. (2021). Effect of Postactivation Potentiation After Medium vs. High Inertia Eccentric Overload Exercise on Standing Long Jump, Countermovement Jump, and Change of Direction Performance. *Journal of strength and conditioning research*, *35*(9), 2616–2621. https://doi.org/10.1519/JSC.0000000000003214

Benjanuvatra N, Lay BS, Alderson JA, Blanksby BA. (2013). Comparison of ground reaction force asymmetry in one- and two-legged countermovement jumps. J Strength Cond Res;27(10):2700–7.

Bishop C, Abbott W, Brashill C, Turner A, Lake J, Read P. (2022) Bilateral vs. Unilateral Countermovement Jumps: Comparing the Magnitude and Direction of Asymmetry in Elite

Academy Soccer Players. J Strength Cond Res. Jun 1;36(6):1660-1666. doi: 10.1519/JSC.0000000000003679.

Blanch, P., & Gabbett, T. J. (2016). Has the athlete trained enough to return to play safely? The acute:chronic workload ratio permits clinicians to quantify a player's risk of subsequent injury. *British journal of sports medicine*, *50*(8), 471–475. https://doi.org/10.1136/bjsports-2015-095445

Bowen, L., Gross, A. S., Gimpel, M., & Li, F. X. (2017). Accumulated workloads and the acute:chronic workload ratio relate to injury risk in elite youth football players. *British journal of sports medicine*, *51*(5), 452–459. https://doi.org/10.1136/bjsports-2015-095820

Brooks, J. H., & Kemp, S. P. (2011). Injury-prevention priorities according to playing position in professional rugby union players. *British journal of sports medicine*, *45*(10), 765–775. https://doi.org/10.1136/bjsm.2009.066985

Brophy RH, Schmitz L, Wright RW, Dunn WR, Parker RD, Andrish JT, McCarty EC, Spindler KP. (2012). Return to play and future ACL injury risk after ACL reconstruction in soccer athletes from the Multicenter Orthopaedic Outcomes Network (MOON) group. Am J Sports Med. Nov;40(11):2517-22. doi: 10.1177/0363546512459476.

Buchheit, M., Samozino, P., Glynn, J. A., Michael, B. S., Al Haddad, H., Mendez-Villanueva, A., & Morin, J. B. (2014). Mechanical determinants of acceleration and maximal sprinting speed in highly trained young soccer players. *Journal of sports sciences*, *32*(20), 1906–1913. https://doi.org/10.1080/02640414.2014.965191

Buchheit M. (2014). Monitoring training status with HR measures: do all roads lead to Rome?. *Frontiers in physiology*, *5*, 73. https://doi.org/10.3389/fphys.2014.00073

Buchheit, M., Manouvrier, C., Cassirame, J., & Morin, J. B. (2015). Monitoring Locomotor Load in Soccer: Is Metabolic Power, Powerful?. *International journal of sports medicine*, *36*(14), 1149–1155. https://doi.org/10.1055/s-0035-1555927

Buckthorpe, M., Wright, S., Bruce-Low, S., Nanni, G., Sturdy, T., Gross, A. S., Bowen, L., Styles, B., Della Villa, S., Davison, M., & Gimpel, M. (2019). Recommendations for hamstring injury prevention in elite football: translating research into practice. *British journal of sports medicine*, *53*(7), 449–456. https://doi.org/10.1136/bjsports-2018-099616

Burgi, C. R., Peters, S., Ardern, C. L., Magill, J. R., Gomez, C. D., Sylvain, J., & Reiman, M. P. (2019). Which criteria are used to clear patients to return to sport after primary ACL reconstruction? A scoping review. *British journal of sports medicine*, *53*(18), 1154–1161. https://doi.org/10.1136/bjsports-2018-099982

Bourne MN, Opar DA, Williams MD, Al Najjar A, Shield AJ. (2016) Muscle activation patterns in the Nordic hamstring exercise: Impact of prior strain injury. Scand J Med Sci Sports. Jun;26(6):666-74. doi: 10.1111/sms.12494.

Carling, C., McCall, A., Le Gall, F., & Dupont, G. (2016). The impact of short periods of match congestion on injury risk and patterns in an elite football club. *British journal of sports medicine*, *50*(12), 764–768. https://doi.org/10.1136/bjsports-2015-095501

Chan M-S, Sigward SM. (2019). Loading Behaviors Do Not Match Loading Abilities Post anterior Cruciate Ligament Reconstruction. Med Sci Sports Exerc 51(8):1626–34.

Costley JAE, Miles JJ, King E, Daniels KAJ. (2023). Vertical jump impulse deficits persist from six to nine months after ACL reconstruction. Sports Biomech. Jan;22(1):123-141. doi: 10.1080/14763141.2021.1945137.

Collings TJ, Diamond LE, Barrett RS, Timmins RG, Hickey JT, DU Moulin WS, Williams MD, Beerworth KA, Bourne MN.(2022). Strength and Biomechanical Risk Factors for Noncontact ACL Injury in Elite Female Footballers: A Prospective Study. Med Sci Sports Exerc. Aug 1;54(8):1242-1251. doi: 10.1249/MSS.0000000000002908.

Cohen DD, Burton A, Wells C, Taberner M, Diaz MA, Graham-Smith P. (2020) Single v double leg countermovement jump tests; not half an apple. Aspetar Sports Med J;9:34–41.

Cohen & Kennedy, 2021 NSCA

Colby, M. J., Dawson, B., Heasman, J., Rogalski, B., & Gabbett, T. J. (2014). Accelerometer and GPS-derived running loads and injury risk in elite Australian footballers. *Journal of strength and conditioning research*, *28*(8), 2244–2252. https://doi.org/10.1519/JSC.0000000000000362

Comfort, P., Dos'Santos, T., Beckham, G. K., Stone, M. H., Guppy, S. N., & Haff, G. G. (2019). Standardization and Methodological Considerations for the Isometric Midthigh Pull. *Strength and Conditioning Journal, 41*(2), 57-79. http://dx.doi.org/10.1519/SSC.0000000000000433

Coughlan, G. F., Green, B. S., Pook, P. T., Toolan, E., & O'Connor, S. P. (2011). Physical game demands in elite rugby union: a global positioning system analysis and possible implications for rehabilitation. *The Journal of orthopaedic and sports physical therapy*, *41*(8), 600–605. https://doi.org/10.2519/jospt.2011.3508

Cummins, C., Orr, R., O'Connor, H., & West, C. (2013). Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. *Sports medicine (Auckland, N.Z.)*, *43*(10), 1025–1042. https://doi.org/10.1007/s40279-013-0069-2

di Prampero, P. E., & Osgnach, C. (2018). Metabolic Power in Team Sports - Part 1: An Update. *International journal of sports medicine*, *39*(8), 581–587. https://doi.org/10.1055/a-0592-7660

Dunlop, G., Ardern, C. L., Andersen, T. E., Lewin, C., Dupont, G., Ashworth, B., O'Driscoll, G., Rolls, A., Brown, S., & McCall, A. (2020). Return-to-Play Practices Following Hamstring Injury:

A Worldwide Survey of 131 Premier League Football Teams. *Sports medicine (Auckland, N.Z.)*, *50*(4), 829–840. https://doi.org/10.1007/s40279-019-01199-2

Duthie, G., Pyne, D., & Hooper, S. (2003). Applied physiology and game analysis of rugby union. *Sports medicine (Auckland, N.Z.)*, *33*(13), 973–991. https://doi.org/10.2165/00007256-200333130-00003

Ehrmann, F. E., Duncan, C. S., Sindhusake, D., Franzsen, W. N., & Greene, D. A. (2016). GPS and Injury Prevention in Professional Soccer. *Journal of strength and conditioning research*, *30*(2), 360–367. https://doi.org/10.1519/JSC.0000000000001093

Engel G. L. (1977). The need for a new medical model: a challenge for biomedicine. *Science (New York, N.Y.)*, *196*(4286), 129–136. https://doi.org/10.1126/science.847460

Finch, N. A., Zasowski, E. J., Murray, K. P., Mynatt, R. P., Zhao, J. J., Yost, R., Pogue, J. M., & Rybak, M. J. (2017). A Quasi-Experiment To Study the Impact of Vancomycin Area under the Concentration-Time Curve-Guided Dosing on Vancomycin-Associated Nephrotoxicity. *Antimicrobial agents and chemotherapy*, *61*(12), e01293-17. https://doi.org/10.1128/AAC.01293-17

Flanagan SD, Proessl F, Dunn-Lewis C, Sterczala AJ, Connaboy C, Canino MC, Beethe AZ, Eagle SR, Szivak TK, Onate JA, Volek JS, Maresh CM, Kaeding CC, Kraemer WJ. (2021). Differences in brain structure and theta burst stimulation-induced plasticity implicate the corticomotor system in loss of function after musculoskeletal injury. J Neurophysiol. Apr 1;125(4):1006-1021. doi: 10.1152/jn.00689.2020.

Fuller, C. W., & Walker, J. (2006). Quantifying the functional rehabilitation of injured football players. *British journal of sports medicine*, *40*(2), 151–157. https://doi.org/10.1136/bjsm.2005.021048

Gabbett, T. J., & Ullah, S. (2012). Relationship between running loads and soft-tissue injury in elite team sport athletes. *Journal of strength and conditioning research*, *26*(4), 953–960. https://doi.org/10.1519/JSC.0b013e3182302023

Gabbett T. J. (2016). The training-injury prevention paradox: should athletes be training smarter and harder?. *British journal of sports medicine*, *50*(5), 273–280. https://doi.org/10.1136/bjsports-2015-095788

Glasgow, P., Phillips, N., & Bleakley, C. (2015). Optimal loading: key variables and mechanisms. *British journal of sports medicine*, *49*(5), 278–279. https://doi.org/10.1136/bjsports-2014-094443

Hägglund, M., Waldén, M., & Ekstrand, J. (2005). Injury incidence and distribution in elite football--a prospective study of the Danish and the Swedish top divisions. *Scandinavian journal of medicine & science in sports*, *15*(1), 21–28. https://doi.org/10.1111/j.1600-0838.2004.00395.x

Hägglund, M., Waldén, M., Magnusson, H., Kristenson, K., Bengtsson, H., & Ekstrand, J. (2013). Injuries affect team performance negatively in professional football: an 11-year follow-up of the UEFA Champions League injury study. *British journal of sports medicine*, *47*(12), 738–742. https://doi.org/10.1136/bjsports-2013-092215

Herring SA, Bergfeld JA, Boyd J, et al.(2002) The team physician and return-to-play issues: a consensus statement. Med Sci Sports Exerc; 34 (7): 1212–4.

Hewett, T. E., Ford, K. R., Hoogenboom, B. J., & Myer, G. D. (2010). Understanding and preventing acl injuries: current biomechanical and epidemiologic considerations - update 2010. *North American journal of sports physical therapy : NAJSPT*, *5*(4), 234–251.

Hoppe, D. J., Truntzer, J. N., Shapiro, L. M., Abrams, G. D., & Safran, M. R. (2017). Diagnostic Accuracy of 3 Physical Examination Tests in the Assessment of Hip Microinstability. *Orthopaedic journal of sports medicine*, *5*(11), 2325967117740121. https://doi.org/10.1177/2325967117740121

Hulin, B. T., Gabbett, T. J., Blanch, P., Chapman, P., Bailey, D., & Orchard, J. W. (2014). Spikes in acute workload are associated with increased injury risk in elite cricket fast bowlers. *British journal of sports medicine*, *48*(8), 708–712. https://doi.org/10.1136/bjsports-2013-092524

Hulin, B. T., Gabbett, T. J., Lawson, D. W., Caputi, P., & Sampson, J. A. (2016). The acute:chronic workload ratio predicts injury: high chronic workload may decrease injury risk in elite rugby league players. *British journal of sports medicine*, *50*(4), 231–236. https://doi.org/10.1136/bjsports-2015-094817

Impellizzeri, F. M., Marcora, S. M., & Coutts, A. J. (2019). Internal and External Training Load: 15 Years On. *International journal of sports physiology and performance*, *14*(2), 270–273. https://doi.org/10.1123/ijspp.2018-0935

Ithurburn MP, Paterno M V., Thomas S, Pennell ML, Evans KD, Magnussen RA, et al. (2019). Change in Drop-Landing Mechanics Over 2 Years in Young Athletes After Anterior Cruciate Ligament Reconstruction. Am J Sports Med. Sep 1;47(11):2608–16.

Jordan, M. J., Morris, N., Lane, M., Barnert, J., MacGregor, K., Heard, M., Robinson, S., & Herzog, W. (2020). Monitoring the Return to Sport Transition After ACL Injury: An Alpine Ski Racing Case Study. *Frontiers in sports and active living*, *2*, 12. https://doi.org/10.3389/fspor.2020.00012

King, E., Richter, C., Franklyn-Miller, A., Wadey, R., Moran, R., & Strike, S. (2019). Back to Normal Symmetry? Biomechanical Variables Remain More Asymmetrical Than Normal During Jump and Change-of-Direction Testing 9 Months After Anterior Cruciate Ligament Reconstruction. *The American journal of sports medicine*, *47*(5), 1175–1185. https://doi.org/10.1177/0363546519830656

King E, Richter C, Franklyn-Miller A, Daniels K, Wadey R, Jackson M, Moran R, Strike S. (2018) Biomechanical but not timed performance asymmetries persist between limbs 9 months after ACL reconstruction during planned and unplanned change of direction. J Biomech. Nov 16;81:93-103. doi: 10.1016/j.jbiomech.2018.09.021

Kotsifaki, A., Korakakis, V., Whiteley, R., Van Rossom, S., & Jonkers, I. (2020). Measuring only hop distance during single leg hop testing is insufficient to detect deficits in knee function after ACL reconstruction: a systematic review and meta-analysis. *British journal of sports medicine*, *54*(3), 139–153. https://doi.org/10.1136/bjsports-2018-099918

Kotsifaki A, Van Rossom S, Whiteley R, Korakakis V, Bahr R, D'Hooghe P, Papakostas E, Sideris V, Farooq A, Jonkers I. (2022). Between-Limb Symmetry in ACL and Tibiofemoral Contact Forces in Athletes After ACL Reconstruction and Clearance for Return to Sport. Orthop J Sports Med. 2022a Apr 11;10(4):23259671221084742. doi: 10.1177/23259671221084742.

Kotsifaki A, Van Rossom S, Whiteley R, Korakakis V, Bahr R, Sideris V, Smith PG, Jonkers I. (2022). Symmetry in Triple Hop Distance Hides Asymmetries in Knee Function After ACL Reconstruction in Athletes at Return to Sports. Am J Sports Med. 2022b Feb;50(2):441-450. doi: 10.1177/03635465211063192.

Kotsifaki A, Van Rossom S, Whiteley R, Korakakis V, Bahr R, Sideris V, Jonkers I. (2022). Single leg vertical jump performance identifies knee function deficits at return to sport after ACL reconstruction in male athletes. Br J Sports Med. 2022 May;56(9):490-498. doi: 10.1136/bjsports-2021-104692. Epub 2022c Feb 8.

Lolli, L., Batterham, A. M., Hawkins, R., Kelly, D. M., Strudwick, A. J., Thorpe, R. T., Gregson, W., & Atkinson, G. (2019). The acute-to-chronic workload ratio: an inaccurate scaling index for an unnecessary normalisation process?. *British journal of sports medicine*, *53*(24), 1510–1512. https://doi.org/10.1136/bjsports-2017-098884

Maestroni, L., Read, P., Bishop, C., & Turner, A. (2020). Strength and Power Training in Rehabilitation: Underpinning Principles and Practical Strategies to Return Athletes to High Performance. *Sports medicine (Auckland, N.Z.)*, *50*(2), 239–252. https://doi.org/10.1007/s40279-019-01195-6

Malone, S., Roe, M., Doran, D. A., Gabbett, T. J., & Collins, K. (2017). High chronic training loads and exposure to bouts of maximal velocity running reduce injury risk in elite Gaelic football. *Journal of science and medicine in sport*, *20*(3), 250–254. https://doi.org/10.1016/j.jsams.2016.08.005

Malone, S., Hughes, B., Doran, D. A., Collins, K., & Gabbett, T. J. (2019). Can the workload-injury relationship be moderated by improved strength, speed and repeated-sprint qualities?. *Journal of science and medicine in sport*, *22*(1), 29–34. https://doi.org/10.1016/j.jsams.2018.01.010

McCall, A., Carling, C., Davison, M., Nedelec, M., Le Gall, F., Berthoin, S., & Dupont, G. (2015). Injury risk factors, screening tests and preventative strategies: a systematic review of the evidence that underpins the perceptions and practices of 44 football (soccer) teams from various premier leagues. *British journal of sports medicine*, *49*(9), 583–589. https://doi.org/10.1136/bjsports-2014-094104

Miras-Moreno S, Pérez-Castilla A, Rojas FJ, Janicijevic D, De la Cruz JC, Cepero M, García-Ramos A. (2021). Inter-limb differences in unilateral countermovement jump height are not associated with the inter-limb differences in bilateral countermovement jump force production. Sports Biomech. Sep 22:1-13. doi:10.1080/14763141.2021.1980091.

Myer GD, Martin L Jr, Ford KR, Paterno MV, Schmitt LC, Heidt RS Jr, Colosimo A, Hewett TE. (2012) No association of time from surgery with functional deficits in athletes after anterior cruciate ligament reconstruction: evidence for objective return-to-sport criteria. Am J Sports Med. Oct;40(10):2256-63. doi: 10.1177/0363546512454656.

Nagelli CV, Hewett TE. (2017). Should return to sport be delayed until 2 years after anterior cruciate ligament reconstruction? Biological and functional considerations. Sports Med;47:221–32.

Oberhofer, K., Hosseini Nasab, S. H., Schütz, P., Postolka, B., Snedeker, J. G., Taylor, W. R., & List, R. (2017). The influence of muscle-tendon forces on ACL loading during jump landing: a systematic review. *Muscles, ligaments and tendons journal*, *7*(1), 125–135. https://doi.org/10.11138/mltj/2017.7.1.125

Orchard, J., & Best, T. M. (2002). The management of muscle strain injuries: an early return versus the risk of recurrence. *Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine*, *12*(1), 3–5. https://doi.org/10.1097/00042752-200201000-00004

Osgnach, C., Poser, S., Bernardini, R., Rinaldo, R., & di Prampero, P. E. (2010). Energy cost and metabolic power in elite soccer: a new match analysis approach. *Medicine and science in sports and exercise*, *42*(1), 170–178. https://doi.org/10.1249/MSS.0b013e3181ae5cfd

Paterno, M. V., Ford, K. R., Myer, G. D., Heyl, R., & Hewett, T. E. (2007). Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. *Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine*, *17*(4), 258–262. https://doi.org/10.1097/JSM.0b013e31804c77ea

Pickering C, Kiely J. (2019). Do Non-Responders to Exercise Exist-and If So, What Should We Do About Them? Sports Med; 49(1):1-7

Pruna R, Artells R, Ribas J, Montoro B, Cos F, Muñoz C, Rodas G, Maffulli N. (2013). Single nucleotide polymorphisms associated with non-contact soft tissue injuries in elite professional soccer players: influence on degree of injury and recovery time. BMC Musculoskelet Disord. Jul 26;14:221. doi: 10.1186/1471-2474-14-221.

Read, P. J., Turner, A. N., Clarke, R., Applebee, S., & Hughes, J. (2019). Knee Angle Affects Posterior Chain Muscle Activation During an Isometric Test Used in Soccer Players. *Sports (Basel, Switzerland)*, *7*(1), 13. https://doi.org/10.3390/sports7010013

Reid, A., Birmingham, T. B., Stratford, P. W., Alcock, G. K., & Giffin, J. R. (2007). Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. *Physical therapy*, *87*(3), 337–349. https://doi.org/10.2522/ptj.20060143

Reid, L. C., Cowman, J. R., Green, B. S., & Coughlan, G. F. (2013). Return to play in elite rugby union: application of global positioning system technology in return-to-running programs. *Journal of sport rehabilitation*, *22*(2), 122–129. https://doi.org/10.1123/jsr.22.2.122

Roos PE, Button K, Van Deursen RWM. (2014). Motor control strategies during double leg squat following anterior cruciate ligament rupture and reconstruction: An observational study. J Neuroeng Rehabil. Feb 28;11(1).

Shrier, I. (2015). Strategic Assessment of Risk and Risk Tolerance (StARRT) framework for return-to-play decision-making. *British journal of sports medicine*, *49*(20), 1311–1315. https://doi.org/10.1136/bjsports-2014-094569

Stares, J., Dawson, B., Peeling, P., Drew, M., Heasman, J., Rogalski, B., & Colby, M. (2018). How much is enough in rehabilitation? High running workloads following lower limb muscle injury delay return to play but protect against subsequent injury. *Journal of science and medicine in sport*, *21*(10), 1019–1024. https://doi.org/10.1016/j.jsams.2018.03.012

SGP-ACL: Cohen DD, Burton A, Wells C, Mackenzie B, Richter C, Taberner M. BOSTAA conference. 2021

Stares JJ, Dawson B, Peeling P, Heasman J, Rogalski B, Fahey-Gilmour J, Dupont G, Drew MK, Welvaert M, Toohey L. (2019). Subsequent Injury Risk Is Elevated Above Baseline After Return to Play: A 5-Year Prospective Study in Elite Australian Football. Am J Sports Med. Jul;47(9):2225-2231. doi: 10.1177/0363546519852622.

Taberner M, Cohen DD. (2018) Physical preparation of the football player with an intramuscular hamstring tendon tear: clinical perspective with video demonstrations. Br J Sports Med. Oct;52(19):1275-1278. doi: 10.1136/bjsports-2017-098817.

Taberner M, Allen T, Cohen DD.(2019) Progressing rehabilitation after injury: consider the 'control-chaos continuum'.Br J Sports Med. Sep;53(18):1132-1136. doi: 10.1136/bjsports-2018-100157.

Taberner M, O'keefe J, Dunn A, Cohen DD. (2022) Return to sport and beyond following intramuscular tendon hamstring injury: A case report of an English Premier League football player.Phys Ther Sport. Jul;56:38-47. doi: 10.1016/j.ptsp.2022.05.013.

Taberner M, van Dyk N, Allen T, Jain N, Richter C, Drust B, Betancur E, Cohen DD.(2020) Physical preparation and return to performance of an elite female football player following ACL reconstruction: a journey to the FIFA Women's World Cup. BMJ Open Sport Exerc Med. 2020a Dec 1;6(1):e000843. doi: 10.1136/bmjsem-2020-000843.

Taberner M, Haddad FS, Dunn A, Newall A, Parker L, Betancur E, Cohen DD. (2020) Managing the return to sport of the elite footballer following semimembranosus reconstruction. BMJ Open Sport Exerc Med. 2020b Oct 26;6(1):e000898. doi: 10.1136/bmjsem-2020-000898

Thornton, H. R., Delaney, J. A., Duthie, G. M., & Dascombe, B. J. (2019). Developing Athlete Monitoring Systems in Team Sports: Data Analysis and Visualization. *International journal of sports physiology and performance*, *14*(6), 698–705. https://doi.org/10.1123/ijspp.2018-0169

Vanrenterghem, J., Nedergaard, N. J., Robinson, M. A., & Drust, B. (2017). Training Load Monitoring in Team Sports: A Novel Framework Separating Physiological and Biomechanical Load-Adaptation Pathways. *Sports medicine (Auckland, N.Z.)*, *47*(11), 2135–2142. https://doi.org/10.1007/s40279-017-0714-2

Watanabe, S., Takahashi, T., Takeba, J., & Miura, H. (2018). Factors associated with the prevalence of back pain and work absence in shipyard workers. *BMC musculoskeletal disorders*, *19*(1), 12. https://doi.org/10.1186/s12891-018-1931-z

Weiler, R., Monte-Colombo, M., Mitchell, A., & Haddad, F. (2015). Non-operative management of a complete anterior cruciate ligament injury in an English Premier League football player with return to play in less than 8 weeks: applying common sense in the absence of evidence. *BMJ case reports*, *2015*, bcr2014208012. https://doi.org/10.1136/bcr-2014-208012

Wren TAL, Mueske NM, Brophy CH, Pace JL, Katzel MJ, Edison BR, Vandenberg CD, Zaslow TL. (2018). Hop Distance Symmetry Does Not Indicate Normal Landing Biomechanics in Adolescent Athletes With Recent Anterior Cruciate Ligament Reconstruction.J Orthop Sports Phys Ther. Aug;48(8):622-629. doi: 10.2519/jospt.2018.7817.

Wellsandt E, Failla MJ, Snyder-Mackler L. (2017). Limb Symmetry Indexes Can Overestimate Knee Function After Anterior Cruciate Ligament Injury. J Orthop Sports Phys Ther. May;47(5):334-338. doi: 10.2519/jospt.2017.7285.

Zambaldi, M., Beasley, I., & Rushton, A. (2017). Return to play criteria after hamstring muscle injury in professional football: a Delphi consensus study. *British journal of sports medicine*, *51*(16), 1221–1226. https://doi.org/10.1136/bjsports-2016-097131