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

1. Declines in contralateral healthy limb performance undermine the value of a limb symmetry index as a benchmark for RTS.

2. Normalisation of output variables such as distance hopped does not equate to recovery of underlying functional deficits identified by biomechanical assessment of movement strategy.

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

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

"the SL test provides a more valid measurement of a limb’s strength or power..."
and inter-limb symmetries, while data from the DL CMJ should be interpreted with caution".14

"bilateral movements were more suited to reveal possible asymmetries in GRFs, because the patients could spread the load between the legs and use inter-limb compensation strategies".1

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

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

A greater understanding of neuromuscular performance deficits and individual responses post-ACLR can enhance the individualisation of exercise prescription and underpin a "precision medicine" approach in rehabilitation. The ultimate aim of a reduction in the figure of < 1/2 of players returning to competitive sport after ACLR15 and reducing risk of re-injury.

Why the DL-CMJ?
Evidence from training and fatigue-response literature demonstrate bilateral DL-CMJ variables provide valuable insights on underlying movement/kinetic strategy and in particular, the potential to quantify eccentric or "deceleration" performance5,6,9,18 during a high velocity triple extension activity. Force platform assessment of CMJ performance following fatiguing exercise or after training interventions have shown that compared to "conventional" output variables such as jump height and peak power, specific bilateral "alternative-variables" such as flight time:contraction time (FT:CT) are more sensitive markers of acute and residual fatigue and chronic training adaptations9. For example, acute and residual fatigue following competition or high intensity intermittent activity, may not manifest in a reduction in jump height but is expressed in alterations in jump strategy including increased duration of the eccentric and concentric phases and total contraction time9,20 and changes in other kinetic variables. Therefore, while there is a justifiable interest in phase-specific asymmetries and/or deficits5,9,10,11,13, evidence9 case studies9 and the authors’ experience with athlete rehabilitation informed by force platform data for over two decades suggests that bilateral DL-CMJ strategy variables also add insight into athlete status and response to loading during rehabilitation and RTS. This aligns with the evidence that recovery of performance output (i.e. distance hopped) in clinical hop tests may mask persistent strategy deficits following ACLR11,22. Further supporting this, a recent review concluded that single leg hop for distance (SLHD) asymmetries post-ACLR do not reflect residual functional deficits detected by biomechanical alterations in take-off and landing strategy. For example, kinematic analysis of hops in patients post-ACLR showed both those with and without hop distance symmetry off-loaded the ACLR knee. An asymmetrical hop distance was associated with an ankle dominant strategy while symmetry was associated with a hip dominant strategy. Similarly, King21 found no significant inter-limb differences in either hop distance or performance times in change of direction tasks 9 months post-ACLR but did identify several significant kinetic and kinematic asymmetries during the performance of these movements. Therefore, achieving symmetry in performance outputs in common clinical tests does not appear to equate to either knee kinetic symmetry during the tests or to symmetry in other athletic tasks. While defining the precise nature of these biomechanical alterations requires kinematic analysis, and in the absence of this technology, CMJ vGRF derived eccentric, concentric and landing phase bilateral variables and asymmetries may provide a surrogate means to identify and quantify alterations and deficits in both neuromuscular strategy and capacity that underpin movement55.
Since horizontal hop test variants are more commonly used clinically, fewer studies describe SL-CMJ performance post-ACLR, yet SL-jump height asymmetries are reported both at 6 months\textsuperscript{23,24} and > 2 years post ACLR\textsuperscript{25}. Therefore, while SL-CMJ is moderately correlated with isokinetic knee strength,\textsuperscript{25} in parallel with the observations around SLHD post ACLR, SL-jump height may not reflect knee kinetic deficits due to inter-joint compensations at the ankle and hip\textsuperscript{26,27}.

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

DL activities provide more options to unload the previously injured knee; primarily via inter-limb (involved limb to uninvolved), compensatory or avoidance strategies\textsuperscript{18,20} easily quantified by vGRF alone, and also inter-joint (involved knee to involved ankle and hip) strategies\textsuperscript{27,28} which require kinematics to quantify. When considering the “value” of SL Vs. DL-CMJ asymmetry data and relevance to functional outcomes, Baumgart and colleagues’ work\textsuperscript{29} which assessed individuals 32 months post-ACLR with both tests, provides an important observation; all DL-CMJ vGRF asymmetries they evaluated showed large and significant differences in individuals with high compared to low subjective knee function, while asymmetry in SL-CMJ jump height did not.

**SL vs. DL jump – Strategy vs. Capacity?**

A mismatch between single v double limb asymmetries is also observed in supported SL v DL isometric knee extension tasks\textsuperscript{27}, indicating that this phenomenon is not exclusive to jump-land activities. Furthermore, as asymmetries are also expressed during submaximal bilateral contractions where maximal limb capacity is not limiting, researchers and clinicians have emphasised the neural origins of bilateral task asymmetries\textsuperscript{23,28}. In recent work in post-ACLR patients, Chan & Sigward\textsuperscript{28} showed that asymmetries during (submaximal) squat and sit-to-stand tasks could be acutely corrected with instructions and real-time feedback, indicative of their loading behaviour not reflecting their capacity to load. Chan & Sigward suggest that asymmetries in DL activities may be driven by “learned non-use”, a phenomenon described in post-stroke patients, whereby individuals with unilateral neurological deficits with the ability to use the involved limb choose not to when given the option of preferred limb selection, but do so when the uninvolved arm is constrained\textsuperscript{29}.

Given evidence that asymmetries in SL-CMJ and drop jump performance are associated with poorer change of direction (COD) ability\textsuperscript{9}, and SL-CMJ landing force asymmetry with lower limb injury risk in youth footballers\textsuperscript{9}, SL measurements clearly provide valuable information, at least in healthy athletes. However, quantifying kinetic compensatory strategies following ACLR by simultaneous capture of vGRF in both limbs during the same task\textsuperscript{28} is a critical part of understanding progress during rehabilitation and in light of the persistence of these asymmetries in player's post return to competition (RTC), of informing “post-hab” i.e. conditioning to address residual deficits not addressed prior to RTS.

**SL v DL asymmetries post-ACLR in professional footballers**

Figure 1 shows selected SL-CMJ and DL-CMJ asymmetries in post-ACLR professional footballers (mean 24 weeks and 32 weeks’ post-surgery) (un-published data). These values broadly align with that reported in non-elites 18 months post-ACL\textsuperscript{1} and in professional footballers with various prior lower limb injuries post-RTC\textsuperscript{12}, both underlining the persistence of specific asymmetries, and also suggesting that the inter-limb compensatory strategies are not exclusive to ACL injury. In terms of load reduction/acceptance capacity, data derived in the CMJ eccentric deceleration (ED) and landing phases are of specific interest. The magnitude and effect sizes of asymmetries observed in these phases in healthy individuals with prior injury suggest that inter-limb compensatory strategies which reduce eccentric loading and impact forces are highly persistent\textsuperscript{9,12} and may require special attention.

**“Anatomy” of the SL- and DL-CMJ**

Using body segmental mass ratios, it can be estimated that active leg load in a SL movement is ≈1.62 times of those in a DL movement. Similarly, using SL and DL-
CMJ peak force data in (N = 15) healthy professional male players (Table 1), we estimate a similar ratio in concentric peak force of 1.60.

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

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

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

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<th>SL-CMJ</th>
<th>DL-CMJ</th>
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<td><em>Concentric peak ground reaction force (N)</em></td>
<td><strong>Left</strong></td>
<td><strong>Right</strong></td>
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Inadequate acceleration in the countermovement descent is analogous to testing car brakes at 5 mph – yes it provides information, but would you consider data obtained under those conditions valuable in informing decisions you need to make on the readiness of those brakes for use on the highway at 70 mph?

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

**Table 1**

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**Figure 2:** What are the speed and depth differences in Bilateral Vs Unilateral CMJ? And how do these differences change in ACL-R at 6 months vs healthy athletes? % BW refers to the % of body weight each limb is supporting.
produce adequate velocity in the SL-CMJ to acquire valid, usable eccentric data.

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

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

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

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

Figure 3: DL-CMJ injured and injured limb force-time curves, and selected outputs and asymmetries in an elite player measured at 6 and 8 months post-ACLR. Inj. = Injured; Uninj. = Uninjured; Con. = Concentric; Ecc. = Eccentric; decel. = deceleration; RFD = Rate of force development; ILA = Absolute inter-limb asymmetry (%).
For example, if the trends shown for the player in figure 3 were interpreted solely on the basis of changes in EDRFD asymmetry %, one might conclude that performance in their injured limb had deteriorated. The player does however exhibit some progress, indicated by the absolute increase in the magnitude of EDRFD in that limb, their increased asymmetry being due to the healthy limb taking a larger share of the increased deceleration demand resulting from higher EPV. Ideal deceleration capacity progress is however exemplified by player 2 (table 2); increased overall eccentric demands (increased EPV and total EDRFD) accompanied by a decrease in injured limb off-loading (reduced EDRFD asymmetry) due to a larger increase in EDRFD on the injured vs. uninjured limb. Also note their large increase in FT:CT, alongside a minimal increase in jump height – showing that these bilateral strategy/kinetic variables are able to identify underlying deficits where output might otherwise indicate full recovery\textsuperscript{10} and also reveal important progress indicators when jump height is stable and suggestive of ineffective programming/poor response.

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

\textbf{SL vs. DL peak landing force asymmetries}

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

\begin{table}[h]
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\begin{tabular}{|l|c|c|c|c|}
\hline
   & \textbf{Player 1} & & \textbf{Player 2} & \\
\hline
\textbf{Date} & 08/04 & 03/06 & 20/05 & 01/07 \\
\hline
\textbf{Jump Height (cm)} & 21.6 & 27.9 & 40.1 & 41.4 \\
\hline
\textbf{FT:CT} & 0.43 & 0.70 & 0.63 & 0.76 \\
\hline
\textbf{Con Peak Velocity (m.s)} & 2.1 & 2.34 & 2.88 & 2.94 \\
\hline
\textbf{Ecc Peak Velocity (m.s)} & 0.66 & 1.11 & 1.15 & 1.33 \\
\hline
\textbf{CM Depth (cm)} & 25.8 & 26.8 & 34.8 & 32.2 \\
\hline
\textbf{Ecc Decel RFD (N)} & 681/821 & 1871/2582 & 2149/3044 & 4558/5923 \\
\hline
\% & 8 & 27 & 29 & 14 \\
\hline
\textbf{Con-Impulse (Ns)} & 138/181 & 138/166 & 190/232 & 184/226 \\
\hline
\% & 23 & 17 & 18 & 19 \\
\hline
\textbf{Peak Landing Force (N)} & 1560/1656 & 2200/2180 & 1651/2367 & 2335/2740 \\
\hline
\% & 6 & -1 & 29 & 16 \\
\hline
\end{tabular}
\caption{Case examples showing selected DL and SL-CMJ variables and asymmetries at two time points post-ACLR. Injured limb indicated by red font. FT:CT=Flight:contraction time. Con=Concentric. Ecc=Eccentric. CM=Countermovement. RFD=Rate of force development.}
\end{table}
Following ACLR\(^3\), the differing demands of the two tests may reveal variations in the strategies adopted at different time points during and post RTS. We have observed that at 6 months, > 2/3 players display SL and DL-CMJ landing force patterns representative of those shown in Figure 4. A point of consideration in peak landing force analysis and permitting a comparison of injured vs. uninjured limb landing asymmetries in the SL-CMJ, is the use of a jump height adjusted peak landing force index (peak landing force(N)/jump height (cm)) to try and account for the greater passive impact load on the uninjured side due to landing from a greater jump height.

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

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

**Future directions**

While compensatory strategies that shift mechanical load away from the injured joint may be an appropriate adaptation during the early post-operative phase, they could be considered maladaptive if they persist beyond the recovery of mechanical loading capacity\(^3\), and manifest in low load activities such as the squat and sit to stand\(^2\). Landing asymmetries are a secondary risk factor for subsequent ACL injury\(^9\) while chronic joint under loading can increase risk of osteoarthritis in the unloaded limb\(^8\). This poses an important question – are unloading strategies observed in the eccentric deceleration and landing phases at 6, 8 months post ACLR, and beyond, appropriate adjustments to some degree relative to the capacity and tissue status or should they be viewed simply as learned patterns of underuse which should be corrected? Chan & Sigward\(^9\) suggest that addressing underuse early in rehabilitation with real-time load-feedback during exercises may be critical to prevent maladaptive unloading. In addition, given the persistence of eccentric/landing phase avoidance strategies observed post ACLR, and the importance of eccentric control of knee flexion, these deficits in particular should be identified and addressed.

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

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**Figure 4**: What goes up must come down – use of different strategies on landing to unload the injured knee?
deficits warrant an increased emphasis on unilateral strength training. The differing load and eccentric velocity demands of the SL- and DL-CMJ and resulting outputs and asymmetries might also be considered as a proxy eccentric strength-velocity profiling tool to direct emphasis towards high load versus high velocity eccentric loading. This approach can also be further complemented by assessing kinetics during more demanding DJ and SL-DJ activities. Concentric force-velocity profiling is a popular aspect of exercise program design in the healthy athlete. In the post-ACLR athlete, attention to observed force reduction and deceleration qualities with varied load, loading rates and velocity demands is warranted to better understand individual response to loading during rehabilitation and inform prescription. While recognising the additional information that full biomechanical analysis of SL and DL jump-land and cutting movements provides, the wealth of reliable and often benchmarked, intelligence on athlete performance, strategy and asymmetries that the dual platform DL-CMJ generates in a single, rapid and simple to implement test makes it an essential practical tool for frequent monitoring during and post-RTS.

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

References
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