APPENDIX

THE BILATERAL CMJ: CONTEXT OF USE IN REHABILITATION AND RETURN TO SPORT

Traditionally, strength and power diagnostic tests post-ACLR have evaluated limb symmetry indexes (LSI) of isokinetic strength (equipment permitting) or LSI derived from “clinical tests” such as single-leg hops for distance, or single-leg jump height. On the other end of the spectrum, more time and financially demanding 3D kinetic-kinematic analysis of the drop jump both during rehabilitation and post RTS has revealed asymmetries/deficits associated with poor function and elevated risk of ACL injury recurrence.[1] However, in elite football, the countermovement jump (CMJ) is a more commonly used jump test, resulting in greater athlete familiarity with the assessment, and an increased availability of pre-injury data. These advantages combined with a substantial evidence base of detailing post-ACL analysis of mechanics across the phases of the CMJ, without kinematics,[2,3,4,5,6,7,8] and the potential to implement the test earlier in rehabilitation, has led to an increased interest in the use of kinetic data derived from bilateral (double-leg) CMJ assessments on dual force platforms during, and post-rehabilitation. Fundamentally, this provides a practical, reliable and efficient means to frequently acquire data associated with knee function in both sports and clinical settings.[2,3] Evidence related to CMJ performance post-ACLR is largely based on interlimb force or impulse eccentric (downward), concentric (upward) and landing phases asymmetries (figure 3B) obtained during simultaneous capture of left and right limb force and impulse outputs during the bilateral CMJ.[2,3,4,5,6,7,8] Combined limb vertical GRF is also calculated, and via standard equations impulse, acceleration, velocity and power are derived (described previously)[9] from which CMJ-TYP and ALT variables with well-established sensitivity are calculated (figure 3A).[10] While it is also useful to have single-leg CMJ healthy benchmark data, bilateral CMJs are more commonly implemented for practical reasons, and as they are richer source of data, particularly in relation to high-velocity eccentric performance.[3] Furthermore, paralleling evidence that single-leg hop distance symmetry fails to reflect underlying neuromuscular/biomechanical deficits and compensatory strategies in post-ACL patients.[11] Baumgart *et al*.[6,7] observed no significant asymmetry in single-leg CMJ in patients mean 18-months post-ACL, significant asymmetries in the eccentric deceleration and landing phases of the bilateral CMJ were however observed. Bilateral asymmetries, characterised as compensatory strategies to reduce high eccentric and impact load on the involved limb and were associated with poorer subjective knee function.[2,6,7] Nonetheless, the single-leg CMJ may provide complementary information around limb capacity albeit with differing load, velocity, range and balance requirements, and thus often demonstrates a differing asymmetry profile than the bilateral variant.[3]

BILATERAL CMJ-ALT VARIABLES IN REHABILITATION AND RETURN TO SPORT

In our experience of CMJ assessment of English Premier League players during rehabilitation for whom pre-injury benchmark data is available,[12,13] we have generally observed a delayed recovery of (bilateral) CMJ-ALT variables relative to that of CMJ-TYP, also evident in the present player post-ACLR (Figures 4 and 5). A recent study suggests that this pattern may follow lower extremity injury *per se,*[14] reporting small to moderate differences in CMJ-ALT variables in professional players who were healthy but had a severe lower extremity injury in the previous season compared to those that had not but only trivial differences in jump height and peak power. Therefore, recovery and / or (if benchmark data not available) progression of CMJ-ALT variables should in addition to asymmetries and individual limb outputs also be considered in quantifying the athlete's status and response to reconditioning post injury.

The present case also highlights some important considerations in the interpretation of the CMJ-ALT trends. Firstly, based on evidence in healthy athletes,[10] her trends between specific timepoints in several CMJ-ALT variables are suggestive of negative adaptations associated with neuromuscular fatigue. These trends, including increased eccentric and concentric duration, decreased flight time:contraction time, decreased eccentric deceleration rate of force development (RFD) and early concentric impulse (i.e. the first 100ms) must however be considered in the context of a large chronic increase in countermovement depth, a proxy for greater flexion during the eccentric phase – resulting in longer eccentric deceleration and concentric phase durations. The increased displacement and duration provide a longer period of over which to decelerate centre of mass prior to transition to the concentric phase, in turn reducing the RFD required to do so. In this case, this reflects a more chronic shift in CMJ strategy, rather than a short-term/residual fatigue response reflecting muscle damage and inflammation in the 24-72 hours following high intensity activity/competition.[10]

FATIGUE-RECOVERY MONITORING WITHIN REHABILITATION AND RETURN TO SPORT

The sensitivity of CMJ-ALT variables to loading mean that the timing of repeated assessments needs to be carefully considered, in order to reduce the risk of "false negatives" whereby meaningful chronic progress is masked by residual fatigue from recent training sessions. Conversely however, CMJ assessments may be deliberately timed to characterise the overall and limb-specific "cost" of a single or series of training sessions – represented by the magnitude of decline of bilateral monitoring variables and relative decline in each limb (asymmetry of fatigue). In the present case, pre-post session CMJs were not implemented but her trends between Max2 and 3, Max3 and 4 (assessments approximately a week apart) illustrate these concepts:

		CMJ-ALT Bilateral			Concentric Impulse-100***			Eccentric Decel RFD***			Eccentric Decel Impulse****		
Test	Jump Height*	FT:CT**	Ecc Dur**	Con Dur**	Total	Inv	N-Inv	Total	Inv	N-Inv	Total	Inv	N-Inv
MAX1	20.7	0.56	499	229	115	56	59	2060	1033	1027	148	77	71
MAX2	25.9 (+25)	0.68 (+20)	454 (-9)	225 (-2)	123	60 (+8)	63 (+6)	3107	1532 (+48)	1575 (+53)	149	81 (+4)	69 (-3)
MAX3	26.9 (+4)	0.65 (-4)	473 (+4)	244 (+8)	105	55 (-8)	50 (-21)	2526	1360 (-11)	1166 (-26)	153	83 (+3)	70 (+2)
MAX4	25.3 (-6)	0.63 (-3)	483 (+2)	237 (-3)	112	55 (-)	57 (+16)	2697	1374 (+1)	1323 (+13)	148	78 (-7)	71 (-)

Table 1: Data and trends for assessments Max 3, Max 4 (timepoints not included in figures and tables showing overall trends during rehabilitation) for selected bilateral *CMJ-TYP and **CMJ-ALT variables and ***variables describing rate or time-limited CMJ mechanics in individual limbs. Value in brackets is the % change between the current and previous test value. *** variables reveal an asymmetrical fatigue-recovery trend underlying the trends in total (Involved + Non-Involved) outputs. ****Eccentric deceleration impulse is determined within same phase as eccentric deceleration RFD and is included to illustrate

that variables within a given phase that are not rate-limited (i.e. impulse) tend to be less responsive to short-term alterations in load.

Substantial improvements were evident in most CMJ variables between Max1 and Max2. Between Max2 and Max3 (implemented following the introduction/increments of on-pitch load) however, we observed declines in (bilateral) CMJ-ALT which we deemed to reflect residual fatigue/delayed recovery. This data illustrates the lower sensitivity or delayed response to fatigue of jump height, whereby it continues to improve during the same week that eccentric and concentric durations extend and concentric impulse-100 and eccentric deceleration RFD decrease.

Also important to monitor is the asymmetrical fatigue response to this substantial increment in on-pitch loading at Max3 i.e. a substantially larger decline in uninvolved than involved limb concentric impulse-100 and eccentric deceleration RFD trends which we interpret as a preferential use of uninvolved limb during the conditioning preceding this test. The improvements between Max3 to Max4 suggest both a substantial recovery of both limbs and a better tolerance to the further increments introduced, but not full recovery of Max2 bilateral CMJ-ALT and individual limb rate and time limited outputs. It is important to highlight that we considered this incomplete recovery or delayed expression of training adaptations acceptable during deliberate and well-monitored overreaching to ensure that she was exposed to adequate sports-specific loading within her conditioning. This was the key goal at this phase of the players rehabilitation not preparation to compete, as several weeks remained until the player was to resume full team training.

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