Module 2. Kinetics in ACL injury, rehabilitation, and RTS

Unit 2.1 Force Platform Jump-land Tests in Rehabilitation and RTS

Introduction

Neither force platform measures nor 3D kinematics form part of classic clinical physical performance measure criteria for return to sport (RTS) following anterior cruciate ligament reconstruction (ACL-R) or other lower limb injuries. Following ACL-R, functional hop tests are probably the most widely used performance assessment measure and RTS criteria. Hop tests provide a low cost, easily applicable measure of “functional” performance, giving a rudimentary global indicator of the status of the operated limb relative to the healthy side via the limb symmetry index - (LSI), or to a preinjury healthy benchmark for the injured limb, if available. However, as highlighted in module 1, the ability of hop tests to quantify knee function/deficits post ACL-R has been challenged, as post ACL-R individuals with low asymmetry in hop distance may show large biomechanical/neuromuscular deficits in hop take-off and landing (Wren et al., 2018; Davies et al., 2020; Kotsifaki et al, 2020; Kotsifaki et al., 2022). Multiple compensations at other joints in the lower body and trunk in particular, can contribute to hop distance and potentially mask deficits in knee function (Kotsifaki et al, 2020; Kotsifaki et al., 2022). Furthermore, as hop tests can, like jump tests without force platforms, only provide outputs of distance or height respectively, without insights on where in the kinetic chain/which phase or neuromuscular qualities are most compromised, their use in informing targeted rehabilitation through the pathway is limited. Isokinetic dynamometry (IKD), provides a more direct and revealing assessment of knee function (Nagai et al., 2020), but factors such as the financial cost of the equipment, time cost and physical demands of the test and lack of portability somewhat limit the regular use of the device during the rehabilitation pathway. Similarly, 3D kinematics is a valuable means of identifying, and quantifying, joint specific deficits in jump-land and other movement assessments (and is discussed in module 3 of this course), but has similar practical limitations (as highlighted in “Force assessment and an introduction to Kinematics” course). In this module, with reference to the athlete in rehabilitation and RTS following ACL-R we focus on information that can be obtained from the assessment of jump-land tests on vGRF force platforms - now widely available in sports and clinical settings. Access to vGRF force platforms does not make the isokinetic dynamometer (IKD), or the 3D kinematics redundant as these technologies provide complementary joint-specific information. However, on-site vGRF dual force platforms represent access to a low athlete time- and physical demand means to quantify dynamic force production and its vGRF kinetic and movement derivatives during various jump-land activities. In the context of rehabilitation, this provides an immense increase in the capacity to identify compensatory strategies and phase specific deficits in eccentric, concentric, and landing that are not evident from hop distance/time or jump *height* data alone. The potential to frequently implement this low demand, high insight test can substantially enhance performance and medical staff's intelligence on athlete status and response to specific loading. Monitoring of kinetic changes provides rapid feedback in the adaptive response, in terms of specific neuromuscular quality, phase and position related metrics within this triple extension assessment. In turn, this data informs modifications to load prescription, where appropriate. The module 2 of "Performance, injury, and rehabilitation assessment Toolbox" course introduces isometric assessments to measure peak force and rate of force development in the context of both healthy and rehabilitating athletes and are referred to later in this course in relation to muscle and tendon injuries. Case studies demonstrating data derived in both jump-land and isometrics in rehabilitation are discussed in module 3 of "Performance, injury, and rehabilitation assessment Toolbox" course.

Countermovement jumps assessments in ACL rehabilitation

As proposed with respect to jump-land testing in the profiling and monitoring of the healthy athlete using force platforms - in rehabilitation following ACL-R (and potentially other ligament injuries), the bilateral or double leg CMJ (DL-CMJ) represents a core assessment. DL-CMJ performance correlates to a number of aspects of sports performance (Vescovi & McGuigan, 2008) and has well established value in monitoring (Claudino et al., 2017; Cohen & Kennedy, 2021). As such, healthy athletes often perform it as part of profiling and monitoring processes. The familiarity of athletes with the assessment is one of the important practical considerations underpinning its implementation, and means that there is also more likely to have pre-injury "benchmark" data for this test than most other jump-land assessments (Taberner et al., 2020; Cohen & Kennedy, 2021).

The DL-CMJ can be introduced early within the rehabilitation pathway (Taberner et al., 2020). This is partly because of the lower load demands on the injured knee, and potentially less fear associated with performing other jump-land assessments such as the double leg drop jump (DLDJ), the single leg CMJ (SLJ) and the single leg drop jump (SLDJ). These more demanding tests (discussed elsewhere in the certificate and within the context of rehabilitation in the toolbox module) are potentially integrated later, with the DL-CMJ assessment retained as a constant across the pathway and into post RTS and return to competition (RTC) monitoring.

It is suggested that the DL-CMJ could be performed as early as 8 weeks after ACL-R surgery (Impellezeri et al, 2007). Submaximal effort tests may also be used and still provide useful information, as highlighted in the Rehab toolbox module. Suggested criteria to meet for performing the test:

- Full knee extension and flexion
- No knee pain or effusion
- Normal weight bearing, walking, stairs, and body weight squat tolerated

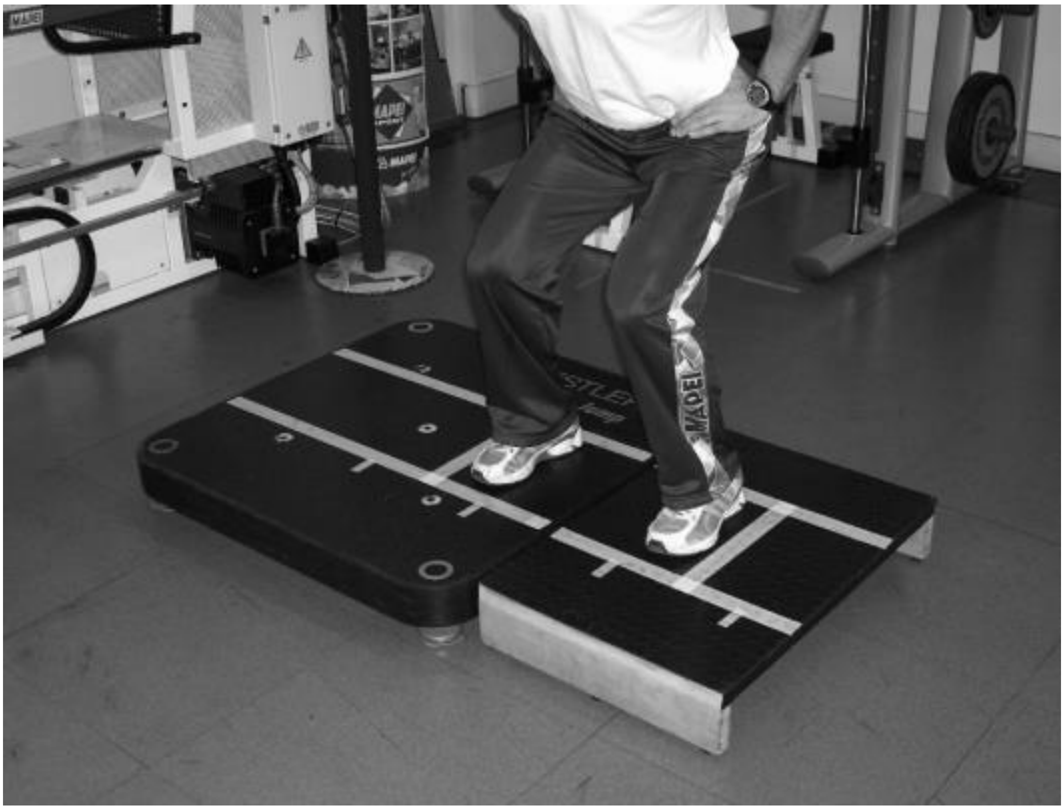
As is the case for the healthy athlete, the designation of the CMJ as core is based on both practical and technical considerations, with the former discussed further in the rehab toolbox. The aim of this module is to describe the technical aspects of the DL-CMJ; the types of data and insights that can be obtained with vGRF force platform CMJ assessment used in rehab, based on published and unpublished evidence. The learner should gain an understanding of some of the characteristics of the tests, how and which variables within those assessments are affected by the ACL-R, expected values and responses to conditioning. The interpretation of this data and case studies demonstrating how it may inform decision making within the rehab pathway and beyond is found in the rehab toolbox module. That module also describes and discusses data obtained from some of the other S & P diagnostic tools such as the SLJ, DL-DJ and DL-DJ. As highlighted in “Force assessment and an introduction to Kinematics” course, a thorough understanding of what can be gained from kinetics derived from the minimal dose testing that the DL-CMJ represents is foundational for appropriate selection and use of other jump-land tests and more detailed joint-specific neuromuscular and biomechanical analysis via isokinetic dynamometry and 3D kinematics.

The DL-CMJ in rehabilitation

The first appearance in the literature of DL-CMJ in the context of rehabilitation was the work of Impellezeri et al (2007), examining force asymmetries in professional male footballers. In their landmark study, Impellerezi et al. examined DL-CMJ peak force interlimb asymmetry (ILA) in a large sample of professional footballers. They also assessed a subset of male and female athletes in rehabilitation 8-12 weeks post-ACLR, and again 7-9 weeks later. They also determined correlations between DL-CMJ peak force and isokinetic leg extension and isometric leg press strength asymmetries finding a large significant correlation with isometric leg press test (r= 0.83; *P <0.001*) and significant moderate correlations between CMJ peak force ILA and concentric isokinetic knee extensor peak torque ILA at 60°/s and 240°/s (r= 0.48; *P <0.001*). Based on significant reductions in peak force asymmetry, from 23 ±3% to 10 ±4% in the rehabilitation component of the study, they also concluded that the DL-CMJ was sensitive to detect deficits in extensor strength post ACL-R and able to quantify improvements in interlimb asymmetry (ILA) and in involved limb performance (which significantly increased from 725 ±117 to 980 ±145 Newtons) during rehabilitation. They also reported good inter-day test-retest reliability of peak force asymmetry in a mixed sample of healthy athletes.

Notably, this study showed a DL-CMJ performed using a single platform and a wooden box of similar height with one foot on a force platform and the other on a wooden platform. The athlete had to perform tests facing in the other direction to obtain data on the other limb as performance was recorded in only one limb at a time.

Figure 1: DL-CMJ test performed with single force platforms. One leg on a force platform (right leg) and one leg on wooden "dummy" platform (left leg).



Source: Impellizzeri et al. (2007). p.2046

This setup was not proposed as the ideal manner of collecting ILA, as unlike with dual platform systems the left and right limb force profiles are not collected simultaneously. However, this was before dual platform systems became ubiquitous and was a pragmatic approach recognising that due to the cost of force platforms at the time, while sports teams and clinics might have access to a single force platform, they were unlikely to have access to two. While today most force platforms used in sports and clinical settings are acquired as pairs or dual platforms, practitioners may apply this protocol and refer to this paper if only a single platform is available to them.

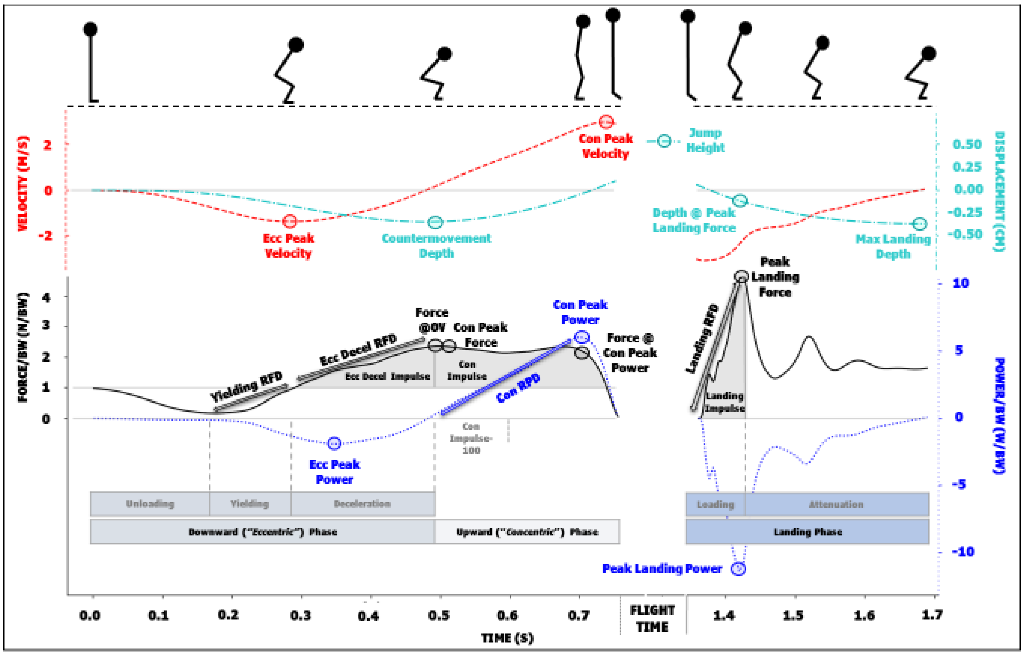
Evolution of CMJ kinetic asymmetry analysis

Following the work of Impellizzeri et al., and the more recent widespread access to dual force platform systems, interest has grown in examining the effect of injury, rehabilitation progress not only on peak force (most frequently located during or at the start of the concentric/upward phase) but also the ILA in DL-CMJ metrics from the other phases of the movement. Exploration of kinetic ILA in other jump-land assessments, (discussed in the Rehab toolbox module) has been less extensive. However, the repertoire of DJ-CMJ ILA metrics is substantial, with values reported in professional and elite footballers, and multisport male athletes during rehabilitation (Miles et al., 2019; Read et al., 2020; Cohen et al., 2020), in male (Cohen et al., 2014; Jordan et al., 2015; Hart et al., 2019) and female athletes (Jordan et al., 2015; Collings et al., 2022) following RTC post-injury and in healthy female (Bishop et al., 2020; Collings et al., 2022) and male athletes (Menzel et al., 2012; Cohen et al., 2014; Miles et al., 2019; Hart et al., 2019; Read et al., 2022; Bishop et al., 2022) without a recent history of severe injury. In addition, waveform analysis (Richter et al, 2014) and other point by point statistical techniques (Baumgart et al., 2017b) are used to identify regions of the jump-land cycle that differ between healthy and ACLR limb and / or versus healthy controls - “agnostically” (i.e., independent of predefined variables/phases).

Mapping the ILA’s

If you have already completed “Force assessment and an introduction to Kinematics” course of this certificate, you will be familiar with the terminology for the phases of the CMJ and a range of bilateral variables derived from the force-time, power-time, velocity-time and displacement-time curves and from the impulses and durations shown in figure 2.

Figure 2: DL-CMJ

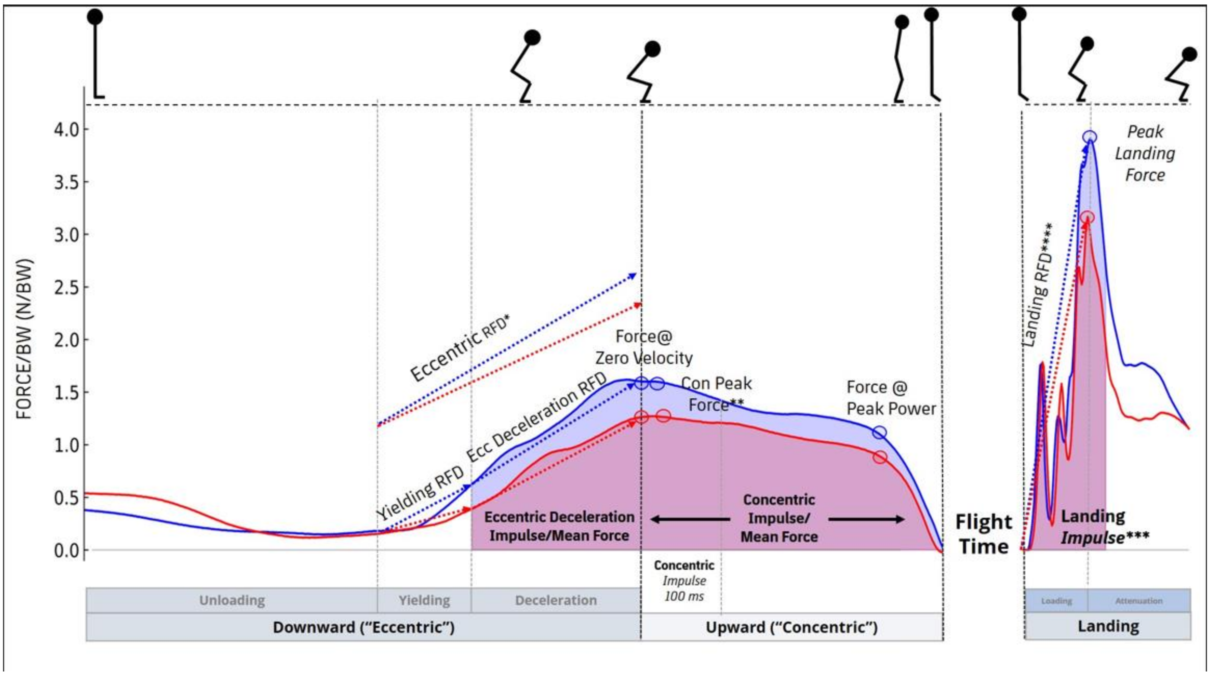


Cohen & Kennedy, NSCA: Essentials of Sports Science (2021)

Source: adapted from Cohen & Kennedy, 2021 (NSCA)

We now focus on kinetic ILA derived from the DL-CMJ, used to describe deficits/ILA during rehabilitation and RTS and “residual deficits” following RTS and return to competition (RTC). These ILA, may also be used in the profiling of healthy athletes as there is some prospective evidence that higher asymmetries in specific metrics are associated with injury risk (Malaver et al.,2019; McSweeney et al. 2022; Cohen et al., unpublished) discussed in the Rehab toolbox module.Note that vGRF force platform assessment allows the valid characterisation of asymmetries derived from the left and right force-time curve across DL-CMJ i.e. peak and mean force, RFD's and impulse. The velocity, power and displacement curves that are generated with vGRF platforms and phase durations, describe the centre of mass (COM) or whole-body position. Asymmetries are therefore not calculated for these metrics.

Figure 3: CMJ phases with selected CMJ kinetic asymmetries



Source: prepared by the author.

BW=bodyweight; N=Newtons; RFD=Rate of force development; Con=Concentric; Ecc= Eccentric

*Eccentric RFD shown in this position for visual clarity but is calculated from the start of the eccentric yielding phase to the end of the eccentric deceleration phase (i.e. it is an overall eccentric RFD that includes both of these phases)

**Con Peak Force is shown in this position but can appear at other points across the concentric phase, depending on the shape of the waveform

***Landing impulse can be calculated at various time points such as 0-40 or 0-70 ms, up to peak force, or to max displacement

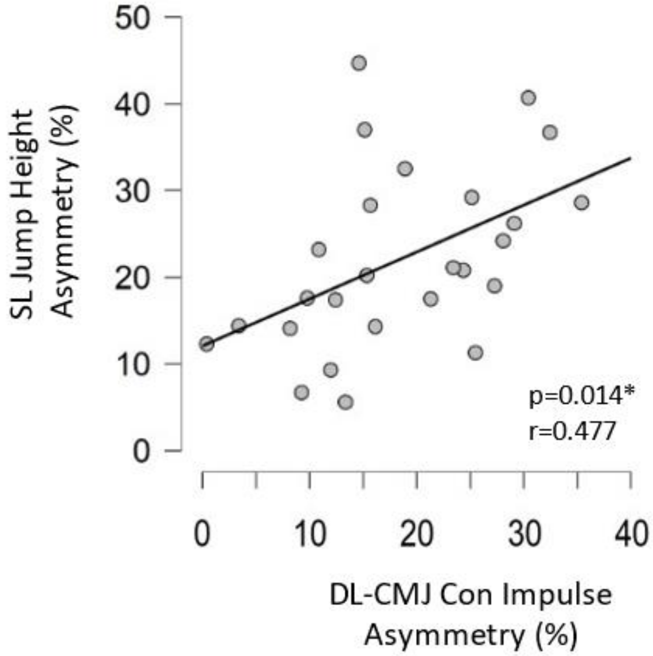
****Landing RFD is shown as calculated from impact to landing peak force, but it may also be calculated to landing peak power or over shorter epochs such as 0-40 or 0-70 ms

This visualisation depicts the use of Left and Right limb peak values to calculate concentric and landing peak force ILA and that these may occur at different timepoints. An alternative approach is to calculate the asymmetry in peak force at peak vGRF which may generate a different result.

Despite potentially being influenced by asymmetrical outputs at other joints in the kinetic chain, vGRF derived ILA's, are significantly associated with lower involved knee moments and knee work in post ACL-R patients (r2 ≥ 0.78, P <0.01) (Dai et al., 2014). These DL jump-land task derived asymmetries have also been described as "compensatory strategies" (Dai et al., 2014; Baumgart et al, 2017) to distinguish them from strength asymmetries obtained in single limb tests - a distinction discussed further below. Interlimb compensation or "avoidance" strategies in the DL-CMJ (and other DL-jump-land tests) manifesting as lower vGRF's on the involved limb appear to represent a protective central nervous adaptation aimed at attenuating loading of the reconstructed knee (Baumgart et al., 2017) or other other soft tissue injury, by shifting load to the uninvolved side. They may also be attributed to altered neuromuscular function, strength deficits, reduced range of motion, pain, and fear of reinjury (Sigward et al., 2018).

With respect to ILA's determined in the DL-CMJ versus the single leg CMJ It is relevant to highlight here that while values do correlate (figure 4) - this correlation is only moderate, and on an individual basis, asymmetries in the same metric may differ both in magnitude and direction. The potential causes and interpretation of this divergence is discussed in the Rehab toolbox module.

Figure 4: Correlation between DL-CMJ and SLJ ILA % in professional footballers during rehabilitation post ACL-R



SL=single countermovement jump
Source: Author's own (SGP-ACL study)

Figure 3 shows a number of the ILA metrics that can be used to characterise interlimb differences in aspects of neuromuscular qualities, phases and / or at specific time points. This substantial list of ILA metrics may seem overwhelming, and appear to have some redundancies, with several variables described that characterise the same phase. Indeed, a combination of time constraints and the need to process and consider a variety of data beyond the kinetic outputs of jump-land assessments in a high-performance (particularly team sport) environment demands a more parsimonious approach - in healthy players. When profiling a whole team or large group of healthy athletes to obtain a global picture of the ILA in each phase, the practitioner would not report or track all of these metrics and would instead use one ILA from the concentric/upward and landing phases and two from the eccentric/downward phase.

However, for practical and technical reasons, it useful to be aware of, and justifiable to use, a wider range of variables when working with a single athlete during rehabilitation as:

1) there is more time to devote to understanding the players status and trends and as the injured players is by definition, more vulnerable, a more thorough inspection of deficits and capabilities is warranted

2) there is limited time to prepare the athlete for exposure to the demands of competition and recover/potentially exceed their previous levels of neuromuscular performance, warranting a thorough examination of both deficits and the effectiveness of targeted reconditioning (is the loading driving the intended adaptations)

3) Injury can be an “opportunity” to not only rehabilitate the site of injury, but develop other neuromuscular qualities relevant to performance/and or robustness

Consider the various different metrics as potentially providing insights on specific neuromuscular qualities, subphases or points within the jump-land cycle.

For example, within the concentric phase, one can assess:

- **Concentric impulse / concentric mean force;** Representing the overall force asymmetry across the phase. Note: impulses and force asymmetries will have the same ILA % value but different units, and either may be used.
- **Concentric peak force**; the maximal instantaneous force within the concentric/upward phase, which depending on the athlete's waveform may occur at the beginning, middle or end towards the latter part of the phase (see “Force assessment and an introduction to Kinematics” course, Module 1 for waveform classifications), and its position may also shift during rehabilitation as a consequence of alterations in waveform shape.
- **Concentric impulse-100**; impulse calculated during the first 100 ms of the phase. Representing the early upward phase impulse from a displacement perspective (i.e. coming out of the lowest position during the upward phase) and from a neuromuscular quality perspective, as a more time constrained metric, reflecting rapid force production.

- **Force @ concentric peak power**; like peak force, asymmetry at a single point, but in contrast con peak force, due to being anchored position-wise to concentric peak power, this metric always reflects ILA near to full knee extension and start of plantar flexion - where con peak power occurs.

The figure does not show other subphase divisions that may prove to be useful such as: ILA for P1 and P2 concentric impulse (1st and 2nd 50% timewise of concentric phase, respectively) or for impulse pre-peak power v impulse post-peak power. Future work may identify metrics that are more sensitive to specific types of injuries or we observed with respect to graft type used for ACL-R (discussed below).

Asymmetries in rehabilitation - one piece of the kinetic puzzle

It is important to underline that with respect to the value of the DL-CMJ and other jump-land kinetic and performance data in informing on status and progress of neuromuscular status during rehabilitation, ILA percentages is a high-level marker and equal or greater emphasis should be placed on trends in absolute output from injured and uninjured limb. It is also important to consider trends in percentage ILA of certain DL-CMJ metrics in the context of the trends in total/COM metrics. For example: eccentric deceleration RFD alongside eccentric peak velocity and countermovement depth and peak landing force asymmetry alongside landing vGRF and jump height relative landing vGRF. Furthermore, as in the monitoring of healthy athletes, in addition to reporting the conventional performance outputs (i.e., jump height and concentric peak power), bilateral kinetic metrics should also be examined. As in the healthy athlete the trends in performance and kinetics outputs may diverge, providing additional insights around underlying alterations in specific neuromuscular qualities/phases and subphases. Furthermore, in addition to the calculation of metrics considered as neuromuscular qualities, whole body (COM) displacement and velocity during eccentric, concentric, and landing phases providing “proxy” kinematics (i.e., COM position, not joint-specific). Integrating and interpreting these bilateral performance and kinetic data, left and right outputs and ILA asymmetries is discussed in the Rehab toolbox module.

ILA metrics - what values to expect

While, as mentioned above, in the literature, a range of DL-CMJ ILAs are reported for athletes in rehabilitation following ACL-R. However, as values for, and analysis of, a number of ILA metrics of potential interest remain unpublished, to provide further guidance to the practitioner we also display the results of a comprehensive analysis of professional footballers during rehabilitation following ACL-R. This study (designated SGP-ACL) was an exploratory analysis of data from professional players at the St.George's Park (SGP) professional footballers association residential rehab program.   to determine the metrics that most strongly distinguished the ACL-R from the healthy player and secondarily, if these results differed according to the graft type.

While discussed below in more detail in the section Calculating and expressing asymmetries, it is pertinent to highlight here that ILA percentages are most commonly calculated using one of two formulas which result in different % values.

Bilateral strength asymmetry (BSA) (Impellizzeri et al., 2007): (stronger limb - weaker limb) / (stronger limb) x 100

Bilateral asymmetry index-1 (BAI-1) (Kobayashi et al., 2013): (stronger limb - weaker limb) / (stronger limb + weaker limb) x 100

Note that stronger and weaker referring to higher and lower values respectively

Table 1a, b, c below provides ILA data on 39 post ACL-R professional footballers a mean of 5.3 months post ACL-R, in comparison to 24 similar level healthy "controls". Values for all variables are mean and SD for % absolute asymmetry (calculated using the BSA) and comparisons made between the ACL-R and healthy groups and effect size (ES) for the difference determined (ES of 0.2-0.5=small, 0.5-0.8 = moderate, 0.8-1.2 = large difference and > 1.2= very large). The comparison with healthy controls is important as we would expect a degree of ILA in these athletes, and the aim is to try and separate injury driven ILA from "normal" ILA.

Table 1a shows that for all the eccentric/downward phase examined, ILA was significantly higher in post ACL-R than control players. However, these metrics show substantially different magnitudes of difference. In particular, eccentric deceleration RFD displayed the largest effect size difference between injured and healthy players, which was more than double that of eccentric deceleration impulse. Note also that while yielding RFD had the largest magnitude of ILA percentage-wise in ACL-R players (31.5%), it was also large in control players (21.7%), and as such the difference and "sensitivity" to injury was lower than other downward phase metrics.

Table 1 (a,b,c): DL-CMJ Asymmetries in professional Footballers 5 months post ACLR (n=39) v Controls (n=24).

a. Eccentric / downward phase metrics

Metric	Control	ACL	P value	Effect size
Yielding RFD	21.7 (20.5)	31.5 (16.4)	0.04*	0.54
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
Deceleration Impulse	11.7 (10.2)	18.3 (13.0)	0.04*	0.55
Force @ Velocity	10.3 (8.8)	18.4 (10.6)	0.003***	0.81

Source: Prepared by the author

All concentric/upward phase variables showed significant large to very large effect size differences despite lower absolute % values in ACL-R players than seen in the downward/eccentric phase. The far lower ILA's in this phase in the healthy players underlying the high sensitivity of metrics in this phase to the effects of ACL-R. Force @ peak power showed the largest ES difference.

1.b Concentric/ upward phase metrics

Metric	Control	ACL	P value	Effect size
Impulse	5.9 (4.2)	18.3 (8.8)	<0.001***	1.67
Impulse-100	8.0 (6.8)	17.8 (9.9)	<0.001***	1.10
Peak Force	22.8 (13.3)	13.4 (11.5)	< 0.001***	1.34
Force@PeakPower	4.2 (2.9)	17.9 (8.9)	<0.001***	1.89

Source: Prepared by the author

In the landing phase, peak landing force best differentiated ACL-R and healthy players amongst some of the typical landing metrics examined. Also note that time constrained impulse on landing (impulse 70 ms) ILA displayed a substantially higher value in the post ACL-R players (36.7%) than overall impulse (24.3%), but similar values in controls, corresponding to a larger effect size difference (1.18 versus 0.85).

1.c Landing phase metrics

Landing	Control	ACL	P value	Effect size
Impulse	13.3 (9.0)	24.3 (14.8)	*0.002***	0.85
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
RFD	10.7 (7.4)	29.5 (21.2)	*< 0.001***	1.0

Source: Prepared by the author

Aside from case studies discussed in the Rehab toolbox module, there are few other examples of values (calculated using BSA) for these metrics in athletes undergoing rehab following ACL-R with which to compare these results and determine whether these values are generalisable and can be used as a guide or target in relation to other athletes undergoing rehabilitation following ACL-R. The use of external normative data in the rehab process and trajectories of improvement is also elaborated on in the Rehab toolbox module.

Read et al., 2020 reported DL-CMJ performance metrics (jump height and peak power) and selected involved and uninvolved limb eccentric and concentric and peak landing outputs and ILA% in a large sample of Qatari professional players at different time points of their rehabilitation post ACL-R (n=166) and in healthy control players - a large (n=204) and likely representative sample of healthy players in the same league. This was not a longitudinal study that tracked the same players tracked through rehabilitation, instead it reports data for different players evaluated at different stages of rehabilitation; < 6 months (mean 19.5 ± 1.9 weeks), 6-9 months (mean 29.1 ± 3.2 weeks), > 9 months (46.0 ± 6.7 weeks). The ILA% data that it presents is not directly comparable to Hart, Cohen et al., 2020 or SGP-ACL as ILA were calculated using BAI. This also applies to the asymmetry quartiles by timepoint that they also provide as a potential reference data with which to classify a given ILA value determined in an ACL-R (or healthy) athlete in your care. Nonetheless, it provides useful insights into DL-CMJ neuromuscular "trends" during rehabilitation following ACL-R. In table 2a., the published data is shown for ILA's, in table 2.b, we have estimated (converted) these values to BSA ILA for easier comparison to other literature cited.

Table 2: ILA in professional footballers at different stages of rehabilitation versus healthy controls

Values from Read et al., 2020 (calculated using BAI-1)				
	< 6 mth	6-9 mth	> 9 mth	healthy
Concentric impulse	11.3±5.8 (9.1-13.4)	9.6 ± 5.6 (8.2-10.9)	7.4 ± 5.1 (6.0-8.8)	2.8 ± 1.8 (2.5-3.1)
Concentric peak force	9.3 ± 5.0 7.4-11.1)	8.0 ± 4.3 (6.9-9.0)	6.6 ± 4.2 (5.5-7.7)	3.0 ± 2.1 (2.7-3.3)
Eccentric deceleration impulse	10.4 ± 7.2 (7.7-13.0)	10.2 ± 6.2 (8.7-11.6)	8.5 ± 5.8 (6.8-10.0)	6.0 ± 4.5 (5.3-6.5)
Eccentric deceleration RFD	17.3 ± 11.6 (13.0-21.5)	15.3 ±12.8 (12.2-18.3)	14.7 ± 11.1 (11.6-17.6)	8.6 ± 7.4 (7.6-9.6)
Peak landing force	15.8 ± 12.4 (11.2-20.3)	13.8 ±11.3 (10.8-16.8)	11.2 ± 8.8 (8.7-13.5)	8.7 ± 6.6 (7.6-9.6)
Data is mean ± standard deviation (lower and upper confidence intervals)				
Read et al., 2020 data converted from BAI-1 to BSA (mean values only)				
	< 6 mth	6-9 mth	> 9 mth	healthy
Concentric impulse	20.5	17.5	14.0	5.5
Concentric peak	17.0	15.0	12.5	6.0

Eccentric deceleration impulse	19.0	18.5	15.5	11.5
Eccentric deceleration RFD	29.5	26.5	25.5	16.0
Peak landing force	27.5	24.5	20.0	16.0

Source: Read et al., 2021

Notably, while for all kinetic ILA's assessed the mean magnitude of ILA was lower the further from surgery, even the > 9 months group (players who on average were 10.5 months post-surgery) eccentric, concentric and landing phase kinetic ILAs were significantly higher than that observed in the healthy matched controls. Similarly, while the bilateral performance variables in this group - jump height and peak power - values were also still significantly lower than observed in controls. As such, while significant lower ILA and higher bilateral performance were observed when comparing some those later in the rehab process (> 6 months) than < 6 months, values were generally not significantly better in the > 9 months group. Only concentric peak force and impulse showed significantly lower ILA in > 9 versus < 9 months post ACL-R. Despite this, elevated concentric impulse ILA was the metric that most consistently differentiated between ACL-R from controls and most strongly associated with a history of ACLR in this cohort.

Interestingly, eccentric deceleration impulse values at >9 months were not significantly different from that of healthy individuals. However, eccentric rate of force development (a metric from the same subphase) was significantly lower, aligning to the findings of SGP-ACL (table 1a above) and in previously injured footballers shown below in table 5 (Hart et al., 2019) as well as with case studies in the literature (Taberner et al., 2020) and presented in the Rehab toolbox module. This is an important distinction suggesting that relative to overall force production/reduction during deceleration which tends to recover earlier post-ACLR, the capacity to reduce forces at a high rate and rapidly decelerate body mass during this eccentric/downward phase is delayed, or that the avoidance of high rates of loading persists longer (Baumgart et al., 2017b). The restoration of this capacity is vital for the athlete returning to high level sports which have considerable changes of direction, intense decelerations and landing demands, activities that place the highest loads on the ACL and are the common mechanisms of rupture (Beaulieu et al., 2023).

Effect of graft type on DL-CMJ asymmetry and performance

As discussed in module 1 of this course, use of BPTB versus HT graft type for ACL-R can result in angle specific differences in quadricep and hamstring torque (Hart et al., 2022). Consideration of the specific force production and absorption differences between graft post ACL-R can contribute to a more targeted approach in terms of S & P diagnostics and reconditioning. While the BPTB is associated with a lower risk of ipsilateral (re)rupture greater alterations in mechanical loading and interlimb compensatory strategies (Miles et al., 2022) could be a contributory factor in the higher incidence of contralateral re-rupture following BPTB versus HT grafts. In the SGP-ACL, we observed that BPTB players had higher DL-CMJ ILA values in specific metrics and differences are reported in multisport athletes (Miles et al , 2019). Graft type differences in joint kinematics are also reported in change of direction (Miles et al., 2022) and in gait (Webster & Feller, 2011) but not in single limb landing tasks (Webster & Feller, 2012).

Miles et al. (2019) compared DL-CMJ concentric, eccentric, and landing absolute asymmetry impulse ILA in multidirectional sport athletes with BPTB (n=22) versus HT (n=22) grafts at approximately 9 months post-surgery. They also examined a healthy control group. Significant differences in magnitude of ILA according to graft were found; eccentric deceleration impulse ILA was nearly 2-fold higher in BPTB (20% ILA) than HT (10% ILA) graft athletes and concentric impulse was also significantly higher in BPTB (13%) versus HT (8%), whereas differences between BPTB and HT in landing impulse were smaller and non-significant. However, compared to the control group (12% asymmetry) BPTB graft athletes this difference was significant whereas HT versus control differences were not.

Contrasting this data with an analysis of the SGP-ACL data (table 3 below) according to graft type revealed some similarities with the findings of Miles et al, and also some key differences. While the magnitude of ILA would be expected to be greater in SGP-ACL due to the earlier time point of assessment relative to surgery (at approximately 5 months). Like Miles et al, in the SGP-ACL group BPTB was higher than HT ILA in the jump phase (eccentric/downward and concentric/upward). However, overall differences in impulse were not significant in either phase, instead eccentric RFD (BPTB: 27.4%, HT: 15.4%) and concentric impulse-100 (BPTB: 20.8 %, HT: 15.8%) distinguished graft type with significant and moderate to large effect sizes. This again highlights the importance of considering rate or time constrained metrics in analysis and shows their superior sensitivity in distinguishing the effects of a specific input - in this case differentiating graft type. In terms of contextualising the level of athlete, mean jump was approximately 28 cm at 9 months post ACL-R compared to approximately 34 cm in the AGP-ACL sample at around 5 months post-surgery (table 4).

The SGP-ACL athletes were professional players with full time rehabilitation daily, with professional sports rehabilitation, strength, and conditioning and physiotherapy staff, which may have impacted on their improved overall recovery and minimised differences, yet these higher sensitivity metrics still identified differences which can as highlighted in module 1 with respect to isokinetic torque-angle differences, guide towards a more graft-specific monitoring and loading to identify and target neuromuscular deficits.

Table 3: DL-CMJ ILA in professional footballers (SGP-ACL) during rehabilitation following ACL-R according to graft type

Absolute Asymmetry (%)	**Eccentric/Downward**		**Concentric/Upward**		**Landing**
Mean (SD)	**Impulse**	**RFD**	**Impulse**	**Impulse - 100 ms**	**Peak Force**
BPTB	20.0 (13.7)	**27.4 (12.7)**	20.1 (8.7)	**20.8 (9.4)**	24.5 (16.4)
HTA	15.8 (11.5)	**15.4 (10.8)**	16.1 (8.7)	**13.5 (9.6)**	29.4 (16.9)
p value	0.34	**0.00***	0.18	**0.03***	0.38
Effect Size	0.32	**0.91**	0.45	**0.73**	0.30

Source: Prepared by the author

BPTB=players with bone-patellar-tendon-bone grafts (n=25); HTA=players with hamstring tendon graft (n=14); RFD=rate of force development;

P value and effect size calculated for comparison between absolute asymmetry values in BPTB v HTA. * Indicates a significant difference.

Interestingly, as shown in table 4, we found no significant graft type differences in DL-CMJ bilateral performance and kinetic metrics and no significant difference in the SLJ-height. Miles et al., 2019 also did not find graft specific differences in DL-CMJ jump height but did not present SLJ data.

Table 4: Double leg and single leg CMJ performance in professional footballers during rehabilitation following ACL-R according to graft type

Double leg CMJ (Bilateral Performance)			Single leg Jump
Mean (SD)	**Jump Height (cm)**	**Flight time: Contraction Time**	**Jump Height (cm)**
BPTB	34.0 (6.0)	0.63 (0.13)	21.8 (9.7)
HTA	34.6 (4.9)	0.61 (0.14)	22.5 (12.3)
p value for difference	0.76	0.70	0.88
Effect Size	0.10	0.13	0.06

Source: Prepared by the author

Residual deficits / persistent CMJ ILA asymmetries

As highlighted in module 1 of this course, residual deficits, as characterised by ILA in neuromuscular performance, are observed years after RTS. With respect to jump-land kinetic-ILA observed in healthy athletes with prior injury, the major driver and largest volume of research around force platform-assessed jump-land kinetics in relation to injury was driven by the interest in understanding modifiable risk factors for primary ACL rupture, and reinjury in female athletes. Hewett, Myers and colleagues at the Cincinnati Children's Hospital in the early 2000's used the DL-drop jump as an assessment tool to identify kinetic and kinematic patterns and asymmetries associated with prior ACL and to screen for risk of reinjury (i.e

Hewett et al., 2005; 2006; Paterno et al., 2015). Drop jump screening research later became increasingly focused on 3D biomechanics and variables related to joint moments and joint angles, with little examination of vGRF kinetics with some more recent exceptions (King et al.,2021a, b) discussed in the Drop jump and single leg drop jump section of the Rehab toolbox module. The earlier studies noted asymmetries DJ-landing asymmetries in female athletes' years after RTS following ACL-R (Paterno et al., 2007) characterised as residual deficits or persistent avoidance strategies.

DL-CMJ residual deficits

Elevated DL-CMJ kinetic ILA are also reported months to years after rehabilitation and return to high level training and competition. Cohen et al., (2014) and Jordan et al, (2015) were the first to report higher asymmetries in specific CMJ-DL metrics in elite male athletes with prior severe lower limb injury (not only ACL-R), and prior ACL-R, respectively. Jordan et al., 2015 examined ILA in the jump phase in elite skiers at a mean of 26.2 (± 11.8) months post ACLR. Using the asymmetry index (AI) (see below Calculating and expressing asymmetries), Jordan et al (2015) compared ILA in the CMJ and squat jump in a small sample of male and female elite skiers with (n=9) or without (n=9) a prior ACL-R. Despite having the substantial period of time since surgery and return to sport, concentric impulse ILA was significantly higher (mean AI:6.8%, confidence interval (CI): 1.5 to 12.0) than in skiers without a history of ACL-R (mean AI: 0.6% CI: −1.3 to 2.4). The only other ILA metric they examined - eccentric deceleration impulse - higher in those with prior ACL-R (mean AI: 5.2%, CI: −4.5 to 14.9) than in uninjured athletes (mean AI: 1.0%, CI: −1.5 to 3.5) but this difference was not significant. The authors highlight that one of the injured athletes displayed had 16.5% higher eccentric deceleration impulse on their previously injured side, which in a small sample can impact statistical analysis - the larger confidence interval for eccentric deceleration impulse AI; from -4.5 % favouring the injured limb to 14.9% favouring the uninjured side, is indicative of a wider range of values in the injured athletes is a manifestation of this. They also note that the athlete with the highest eccentric deceleration impulse AI value (20.5%) subsequently suffered a contralateral limb medial collateral ligament injury. Other data referred to in this module support the sensitivity of eccentric deceleration phase ILA - particularly eccentric deceleration RFD.

Although in a non-athletic cohort, Baumgart and colleagues work (2017a, b) are important in advancing the understanding of post ACL-R residual kinetic ILA's. In these studies, they examined DL-CMJ, SLJ, isokinetic strength, and other neuromuscular performance assessments in a cohort of patients a mean 31 (±7) months post-surgery - years after returning to normal activities post-ACLR. They also stratified patients according to high or low International Knee Documentation Committee (IKDC) score - a standardised questionnaire which assesses perceived knee symptoms, function and sporting activities (higher scores=better function) allowing them to not only compare ILA values in patients versus healthy controls, but also in high v low function patients.

In their first study, injured v uninjured limb outputs and asymmetries were calculated for four vGRF CMJ metrics: take-off phase net impulse (i.e., a composite of eccentric deceleration + concentric impulse) and peak force, landing impulse and landing peak force. A lower functional score was not associated with a lower jump height (high function: 27.2 ± 8.7; low function: 28.4 ± 8.7, non-significant). There were significant differences in involved v uninvolved limb in all 4 CMJ metrics, however only the landing peak force (LPF) (but not landing impulse) and takeoff impulse (TOI) asymmetries (but not take off peak force) were significantly higher in the low function (LPF:16.8 ± 14.1, TOI: 33.3 ± 23.4) than high function (LPF: 7.9 ± 13.3, TOI: 1.3 ± 35.4) patients. They performed a second more comprehensive analysis of take-off phase kinetics within the same cohort (Baumgart et al., 2017b). They noted that significantly lower peak force, force at zero velocity, eccentric (deceleration) impulse and concentric impulse in the patients with ACL-R history, but that the eccentric/downward did and the concentric/upward metrics did not differentiate high versus low IKDC score. They also performed functional data analysis; an analysis of normalised waveforms comparing involved and non-involved limb outputs across the take-off phase in high versus low function patients. This analysis confirmed that the eccentric deceleration phase was the predominant area of DL-CMJ interlimb compensation strategy. Notably, despite these significant strategies identified in the DL-CMJ, while IKD quadricep peak torque ILA values were higher in low (11.4 ± 22.0) versus high (6.4 ± 10.3) function patients, these differences were not significant. Potentially aligning with this finding given that both are single limb assessments and significant associations between SLJ-height and IKD performance are reported (Petschnig et al, 1998; Ohji et al., 2021), only one SLJ ILA metric examined significantly differed according to knee function - force at zero velocity - and jump height ILA did not. The role of the SLJ in RTS post ACLR is discussed in the Rehab toolbox, but Baumgart's findings question its sensitivity in the detection of deficits and function, relative to the DL-DMJ, at least in ACLR patient cohorts.

Baumgart concluded that "patients with high subjective knee function (1) a reduced eccentric load, (2) an inter-limb compensation during bilateral movements, and (3) the avoidance of high vertical impact forces". Similarly, Cohen et al., (2014), found that significantly higher DL-CMJ peak landing but not peak take-off force ILA differentiated healthy elite footballers in preseason who had or had not sustained a lower limb injury leading to > 7 days of time loss in the previous season.

Hart et al. (2019) performed the most comprehensive analysis metric-wise of DL-CMJ ILA's exploring multiple asymmetry metrics from both the eccentric and concentric phases in athletes with prior injury but RTC. The aim, like SGP-ACL, was to determine if sensitivity to prior injury differs across a range of variables representing different points within the jump cycle. An important finding of Hart et al, confirming what we highlighted during rehabilitation in SGP-ACL is that prior injury is associated with increased ILA in specific metrics rather than elevated asymmetries globally.

Stratification was done according to whether or not during the prior season they had had a severe unilateral lower limb injury (defined as >28 days' time loss due to injury). This included both muscle, ligament and tendon injuries, but the majority of were ligament or cartilage (58%), mainly knee and also ankle (30%). Note that eccentric deceleration RFD asymmetries were significantly higher in the previously injured group, with a large effect size, while the eccentric deceleration impulse differences were not - a key finding in the context that eccentric deceleration impulse has been proposed in preference over eccentric deceleration RFD due to former's greater reliability.

Table 5: Selected DL-CMJ ILA in healthy professional footballers

Asymmetry	Status	Absolute asymmetry (%) Mean ± SD	Effect size for difference
Concentric impulse*	Mixed	6.0 ± 4.9	
	Previously injured	7.7 ± 3.7	1.1
	Uninjured	4.1 ± 2.8	
Concentric peak force*	Mixed	3.7 ± 5.0	
	Previously injured	9.3 ± 5.9	1.4
	Uninjured	3.4 ± 2.3	
Eccentric deceleration impulse	Mixed	10.1 ± 7.8	
	Previously injured	12.1 ± 8.6	0.24
	Uninjured	10.3 ± 7.3	
Eccentric deceleration RFD*	Mixed	13.8 ± 11.3	
	Previously injured	20.5 ± 10.6	1.05
	Uninjured	10.5 ± 8.2	

Source: Hart et al 2019

All players were considered healthy at time of testing. Previously injured and Uninjured, were players with, or without, at least one severe lower limb injury (> 28 days' time loss) in the previous 12 months (data from Hart et al., 2019); Mixed= a separate sample of healthy professional footballers (author's own source), independent of previous injury history

*Indicates a significant difference ($p < 0.05$) in % asymmetry between previously injured and Uninjured groups

Cutpoints

It is important to be aware that there is not sufficient data from prospective studies of primary or secondary (recurrence) injury incidence in relation to the baseline DL-CMJ asymmetries to establish these cut-points based on risk. Until then, we recommend that practitioners use variable-specific statistical cut-points based on mean and standard deviation when aiming to classify a given magnitude of DL-CMJ kinetic asymmetry in an athlete as normal or elevated. Data from studies such as during, following Hart et al, 2019; Read et al., 2020 and SGP-ACL, indicate that these cutpoints for classification should be not only phase-, but also variable-, specific Cohen & Kennedy, 2021). For example, in table 5 above, different variables within the same phase or subphase may yield substantially different values and importantly, these variables also show a different strength of association to prior injury). Therefore, either applying “conventional” standards for elevated asymmetry such as 10% or 15% (which may or may not be valid cutpoints in other strength, power or functional tests) or use of a global cutpoint for all CMJ asymmetries is likely to result in misclassification. This may also prove to be the case in relation to kinetic asymmetries in other jump-land tests, but this has yet to be examined sufficiently.

Calculating and expressing asymmetries

When reading research and when using force platform software which calculates auto calculates variables it is important to be aware that interlimb asymmetry can be calculated in a number of different ways. The use of different formulas can result in substantially different values which can obviously influence your interpretation and potentially complicate comparisons of data collected with that literature evidence or data shared with you by another practitioner. Bishop et al. (2021) provides a thorough discussion and examples of the various calculations. However, with respect to the calculation of asymmetries in the DL-CMJ or DL-DJ or other bilateral jump-land or isometric tests the most common formulas used in research and software are the “bilateral strength asymmetry” (BSA) and the bilateral asymmetry index-1 (BAI-1). Contrasting the data in tables 2a and 2b above, illustrate the discrepancy between the interlimb asymmetry % generated by these formulas based on the same L and R limb outputs obtained in a DL-CMJ:

BSA: ((stronger limb - weaker limb) / stronger limb)) x 100

BAI-1: ((stronger limb - weaker limb)/(stronger limb + weaker limb)) x 100

Bishop et al. also argue that while the BSA formula used in Impellizzeri et al’s (2007) landmark work is the most appropriate formula to use when calculating interlimb asymmetries derived from single-limb testing, the BAI-1 is a more appropriate formula for use in determining interlimb asymmetries during bilateral (double leg) tests. They also highlight the more complex symmetry angle formula (Zifchock et al. 2008), which avoids the issue associated with other asymmetry indexes - in that the values would be different depending on which leg is used as reference. While these are (valid) methodological points, the no formula has been shown to be better at detecting prospective risk, residual deficits following prior injury - these comparisons have yet to be examined in research. Also note that the BSA is widely used in research studies of DL-CMJ (Hart et al., 2019; Jordan et al., 2015) and by the most widely used force platform system in sports: Vald Performance-ForceDecks. However, as other software systems and research (Read et al, 2020) may use BAI, LSI or other formulas, the important message is that, which Bishop et al (2021) highlights, is that practitioners should be aware of the variety of formulas and should read the methods sections of asymmetry research to determine whether or not the information is directly comparable to the ILA's your database. If either the reference ILA's or yours would need to be recalculated to enable valid comparison.

Also note, that in addition to calculating asymmetries according to a given formula, the practitioner, researcher or software may express the resulting % value using absolute (i.e. positive) values, or they may be presented with a +ve or -ve directional sign. For example, a negative % value indicating a higher value on the left, and a positive value a higher value on the right. Data is expressed in this way in some force platform software also and has been used in some research studies to describe the mean for the population (Jordan et al. 2015). Note, however, that retaining a negative sign when characterising asymmetry within a normal (i.e., uninjured) population can result in a mean asymmetry of around 0 as the negative and positive values cancel each other. As such when examining and presenting the asymmetry profile in a group of healthy athletes, it is useful to report data in your group in both ways (as shown in the Rehab toolbox module). As described above with respect to the calculation of the LSI, which assumes using a reference of injured and healthy limb this is much simpler.

Summary

- The DL-CMJ is a simple, reliable and easy to implement tests which with many athletes are familiar and for whom historical healthy preinjury benchmark data is often available.
- Dual force platform DL-CMJ provides bilateral performance and kinetic data, and involved and uninvolved outputs from which ILA can be calculated - representing compensatory strategies and reflects underlying deficits in knee performance
- The DL-CMJ can be used throughout the RTS pathway to inform on chronic and short-term responses to training load/types and can be complemented with other more demanding jump-land (and isometric) assessments
- Specific ILA metrics within the eccentric/downward, concentric/upward and landing phases show greater sensitivity to current and prior injury
- Within the eccentric/downward phase deceleration or overall eccentric RFD appears to provide the greater sensitivity to prior injury than overall impulse in the phase and to better distinguish graft type specific deficits. Similarly, in the landing phase peak or time constrained impulse show superior sensitivity.
- Concentric/upward phase metrics are strongly affected by ACL-R and show high sensitivity to prior injury, with the time constrained impulse (con impulse-100) distinguishing graft type.
- These specific ILA metrics can be used to identify graft-specific deficits that are not detected by jump height DL or SL, and can be used to better inform the targeting of-specific conditioning and quantify response to this loading.
- While there are sources of normative data for ILA that can be used as a guide to estimate relative status and progress at specific post-surgery time points, for a valid comparison ILA must be calculated using the same formula.
- Practitioners should also be aware of the substantial differences in reported values within the category of “professional athletes”

The Rehab toolbox module will go beyond mean data for groups and present case studies and perspectives that address the individual variabilities and context, necessary to consider in the use of this objective data. It will also elaborate on the information provided by other jump-land assessments.

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