Vertical jump impulse deficits persist from six to nine months after ACL reconstruction

Jill A. E. Costley[1], Joshua J. Miles[1,2], Enda King[1,3], Katherine A. J. Daniels[1,4,5]

[1]Sports Medicine Research Department, Sports Surgery Clinic, Dublin, Republic of Ireland

[2]Department for Health, University of Bath, Bath, UK

[3]Department of Life Sciences, Roehampton University, London, UK

[4]Queen's School of Engineering, University of Bristol, Bristol, UK

[5]Department of Sport and Exercise Sciences, Manchester Metropolitan University, Manchester, UK

Correspondence

Jill Costley, Sports Medicine Research Department, Sports Surgery Clinic, Dublin, Republic of Ireland.

Email: jillcostley@sportssurgeryclinic.com

Abstract

Later-stage rehabilitation following ACL reconstruction (ACLR) provides a valuable opportunity to target performance deficits before return to sport. This study aimed to: 1) evaluate bilateral counter-movement jump (CMJ) phase-specific impulse and isokinetic strength inter-limb asymmetry progression from six to nine months post-ACLR; and 2) examine the extent to which individual changes in strength asymmetry could explain changes in impulse asymmetry. Male athletes (n=44) with a hamstring tendon or bone-patellar tendon-bone autograft were tested six and nine months post-ACLR. Two-way mixed-model ANOVAs were used to identify inter-session and inter-graft differences in CMJ phase-specific impulse asymmetries and knee isokinetic flexor and extensor strength asymmetries, as well as in absolute impulse and strength values of independent (ACLR/uninvolved) limbs. Linear regression models were used to assess the relationship between changes in impulse asymmetry and strength asymmetry. Reductions in strength asymmetry arose from improved ACLR-limb performance, whereas concentric impulse asymmetry reduced consequent to decreased uninvolved-limb performance and eccentric deceleration impulses decreased bilaterally. Graft type did not modulate findings. Changes in strength asymmetry had little or no ability to explain changes in impulse asymmetry. Consideration of approaches which may influence persisting deficits observed bi-laterally throughout vertical jumping performance post-ACLR may enhance rehabilitation practice.

KEYWORDS

anterior cruciate ligament reconstruction, isokinetic strength, IKDC, rehabilitation, return to sport

INTRODUCTION

Anterior cruciate ligament (ACL) rupture is a common injury in multi-directional field sports.[1] Surgical reconstruction of the ACL with either a bone-patellar-tendon-bone (BPTB) or hamstring (semitendinosus/gracilis) tendon (HT) autograft is the most commonly selected treatment for athletes who wish to return to sport (RTS).[2–5] Following ACLR, inter-limb deficits in neuromuscular activation, strength and power metrics are evident as a result of the injury sustained and of graft harvesting.[6–8] Appropriate post-operative rehabilitation to address functional inter-limb asymmetries is paramount for improving performance capabilities and reducing re-injury rates.[9,10] Successful rehabilitation also reduces the risk of further damage to chondral and meniscal structures and the onset of associated co-morbidities such as post-traumatic knee osteoarthritis.[11]

A widely-evaluated parameter of lower-limb function post-ACLR is knee extensor/flexor muscle strength, assessed using isokinetic dynamometry (IKD).[10,12] Although inter-limb strength symmetry is associated with a lower risk of re-injury following ACLR,[10] asymmetries in temporally-related metrics (rate of force development, impulse, etc.) frequently prevail beyond the attainment of a symmetrical strength profile, even after RTS.[13,14] Pre-RTS assessment of neuromuscular 'readiness' should, therefore, also consider the demands of the sport being returned to.[15] In multi-directional field sports, jumping and landing motions are ubiquitous multi-joint actions and are often characterised by concentric and eccentric demands.[16,17] Additionally, high eccentric loading upon initial ground contact (<50 ms) during rapid deceleration is a known mechanism of non-contact ACL rupture.[18] For such reasons, the double leg counter-movement jump (CMJ) is often of interest in RTS assessment.[13–15] In particular, the evaluation of phase-specific CMJ impulses, obtained from the integration of the force-time profile, has enabled the quantification and characterisation of asymmetry of distinct components of a single movement.[15,17,19]

Vertical ground reaction force (GRF) impulse asymmetry has been identified as a surrogate marker of knee kinetic deficits (moments and work)[20] associated with heightened ACL re-injury risk.[21] Although CMJ concentric phase symmetry has been found to improve with time after surgery,[22] eccentric properties have displayed persistent deficits[17,22,23] especially following BPTB-ACLR,[17] and slower recovery.[22] However, recent evidence suggests that rates of recovery may be influenced by graft type. For example, Cristiani *et al.*[24] reported that inferior extensor strength symmetry of BPTB-ACLR, relative to HT-ACLR, required up to 24 months post-operatively to be addressed. Heightened functional performance asymmetries within BPTB individuals, as assessed by single leg hop distance (SLDH), required only six months post-ACLR.[24] Yet, the SLDH test lacks the sensitivity to detect altered technical execution[25–27] and its ability to predict successful outcomes following ACLR has been questioned.[28] Due to the common eccentric mechanism of ACL injury[29], the enduring deficits in eccentric qualities reported around the time of RTS[10,17,22] may be of greater concern. Eccentric deficits have been associated with an increased re-injury risk and may contribute to the high rates of contralateral injury exhibited in ACLR populations by encouraging preferential use of the contralateral limb.[17,21] In addition, only a weak relationship has been observed between knee isokinetic strength inter-limb asymmetry and CMJ impulse asymmetry nine months post-ACLR,[17] a time often associated with RTS.[10] Thus, specific consideration of eccentric deficits may be crucial when determining an athlete's readiness to RTS; especially within the BPTB-ACLR population who are reported to display the largest CMJ eccentric deficits, nine months post-surgery.[17]

Later-stage rehabilitation prior to RTS offers a valuable opportunity to optimise clinically-related ACLR outcome measures in preparation for the on-field demands of play.[6,9,10] Understanding the progression of symmetry within key parameters of rehabilitation during this stage may allow persistent asymmetries to be targeted more precisely, thereby increasing specificity of later-stage rehabilitative protocols and RTS criteria. Thus, the aims of this study were two-fold: 1) investigate the presence of systematic changes in CMJ phase-specific impulse and isokinetic strength asymmetries between six and nine months post-ACLR and whether they are affected by graft type and 2) examine the extent to which individual changes in impulse asymmetry can be explained by changes in strength asymmetry. To assist with interpretations, we further evaluated absolute values in all assessed strength and impulse variables of the independent ACLR- and uninvolved-limb to investigate how observed changes in symmetry arose. It was hypothesised that asymmetries in strength and phase-specific impulse would reduce from six to nine months post-ACLR and that the magnitude of the reduction would not be modulated by graft type. We expected that only weak relationships would be found between the progression of strength asymmetries and the progression of CMJ impulse asymmetries, and that this relationship would be strongest for the concentric phase of the jump.

2 | METHODS

2.1 | Participants

Forty-four 18-35-year-old amateur male multidirectional field sport athletes undergoing primary ACLR surgery at the XXX participated in this study. Power analysis (G*Power, version 3.1.9.2, Universität Düsseldorf), recruitment procedure, cohort demographics and anthropometric characteristics were as documented previously:[17] Participants had stated an intention to return to multi-directional field sport and had undergone ACLR using either a hamstrings tendon (HT; semitendinosus and gracilis; n = 22; age 26.1 ± 4.4 years, height 179.4 ± 6.1 cm, body mass 79.8 ± 9.4 kg) or bone-patellar tendon-bone (BPTB; n = 22; age 23.4 ± 4.4 years, height 181.8 ± 6.4 cm, body mass 85.2 ± 11.5 kg) autologous ipsilateral graft. Those with previous ACLR, multiple concurrent ligament reconstructions or without an intention to return to multi-directional field sports were excluded. Participants were predominantly involved in Gaelic football (39%), hurling (23%), soccer (32%) and rugby (16%). Following ACLR, athletes completed two testing sessions: the first session at five to seven months post-surgery ('six-month test') and the following at eight to ten months post-surgery ('nine-month test'). Mean and standard deviation (SD) time from surgery to the six-month test was 6.2±0.4 months (BPTB 6.4±0.4, HT 6.1±0.2) and to the nine-month test was 9.3±0.4 months (BPTB 9.4±0.4, HT 9.1±0.3). At the six- and nine-month testing session respectively, the number of participants that had returned to any level of sport was two and 22, while those who had returned to their pre-injury level of sport was zero and 12. The study was approved by the hospital's research ethics committee and informed written consent was obtained from participants before testing. All testing procedures were as reported in Miles *et al.* [17].

2.2 | Testing procedures

2.2.1 | Counter-movement jump performance

An identical protocol was used in the testing sessions six months and nine months post-ACLR, with each session beginning with the measurement of height and body mass. A standardised warm-up consisting of a two-minute submaximal run at a self-determined pace and five unloaded squats was subsequently performed and followed by two maximal familiarization counter-movement jumps (CMJs). Participants were instructed to jump for maximal height with lower limbs extended while airborne and hands placed on the iliac crests. Three maximal CMJs were then performed on two force platforms (BP400600; AMTI, Massachusetts, USA; 400 x 600 mm) with bilateral vertical ground reaction forces (vGRF) recorded at 1000Hz. Participants then completed a clinical assessment protocol comprising additional jumps and change of direction manoeuvres.

2.2.2 | Concentric knee extensor and flexor strength

After laboratory testing, participants undertook a standardised, seated, isokinetic dynamometry (Cybex Humac NORM, CSMI) testing protocol to assess concentric knee flexor and extensor strength.[12] The uninjured limb was tested first. For each limb, the protocol consisted of three sets of five repetitions (60°/second) interspersed with 60 seconds rest: one submaximal warm-up set followed by two maximal-effort sets with verbal encouragement provided throughout. Concentric knee extensor and flexor peak torque was evaluated through 100° of range from 0° extension and sampled at 100 Hz. Finally, subjective knee function was evaluated via the International Knee Documentation Committee (IKDC) questionnaire.[30]

2.3 | Data processing

The impulse-momentum relationship was used to calculate vertical velocity of the centre of mass (COM) at the instant of CMJ take-off,[31] enabling the determination of peak CMJ height. Three key phases of the CMJ were then identified using COM vertical velocity: *eccentric deceleration* from maximal downwards velocity to zero velocity, *concentric* from zero velocity to take-off, and *landing* from landing to zero velocity (Appendix 1).[15,17] The instants of take-off and landing were identified using a vGRF threshold of 10 N. For each phase, limb-specific impulses were derived by integration of force-time curves with extraction of impulse parameters facilitated by a custom MATLAB script (version 2015a, Mathworks Inc, Massachusetts, USA). The mean of the three trials was used for all analysis.

For evaluation of knee extension-flexion strength, a gravity correction was first applied to IKD outputs. Peak knee extension and flexion torques were then obtained from the maximal-effort set with the largest maximum knee extension torque and repetition peak torque coefficient of <0.1. Both GRF impulses and isokinetic torques were divided by body mass prior to further analysis.

Phase-specific impulse and IKD peak extension and flexion torque asymmetry indices (AIs) were calculated for each group (BPTB/HT) at both time points (six months post-

ACLR/nine months post-ACLR) to assess and monitor the magnitude and direction of injured-limb function relative to the uninjured limb.[15] AI was calculated as:

$$\text{AI} = \frac{(\text{Uninjured limb} - \text{ACLR limb})}{\text{Larger value of the two legs}} \text{ x } 100 \quad (1)$$

A positive AI hence indicated larger value on the uninjured limb whereas a negative AI indicated a larger value on the injured limb.[15,17]

2.4 | Statistical analyses

Descriptive statistics are reported as mean±SD. Standardised effect sizes (ES; Cohen's d) were reported for all comparisons and interpreted as trivial ($d<0.2$), small ($0.2\geq d>0.5$), medium ($0.5\geq d>0.8$), and large ($d\geq 0.8$).[32] Multiple 2x2 mixed-model analysis of variance (ANOVA) tests with factors graft type (BPTB/HT) and time (six/nine months post-ACLR) were used to test for differences in inter-limb asymmetry and for differences in the absolute values of independent limbs (ACLR/uninvolved), for each phase of the CMJ (eccentric deceleration, concentric and landing phases), for IKD knee extensor and flexor strength, and for CMJ height and IKDC scores. Linear regression models were used to determine the amount of variance in 'change in phase-specific impulse AI' explained by either 'change in knee extensor AI' or 'change in knee flexor AI'. An alpha level of 0.05 was used for all statistical tests and analyses were performed using IBM SPSS 2016 (v24, IMB Corp, Somers, NY, USA).

3 | RESULTS

IKDC questionnaire score improved from six to nine months ($F = 19.3$, $p < 0.001$, ES = 0.47). No interaction effect ($F = 0.71$, $p = 0.40$) or effect of graft type ($F = 0.5$, $p =$

0.48) was found with scores increasing in both BPTB (78.2±10.8 to 82.1±11.2) and HT (79.2±8.4 to 84.9±8.0) cohorts. While we found no significant change in CMJ height between testing sessions (F = 1.2, p = 0.27) or between graft types (F = 0.08, p = 0.77), an interaction effect was observed (F = 6.93, p = 0.01) indicating that CMJ height decreased from six to nine months in BPTB athletes (28.9±4.9 to 28.3±4.1 cm) but increased in HT athletes (27.4±7.1 to 28.2±6.4 cm). However, effect sizes were trivial to small (0.02 - 0.25) and represented mean differences in jump height of less than 1.5 cm.

3.1 | Changes in phase-specific impulse AI and isokinetic strength AI from six to nine months post-ACLR

An improvement in strength AI was observed in knee extension (F = 18.02, p < 0.001, ES = -0.50) and knee flexion (F= 6.39, p = 0.02, ES = -0.37) from six to nine months post-ACLR. There were significant main effects of graft type on knee extensor strength AI (F = 11.64, p = 0.001) and flexor strength AI (F = 17.94, p < 0.001), BPTB displaying greater extensor AIs (21.24 vs. 9.95%) and lower flexor AIs (1.24 vs. 14.35%). A significant reduction in phase-specific impulse AI was only found within the concentric phase of the CMJ (F = 24.25, p < 0.001, ES = -0.42). No significant changes (and only trivial effect sizes) were identified for eccentric deceleration AI (F = 2.327, p = 0.14, ES = -0.15) and landing AI (F = 0.506, p = 0.48, ES = 0.11). A main effect of graft type on AI was found for the concentric (F = 10.80, p = 0.002) and eccentric deceleration (F = 20.27, p < 0.001) phases of the CMJ, with larger asymmetries present in BPTB athletes. No significant interaction effects (time*graft) on AI were displayed in either

IKD assessment (*F* = 0.002 - 0.199, *p* = 0.657 – 0.969), nor within any phase of the CMJ (*F* = 0.51 – 3.24, *p* = 0.08 – 0.48).

3.2 | Changes in absolute isokinetic strength and phase-specific impulse of independent ACLR and uninvolved limbs from six to nine months post-ACLR

Absolute values of independent limbs (ACLR/uninvolved) at six- and nine-month testing sessions are displayed in *Table 1* with results of the mixed-model ANOVA presented in *Table 2.*

From six to nine months post-operatively, the ACLR limb displayed increases in extensor and flexor peak torque ($F = 17.25 – 10.66$; $p < 0.001 - 0.002$) yet uninvolved limb strength did not significantly change. A main effect of graft was observed within peak extensor torque of the ACLR-limb, with greater extensor strength displayed by HT-ACLR than BPTB-ACLR individuals ($F = 5.67$; $p = 0.022$). Reductions in eccentric deceleration impulse were apparent in both the ACLR ($F = 8.03$; $p = 0.007$) and uninvolved limb ($F = 13.41$; $p = 0.001$). A main effect of graft on phase-specific impulse was only observed in the ACLR limb with higher eccentric deceleration impulse in HT ($F = 5.63$; $p = 0.022$). A significant reduction in concentric phase impulse occurred within the uninvolved limb ($F = 6.92$; $p = 0.012$). Neither limb exhibited changes in landing impulse over time. No interaction effects (time*graft) were found for any isokinetic strength measure, nor in any CMJ phase, for either limb.

3.3 | Relationship between isokinetic strength and impulse asymmetry changes from six to nine months post-ACLR

There was a weak positive relationship between the change in isokinetic knee extensor strength AI and the change in CMJ eccentric deceleration impulse AI from six to nine months post-ACLR (p = 0.02, r^2 = 0.12). No significant relationship was found between the change in isokinetic knee extensor strength AI and the change in either CMJ concentric impulse AI (p = 0.13, r^2 = 0.05) or landing impulse AI (p = 0.50, r^2 = 0.01) from six to nine months post-ACLR, nor between the change in IKD flexor strength AI and the change in impulse AI within any CMJ phase (p = 0.11 – 0.95, r^2 = < 0.01 – 0.06) during the same period.

4 | DISCUSSION AND IMPLICATIONS

Inter-limb asymmetries decreased between six and nine months post-ACLR for CMJ concentric impulse and for peak torque in knee extension and flexion. Changes in peak torque asymmetries were primarily achieved through an increase in ACLR limb strength, however improvements in concentric impulse asymmetry arose from decrements within the uninvolved limb. Though no significant changes in the eccentric deceleration or landing impulse asymmetries or jump heights were identified, bilateral reductions in eccentric deceleration impulse were observed. Changes in knee extensor and flexor strength asymmetry had little to no ability to explain changes in phase-specific impulse AI. The rate of progression of inter-limb symmetry throughout this later-stage rehabilitation phase did not differ between graft types for any metric.

However, BPTB athletes consistently displayed significantly larger CMJ impulse and knee extensor strength asymmetries, but lower knee flexor strength asymmetries, than HT athletes at both six and nine months post-ACLR. Additionally, absolute eccentric deceleration impulse and knee extensor strength of the ACLR limb were significantly lower in BPTB athletes throughout the investigatory period.

4.1 | Changes in isokinetic strength AI and phase-specific impulse AI from six to nine months post-ACLR

Athletes demonstrated reductions in peak extensor and flexor torque inter-limb asymmetries from six to nine months post-ACLR (Figure 1a). Asymmetry in quadriceps strength has been associated with altered movement patterns in functional tasks (single-legged hopping, landing, walking), heightened osteoarthritic risk and is a further risk factor for re-injury,[10,11,33,34] whilst strengthening of the knee flexors is believed to decrease the stress placed upon the ACL graft by controlling knee valgus and anterior translation and rotation of the tibia.[35,36] Changes in strength AI were predominately achieved through changes in strength of the ACLR limb, as noted in recent literature assessing rehabilitation up to 6 months post-surgery.[37,38] Our findings extend upon these studies and suggest that the uninvolved limb may reasonably be used as a control when monitoring changes in muscle strength during later-stage rehabilitation.

Although the rate of progression in strength symmetry was not dependent upon autograft selection in this study, previous findings suggest a heightened recovery rate of extensor strength symmetry following BPTB- than HT-ACLR[24,39], albeit gradually up to 24 months[24] post-operatively. The three-month observation utilized within our study may, therefore, not be sufficient to detect differential rates between graft types for measures of strength. Nonetheless, larger inter-limb extensor and flexor mechanism deficits in respective BPTB and HT cohorts were observed throughout the investigated rehabilitation period; as previously reported.[8,24] Morbidity associated with graft harvesting[8] likely contributes towards this graft differential response. Thus, a continued focus on strength restoration for both graft types is likely to be warranted.

The concentric phase was the only CMJ phase to have a significant decrease in impulse asymmetry from six to nine months post-ACLR, which occurred in the absence of an identified improvement in jump height. Previous studies have also reported concentric impulse asymmetry to display the most consistent improvements over time following ACLR, in comparison to kinetic asymmetries within other CMJ phases.[14,22] The reduction in concentric impulse AI from six to nine months post-ACLR did not differ depending upon graft type.[24] Although Cristiani *et al.*[24] found higher SLDH symmetry in HT-ACLR four months following surgery, differences between grafts had been negated six months post-operatively and is, thus, in agreement with our findings. However, the improvement in asymmetry as observed within the current study primarily arose from reductions in 'uninvolved' limb performance. Given that impulse is the integral of GRF force over time, reductions in concentric impulse may have potential consequences for rapid force generation, limiting sporting performance upon RTS.[22,40]

No significant changes were identified in impulse asymmetries within the eccentric deceleration or landing phases from six to nine months post-ACLR. Persisting deficits in eccentric qualities following ACLR are consistent with previous reports.[22] However, concurrent bilateral reductions in eccentric impulse were observed. Due to the eccentric mechanism associated with many ACL injuries,[18] the absence of recovery of eccentric function within dynamic movement may contribute to the high rates of re-rupture 11%,[4] or contralateral rupture especially in BPTB- versus HT-reconstructed individuals with contralateral rupture rates of 5-30% and 2-14%, respectively.[4,41,42] Compared to HT-ACLR, ACLR-limb eccentric impulse of the BTPB cohort remained significantly lower throughout later-stage rehabilitation and inter-limb asymmetry remained approximately three-fold greater. Though an emphasis within rehabilitative literature has traditionally been placed upon concentric-based movements,[12,43] concentric exercise may fail to provide the required stimuli for complete restoration of neuromuscular function.[43] Thus, approaches to negate reductions, and enable improvements, in bilateral eccentric functioning should be considered during later-stage rehabilitation.

The use of the uninvolved limb as a ‘control’ to assess readiness of the ACLR limb post-reconstruction in calculations of inter-limb symmetry is a common approach for monitoring rehabilitation status.[23] In the absence of pre-injury data, such assessment has been suggested to allow comparisons of the ACLR-limb to ‘uninjured’ performance.[23] However, as our study highlights, measuring asymmetry progression alone may overestimate functional ACLR-limb performance by concealing deleterious uninvolved limb deficits. Though not assessed here, neural and peripheral deficits are argued to “crossover” to the uninvolved limb occur following ACL rupture and may affect strength and functional performance.[43] Detraining effects may also influence both limbs. Thus, utilising the uninvolved limb as a ‘gold standard’ benchmark for monitoring ACLR-limb performance and function is not an appropriate strategy to use in isolation, and should be used alongside assessments of independent limbs."

4.2 | Relationship between isokinetic strength and impulse asymmetry changes from six to nine months post-ACLR

Phase-specific CMJ impulses displayed notably smaller mean changes in asymmetry than IKD knee flexor and extensor strength (Figure 1). The ability of 'change in knee peak extensor/flexor torque' to explain 'change in impulse symmetry' was also limited, with no significant relationship with concentric or landing phase asymmetry identified and only 12% of the variation in eccentric deceleration phase asymmetry explained by the change in knee peak extensor torque (see Appendix 2). The inadequacy of changes in IKD peak torque to predict and monitor deficits in impulse is a finding supported by others,[13,17,44] and may indicate that asymmetries observed in both metrics are relatively distinct entities.[13] Jumping performance relies on multi-joint and inter-muscular coordination[45] with knee angular velocities of beyond 500°/s,[46] as opposed to the joint-specific IKD assessment (60°/s) most commonly employed to monitor ACLR.[12] Following ACLR, changes in spinal-reflex excitability and muscular activation patterns have been reported,[47,48] with deficits in neuromuscular control associated with both compensatory movement patterns and ACL re-injury risk.[21] Deficits of such may prevail beyond the attainment of symmetry in strength indices[49,50] and may hence require an extended duration of rehabilitation, especially those parameterising eccentric properties.[43]

There are several limitations to this study. Firstly, GRF integrals cannot directly assess joint loading, although inter-limb deficits in vertical GRF impulse can be used as a surrogate indicator of knee kinetic asymmetries[20] associated with ACL re-injury.[21] As rehabilitation progresses, the contribution from other joints to movement may increase in an attempt to counteract persisting effects of ACLR.[51] Additional evaluation of kinematic and joint moments may, therefore, heighten the understanding of ACLR rehabilitation beyond GRF kinetics alone. Secondly, post-operative rehabilitation was neither monitored nor closely controlled, “pre-injury level” sporting participation (exposure to dynamic landing tasks) was greater nine months post-surgery (n=12) than at the six-month test (n=0). The mean age of the HT cohort was also greater than that of the BPBT cohort by 2.6 years. These factors may contribute to the variability displayed in several investigated metrics. Although lower variability would be expected in a more tightly-controlled cohort of elite athletes (such as the cohorts studied by Jordan et al[14] and Read et al[22]), the applicability of findings to a broader athletic population may be reduced. 376 variability, a double leg rather than SL task was selected to limit any associated confounders such as unilateral postural control, common following ACLR.[23,52,53] However, ACL rupture normally occurs during SL tasks (rapid landing/decelerations) during which athletes are not able to compensate with the contralateral limb.[54] Thus, future work should consider changes in absolute performance, as well as inter-limb asymmetry, of limbs during SL tasks following ACLR and to identify the factors that may influence the measured e bilateral regression of the metrics investigated within this study.

5 | CONCLUSION

We observed changes in strength asymmetry from six to nine months post-ACLR that were primarily a result of improved ACLR-limb strength. However, improvements in concentric impulse asymmetry arose from reductions of uninvolved-limb performance.

Though eccentric deceleration impulse asymmetry remained unchanged, bilateral reductions in this metric were also evident. The use of the uninvolved limb as a 'gold standard' benchmark for assessing and monitoring rehabilitation prior to RTS following ACLR may lead to overestimation of functional status of the ACLR-limb by concealing deleterious deficits in both concentric and eccentric qualities of the uninvolved limb. Although autograft type did not affect the progression of intra-limb performance over the investigatory time phase, eccentric impulse and quadriceps strength remained consistently lower following BPTB-ACLR compared to HT-ACLR. Consideration of the approaches that may influence the absence of progression in jump-related qualities of both the ACLR- and uninvolved-limb from six to nine months following ACLR may enhance rehabilitation guidelines and, thus, ACLR outcomes for both autograft types.

6 | PERSPECTIVES

We contribute to the understanding of recovery following ACLR by highlighting that recovery prior to RTS needs to consider both limbs, as well as the capability assessed. Bilateral deficits may be masked, and ACLR-limb functional status overestimated, when using isolated assessments of inter-limb symmetry that utilise post-operative outputs from the uninvolved limb as the "benchmark". In particular, the lack of progression in vertical jump impulse deficits during later-stage rehabilitation and the decrements in uninvolved limb functional performance indicate that more specific, bilateral, interventions and assessments may be required to improve outcomes and reduce re-injury rates after ACLR, irrespective of graft type. Nonetheless, BPTB-reconstructed individuals, who consistently displayed lower eccentric impulse and quadriceps strength in the ACLR limb throughout later-stage rehabilitation, may benefit from earlier specification of rehabilitation (<6 months post-operative) to address the temporal discrepancy in recovery times displayed between grafts. This may assist with addressing the higher rates of contralateral rupture observed in this population.[4,41,42]

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TABLE 1: Relative phase-specific impulses and knee isokinetic strength for independent limbs, six and nine months following bone-patellar-tendon-bone and hamstring-tendon anterior cruciate ligament reconstruction

	BPTB				HT			
	6 months		9 months		6 months		9 months	
	ACLR	Non-ACLR	ACLR	Non-ACLR	ACLR	Non-ACLR	ACLR	Non-ACLR
Extensor strength ($Nm.kg^{-1}.100$)	194.66 ± 48.45	259.74 ± 55.19	219.95 ± 68.48	266.69 ± 55.74	233.39 ± 42.01	269.34 ± 40.20	251.95 ± 46.10	269.99 ± 44.64
Flexor strength ($Nm.kg^{-1}.100$)	151.37 ± 38.78	156.53 ± 31.83	159.38 ± 36.96	159.12 ± 37.31	134.16 ± 26.50	163.12 ± 30.14	144.75 ± 23.96	165.78 ± 31.87
Ecc. decel. impulse ($Ns\ kg^{-1}$)	1.32 ± 0.30	1.68 ± 0.37	1.22 ± 0.20	1.53 ± 0.25	1.52 ± 0.32	1.64 ± 0.37	1.32 ± 0.24	1.37 ± 0.23
Concentric impulse ($Ns\ kg^{-1}$)	2.22 ± 0.29	2.67 ± 0.34	2.14 ± 0.20	2.50 ± 0.27	2.25 ± 0.29	2.53 ± 0.27	2.28 ± 0.27	2.45 ± 0.24
Landing impulse ($Ns\ kg^{-1}$)	1.80 ± 0.28	2.33 ± 0.49	1.76 ± 0.28	2.21 ± 0.29	1.94 ± 0.39	2.14 ± 0.32	1.82 ± 0.36	2.19 ± 0.28

Mean±SD.

Abbreviations: ACLR, anterior cruciate ligament reconstruction; BPTB, bone-patellar-tendon-bone; CMJ, counter-movement jump; Ecc. decel., eccentric deceleration; HT, hamstring tendon.

TABLE 2: Results of the time (six months vs nine months post-ACLR) by graft (BPTB vs HT) mixed-model Analysis of Variance.

	Time (6 vs 9 months)				Graft (BPTB vs HT)				Time*Graft			
	ACLR		Non-ACLR		ACLR		Non-ACLR		ACLR		Non-ACLR	
	F (1, 42)	*P*	F (1, 42)	*P*	F (1, 42)	*P*	F (1, 42)	*P*	F (1, 42)	*P*	F (1, 42)	*P*
Isokinetic strength												
Extensor strength	17.25	<0.001[a]	0.68	0.416	5.67	0.022[a]	0.21	0.651	0.41	0.527	0.46	0.501
Flexor strength	10.66	0.002[a]	0.50	0.480	2.94	0.094	0.520	0.475	0.20	0.653	<0.001	0.990
Phase-specific CMJ												
Ecc. decel.	8.03	0.007[a]	13.41	0.001[a]	5.63	0.022[a]	1.66	0.205	0.939	0.338	1.27	0.266
Concentric	0.42	0.520	6.92	0.012[a]	1.49	0.229	1.81	0.186	1.59	0.214	1.02	0.317
Landing	3.34	0.075	0.754	0.390	1.22	0.276	1.150	0.290	0.79	0.380	4.00	0.052

Note: [a] Significant difference between testing sessions at $p < 0.05$

Abbreviations: ACLR, anterior cruciate ligament reconstruction; BPTB, bone-patellar-tendon-bone; CMJ, counter-movement jump; Ecc. decel., eccentric deceleration; HT, hamstring tendon.

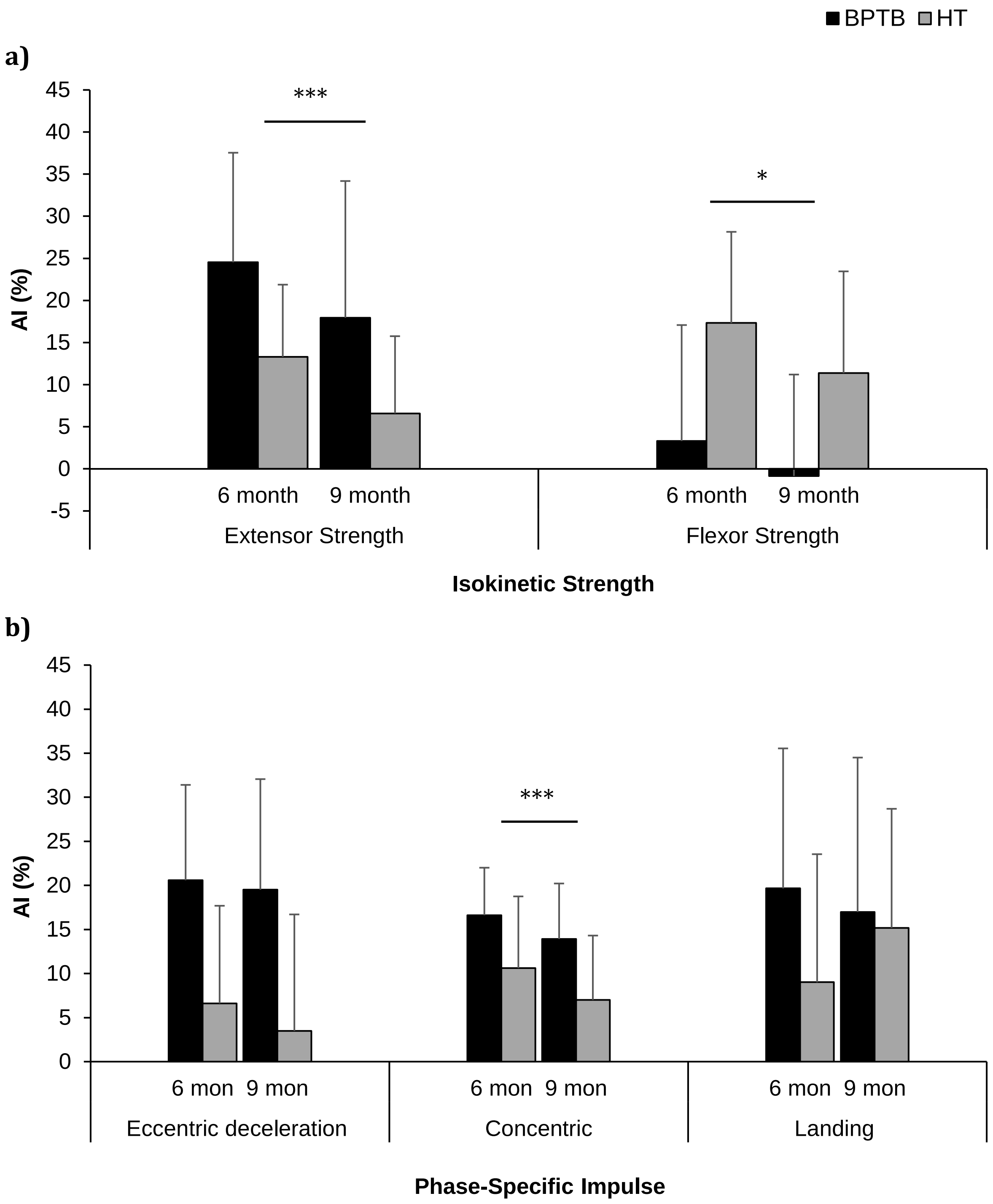

FIGURE 1. Asymmetry indices (AI; %) six and nine months following anterior cruciate ligament reconstruction: a) Isokinetic knee extensor and flexor strength; b) CMJ phase-specific impulse. Note: Bone-patellar-tendon-bone participants consistently exhibited significantly greater AIs in knee extensor strength (p = 0.001) and CMJ

eccentric deceleration ($p < 0.001$) and concentric ($p = 0.002$) impulses, yet lower knee flexor AIs ($p < 0.001$), than HT participants. N=44. Bars represent mean±SD. ***Significant difference between testing sessions at $p \leq 0.001$. *Significant difference between testing sessions at $p < 0.05$."

APPENDIX

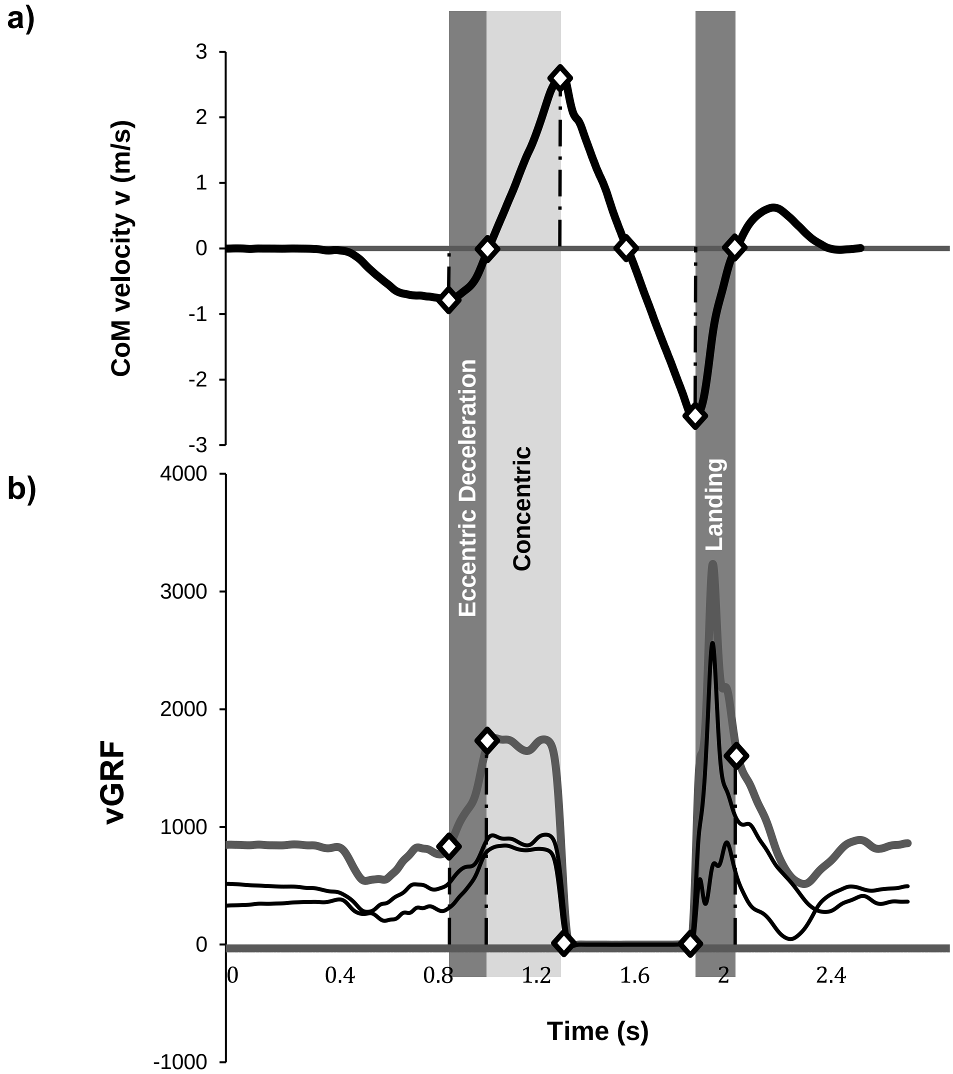

FIGURE A1. An illustrative example of phase breakdown for counter-movement jump impulse (CMJ): (a) Vertical velocity of the centre of mass (CoM vertical v) during the CMJ; (b) bilateral vertical ground reaction force (vGRF) (thick grey line) and unilateral vGRF from individual right and left force plates (thin black lines)

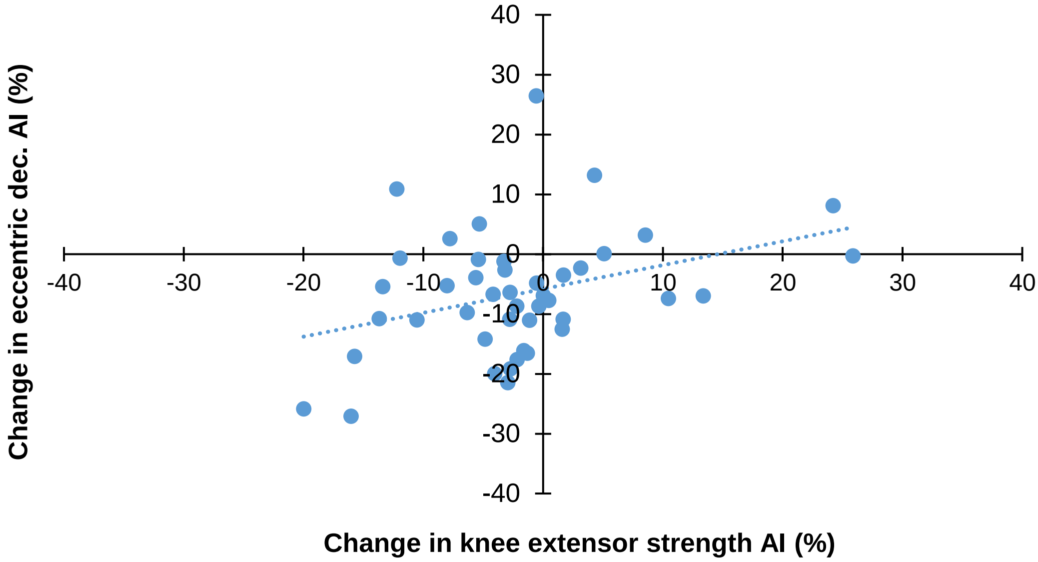

FIGURE A2. Relationship between change in knee extensor strength asymmetry from six to nine months after anterior cruciate ligament reconstruction and change in counter-movement jump (CMJ) phase-specific impulse asymmetry whereby significance was indicated: CMJ eccentric deceleration phase (least squares regression line marked with a broken line)