Title:

Patellar and hamstring autografts are associated with different jump task loading asymmetries after ACL reconstruction

Authors:

Joshua J Miles[1,2], Enda King[1,3], Éanna Cian Falvey[1,4], Katherine A J Daniels[1,5]

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

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

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

[4] Department of Medicine, University College Cork, Ireland

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

Running head:

Graft type and impulse asymmetries after ACLR

Contact:

Dr Katherine Daniels
Sports Surgery Clinic
Sports Medicine department
Northwood Avenue
Santry
Dublin 9
Ireland

k.a.j.daniels@outlook.com
katherinedaniels@sportssurgeryclinic.com
00353 1 526 2355

ABSTRACT

After anterior cruciate ligament reconstruction (ACLR) there is a higher re-injury rate to the contralateral limb in athletes who undergo surgery using a bone-patellar-tendon-bone (BPTB) autograft than using a semitendinosus and gracilis hamstring tendon (HT) autograft. This may be influenced by differing lower-limb loading asymmetries present when athletes of each graft type return to play. The aim of this study was to compare bilateral countermovement jump (CMJ) phase-specific impulse asymmetries between athletes with BPTB and HT autografts nine months post-ACLR, and to identify the relationship between impulse and isokinetic strength asymmetries. Male field sport athletes with a BPTB (n=22) or HT (n=22) autograft were tested approximately nine months post-ACLR. An uninjured control group (n=22) was also tested on a single occasion. Phase-specific bilateral absolute impulse asymmetries were calculated during the CMJ and compared between groups using Kruskal-Wallis and post-hoc testing. A linear regression model was used to assess the relationship between impulse asymmetries and isokinetic concentric knee extensor strength asymmetries. BPTB athletes demonstrated greater impulse asymmetries than HT athletes during the eccentric (p=0.01) and concentric (p=0.008) phases of the jump. Isokinetic strength asymmetry was a significant predictor of CMJ concentric impulse asymmetry in both BPTB (r^2=0.39) and HT athletes (r^2=0.18) but not eccentric impulse asymmetry in any group. The greater loading asymmetries demonstrated by BPTB than HT athletes nine months after ACLR may contribute to the differing incidence rates of contralateral ACL injury. The findings suggest that graft-specific loading asymmetries should be targeted during rehabilitation prior to return to play.

Key words: biomechanics, isokinetic dynamometry, IKDC, counter-movement jump, phase-specific, impulse, ground reaction force

INTRODUCTION

Anterior cruciate ligament (ACL) rupture is a severe knee injury with incidence rates ranging from 0.03-3.67% per year in field sports.[1] The most common treatment is surgical anterior cruciate ligament reconstruction (ACLR), most-often using either a bone-patellar-tendon-bone (BPTB) or a semitendinosus and gracilis hamstring tendon (HT) autograft.[2] Athletes who have had a previous ACLR are at a greater risk of re-injury, with ACL re-injury risk ranging from 6-26% on the operated limb (graft rupture) and from 2-20.5% on the contralateral limb, depending on the follow up time scale.[3–5] Many studies have evaluated the difference in ACL re-injury rates between BPTB and HT grafts.[4,6,7] Thompson et al.[7] prospectively studied 180 ACLR athletes with a 20-year follow up and found a significantly greater contralateral ACL injury rate in BPTB (30%) than HT (14%). Other studies have reported similar findings,[4] although differentiation of re-injury rate is not always evident when the sample size is low.[6] It has been suggested that graft type may also influence the risk of contralateral re-injury when athletes return to high level activity after ACLR.[8]

After ACLR, the injury itself and the disruption at the graft harvest site result in reduced strength and other neuromuscular qualities such as power on the ACLR side, causing an increase in between-limb asymmetry.[9,10] Rehabilitation goals include restoration of inter-limb symmetry in neuromuscular function and strength to the pre-injury level.[11] Large inter-limb asymmetries are associated with poorer knee function and increase the risk of sustaining a second ACL injury after Return To Play (RTP),[12] with ACLR athletes demonstrating greater knee extensor and flexor isokinetic strength asymmetries than healthy controls.[9] Graft donor site has been shown to influence observed strength asymmetries.[13] BPTB athletes were reported to have a greater knee extensor strength deficit and a lower knee flexor strength deficit than HT athletes in the majority of studies.[13] These deficits may be related to morbidity caused during the harvest of the graft.[14,15]

Strength asymmetries have been shown to contribute towards asymmetries in functional performance, Ground Reaction Force (GRF) variables and knee mechanics during sporting movements in ACLR athletes.[16,17] Differences in knee extensor and flexor strength between graft types might hence be expected to translate to GRF asymmetries during jumping and landing activities. Previous studies have found a moderate positive relationship between asymmetries in leg muscle mass and asymmetries in both strength and in GRF variables during bilateral countermovement jumps (CMJ) in ACLR athletes,[18] which may increase the risk of a subsequent ACL injury.[19]

Gold standard measures such as isokinetic dynamometry accurately measure strength asymmetry but in a uniplanar controlled manner.[20] Jumping and landing are key components of multi-directional field sports performance, so unilateral and bilateral CMJ tests are often used to assess lower-limb performance in ACLR athletes during rehabilitation.[21] ACLR athletes demonstrate greater asymmetries in single limb vertical and horizontal jump performance than controls.[9] Dynamic joint loading during a landing task has been reported to differ between graft types, with BPTB athletes found to land with their operated leg in a more-extended position and with a greater peak vertical GRF (GRFv) than HT athletes.[22] Studies investigating asymmetry during bilateral drop jump landings in adolescent cohorts revealed that BPTB athletes have greater asymmetry than HT in external knee flexion moments and knee sagittal plane energy absorption.[23] An advantage of assessing bilateral instead of unilateral movements is to enable analysis of the athlete’s choice of loading strategy to achieve motor tasks. For example, the athlete may offload the operated leg due to fear of knee collapse or pain,[24] increasing the risk of sustaining a second ACL injury.[12]

Force platforms alone may be used to measure GRFv during a CMJ, without the requirement for position sensors to be tracked (as for calculation of joint angles, moments, etc.). When analysing data from the CMJ, single discrete points such as peak GRFv are commonly reported to quantify load[16,17,22] but this approach disregards potentially important information from the majority of the force-time curve. An alternative approach incorporating GRF over the entire movement is to use impulse, the first integral of the GRF-time curve, to quantify loading during CMJ take-off and landing. The jump can then be subdivided into eccentric and concentric movements and impulse assessed within these specific phases to isolate differing muscle actions (Figure 1).[18] Jordan et al.[18] found that elite post-ACLR skiers demonstrated greater phase-specific inter-limb asymmetries than controls during the concentric phase of a CMJ. Athletes scoring lower in the International Documentation Committee subjective form (IKDC) approximately 31 months post-ACLR demonstrated greater eccentric deceleration asymmetries than higher-scoring athletes during unilateral and bilateral CMJs.[25] The influence of graft type on phase-specific impulse asymmetries has not been examined and is potentially of particular interest at the critical time point of 9 months post-surgery, when athletes typically RTP.[8] Graft-specific differences identified could then be targeted during rehabilitation to improve symmetry outcomes prior to RTP.

The primary aim of this study was to compare CMJ phase-specific impulse and isokinetic strength asymmetries in athletes with a BPTB or HT autograft at 9 months post-ACLR and controls. The secondary aim was to assess the relationship between knee extensor strength asymmetries and both eccentric deceleration impulse and concentric impulse asymmetries in BPTB and HT patients. We hypothesised that:

1) Phase-specific impulse asymmetries during a CMJ at 9 months post-ACLR would be greater for BPTB and HT patients than controls. BPTB patients would have greater phase-specific impulse asymmetries than HT patients during the CMJ.

2) Eccentric deceleration and concentric impulse asymmetries during the CMJ would be positively related to knee extensor strength asymmetries in both BPTB and HT patients.

METHODS

Participants

Power analysis (G*Power, version 3.1.9.2, Universität Düsseldorf, Germany) indicated a required sample size of 22 participants in each group to achieve 90% statistical power with an alpha level of 0.05 for the impulse outcome variables, based on pilot data with 10 participants. We employed a smallest worthwhile effect of 10% in the power calculation because 10% asymmetry in GRF variables is commonly used as an RTP criterion after ACLR.[10] Currently no experimental evidence, i.e. normative data or established relationships with outcome measures, suggests a more-appropriate alternative value.[26]

Forty-four eligible ACLR athletes who had a BPTB (n=22) or HT (semitendinosus and gracilis; n=22) autograft from the ipsilateral side were consecutively recruited prior to ACLR from the caseload of two orthopaedic knee consultants at Sports Surgery Clinic, Dublin, Ireland. Inclusion criteria were male, multidirectional field sport athletes aged between 18 and 35 years with the intention to RTP at the same level of participation as prior to the injury. As part of their clinical assessment, the athletes completed a testing session at 8-10 months post-ACLR between July 2015 and July 2017. Rehabilitation was not controlled in the time period between surgery and assessment. Athletes with multiple ligament reconstructions and previous ACL injuries were excluded from the study. Meniscal tears and chondral lesions are common secondary injuries to ACL rupture,[27] therefore athletes with these pathologies were included in the study. 14 BPTB and 12 HT athletes presented for surgery with meniscal tears and 9 BPTB and 5 HT athletes, presented with chondral lesions. A control group (n=22) meeting the same inclusion criteria as the ACLR athletes (male multidirectional field sport athletes aged between 18-35 years) with no previous lower-limb injury actively managed within the previous two years were recruited by word of mouth from the local sporting population and completed a single testing session. Participants were primarily involved in Gaelic sports (Gaelic football and hurling; 66%), soccer (24%) and rugby (10%) and their anthropometric data is reported in Table 1. Participants gave informed written consent prior to testing and the study received ethical approval from Sports Surgery Clinic Hospital Ethics Committee.

Testing Procedures

Height and body mass were measured immediately prior to testing. At the start of each testing session, participants were instructed to complete a warm up consisting of a two minute jog and five body-weight squats. Participants then performed two familiarisation CMJs where they were instructed to maintain hands placed on iliac crests and to jump as high as they could with knees extended during the flight phase. Participants were then asked to complete three maximal-height CMJs on a frame mounted dual force platform system (BP400600, AMTI, USA) that recorded GRF_v at a sampling frequency of 1000 Hz. If any of the jumps deviated from the required technique (e.g. hands removed from iliac crests) they were excluded and the jump was repeated. Jump variables were calculated as a mean of the three jumps. Participants then continued with a battery of vertical and horizontal jumps and multidirectional cutting for clinical testing. This consisted of three bilateral jumps, twelve unilateral jumps on each leg and twelve 90° running change-of-direction (cutting) manoeuvres.

After a ten minute break following completion of laboratory testing, concentric knee extensor and flexor strength were measured using an isokinetic dynamometer (Cybex Humac NORM, CSMI, Massachusetts, USA). All testing sessions were completed following protocol recommendations to assess isokinetic strength after ACLR.[20] Participants were set up in a seated position, with stabilisation belts placed across the thigh and shank on the tested limb. Knee range of motion was set from full extension (0°) to 100° flexion. Participants completed two maximal sets of 5 concentric knee extension and flexion repetitions on each limb at a speed of 60 °/s with verbal encouragement, following a submaximal warm up set. A correction for the gravitational effect on the shank was applied and torque was recorded continuously at 100 Hz. The uninvolved leg was tested first for the ACLR athletes and the dominant limb (self-reported preferred kicking limb) was tested first for the controls. Each ACLR athlete completed the IKDC questionnaire to assess subjective knee function.[28]

Data Processing

Jump height was calculated from the vertical velocity of the centre of body mass (CoM) at take-off, as derived from the impulse-momentum relationship.[29] Take-off was defined as the first instant the sum of GRF_v on both force platforms was less than 10 N and landing was defined as the first instant the sum of GRF_v on both force platforms was greater than 10 N after take-off. CoM vertical velocity was used to define phases of interest: The eccentric deceleration phase was defined as the time interval from maximum negative velocity to zero velocity (lowest CoM position); the concentric phase was defined from zero velocity to the instant of take-off; the landing phase was defined as the time interval from landing to zero velocity (lowest CoM position) (Figure 1). Impulse was calculated separately for the left and right limb for all phases as the first integral of the force-time curve and divided by body mass to allow comparison between groups. All impulse variables were extracted using custom MATLAB scripts (version 2015a, Mathworks Inc., Massachusetts, USA).

The isokinetic dynamometer set with the highest peak knee extension torque and a repetition peak torque coefficient of variation of less than 0.1 was used for analysis. Peak torque relative to body mass during knee extension and flexion was extracted from this set.

Asymmetry Calculation

An asymmetry index (AI) along with the absolute value (AAI) were calculated for each impulse phase and for isokinetic peak torque in flexion and extension for all groups (BPTB, HT, Controls). AI was used for linear regression modelling in order to preserve information regarding the direction of the asymmetry. AAI was used in all between-group comparisons to remove direction from the calculation, as the reference value used in control groups is arbitrary but affects the results of group comparisons.[30]

Control Group

$$\mathrm{AI} = \frac{(\text{Dominant limb} - \text{Non dominant limb})}{\text{Maximum of dominant and non dominant}} \times 100$$

[1]

Dominance was defined as the self-reported limb the participant would use to kick a ball.[31] A positive AI indicated that the value of the parameter was greater for the dominant limb and a negative AI indicated that the value of the parameter was greater for the non-dominant limb.

BPTB and HT Groups

$$\mathrm{AI} = \frac{(\text{Uninjured limb} - \text{ACLR limb})}{\text{Maximum of uninjured and ACLR limb}} \times 100$$

[2]

A positive AI indicated that the value of the parameter was greater for the uninjured limb and a negative AI indicated that the value of the parameter was greater for the injured limb.

For all groups, AAI was calculated for all impulse and isokinetic strength parameters as

$$AAI = \sqrt{AI^2}$$

[3]

Statistical Analysis

Shapiro-Wilk tests were used to determine whether kinetic impulse AAI, isokinetic strength AAI, jump height, IKDC scores, time from injury to surgery and time from surgery to testing session were normally distributed for all groups.

Kruskal-Wallis tests and non-parametric post-hoc testing (Mann-Whitney U tests with Bonferroni-Holm correction for multiple comparisons) were used for between-group comparisons (BPTB, HT and controls) in impulse AAIs for each phase of the CMJ (eccentric deceleration, concentric and landing) and knee extensor and flexor strength AAIs. Freidman tests and non-parametric post-hoc testing (Wilcoxon tests with Bonferroni-Holm correction for multiple comparisons) were used for within-group comparisons in impulse AAIs for each phase of the CMJ. A one-way ANOVA and Tukey HSD post-hoc testing were used for between-group comparisons in jump height. Time from injury to surgery and time from surgery to testing session were compared between BPTB and HT using Mann Whitney U tests. Two tailed independent Student's t-tests were used to compare IKDC scores between BPTB and HT.

A chi-squared goodness of fit test was used to test whether the proportion of participants for which each limb (ACL or uninjured; dominant or non-dominant) produced the greatest magnitude in the kinetic parameter (impulse or torque) differed from that which would be expected if asymmetry direction were random. A linear regression model was used to assess the relationship between eccentric deceleration AI or concentric impulse AI and knee extensor strength AI in all groups.

To determine magnitude of differences, Cohen's *d* effect size (ES) was calculated and interpreted using the following thresholds: ES>0.2 = small; ES>0.5=moderate;

ES>0.8=large.[32] Statistical analyses were performed using IBM SPSS 2016 version 24 for Mac (IBM Inc, Chicago, IL, USA). All summary statistics are reported as mean ± standard deviation (SD). Significance was accepted at α=0.05.

RESULTS

IKDC questionnaire, CMJ height, time from injury to surgery and time from surgery results are reported in Table 2. A main effect of group on jump height was found (F(2, 63) =4.083, *p*=0.02). Post-hoc testing did not identify a difference in jump height between BPTB and HT (*p*=0.93, *ES*=0.10). Controls jumped higher than BPTB (*p*=0.03, *ES*=1.00) but not than HT (*p*=0.07, *ES*=0.64). No differences were found in IKDC scores between BPTB and HT (t=-0.97, *p* =0.34, *ES*=0.29). Time from surgery to testing was 9±14 days greater for BPTB than HT (U=122, *p*=0.005, *ES*=1.06). No difference was found in the time from injury to surgery between BPTB and HT (U=-231, *p*=0.79).

Phase-Specific Impulse AAIs

A main effect of group was found for AAI during all phases (eccentric deceleration phase: χ^2 (2)=9.259, *p*=0.01; concentric phase: χ^2 (2)= 24.093, *p*<0.001; landing phase: χ^2 (2)=6.970, *p*=0.03).

During the eccentric deceleration phase post-hoc testing revealed that BPTB demonstrated a greater AAI than HT (*U*=119, *p*=0.01, *ES*=0.85). No difference in impulse AAI were found between BPTB and controls during this phase, although the difference closely approached significance for BPTB demonstrating greater asymmetries than controls (*U*=150, *p*=0.06, *ES*=0.71). No difference was found in AAI between HT and controls (*U*=-204, *p*=0.37, *ES*=-0.21).

During the concentric phase, BPTB demonstrated a greater AAI than HT (*U*=119, *p*=0.008, *ES*=0.94) and controls (*U*=39, *p*<0.001, *ES*=1.84). HT also had a greater AAI than controls during this phase (*U*=148, *p*=0.03, *ES*=0.77).

During the landing phase, no differences were found in AAI between BPTB and HT (*U*=187, *p*=0.30, *ES*=0.37). BPTB demonstrated a greater landing phase AAI than controls (*U*=132, *p*=0.03, *ES*=0.78). However, no differences were found in AAI between HT and controls during this phase (*U*=181, *p*=0.30, *ES*=0.39). Phase-specific impulse AAIs for all groups are illustrated in Figure 2.

A main effect of impulse phase was found for BPTB (χ^2 (2)=7.182, *p*=0.03) and controls (χ^2 (2)=12.091, *p*=0.01) but not HT (χ^2 (2)=4.727, *p*=0.09). Post-hoc testing revealed BPTB demonstrating a greater AAI in the eccentric deceleration phase than the concentric phase (*p*=0.01, *ES*=0.56). No differences were found in AAI between concentric and landing phases (*p*=0.05, *ES*=0.71) or between eccentric deceleration and landing phases in BPTB (*p*=0.32). Controls showed a greater AAI in the eccentric deceleration and landing phases than the concentric phase (*p*<0.001, *ES*=1.27; *p*=0.03, *ES*=0.86). No difference was found in AAI between the eccentric deceleration and landing phases in the control group (*p*=0.64).

Asymmetry direction

There was a greater number of jumps in which impulse was greater on the uninjured limb than the ACL limb during all phases of the CMJ in BPTB and HT (*p*<0.001). In controls, there was a greater number of jumps in which impulse was greater on the dominant limb than the non-dominant limb during all phases (p<0.001).

Isokinetic Strength

A main effect of group on isokinetic knee extensor strength AAI (χ^2 (2)=19.060, p<0.001) but not on flexor strength AAI (χ^2 (2)=5.519, p=0.06) was identified. Post-hoc testing revealed that BPTB had a greater knee extensor strength AAI than HT (U=102, p=0.002, *ES*=1.17) and controls (U=72, p<0.001, *ES*=1.40). No difference was found between HT and controls in knee extensor strength AAI (U=185, p=0.18). Isokinetic knee extensor and flexor strength AI and AAI results are shown in Table 3.

See Table 4 for relative phase-specific impulses and isokinetic strength for both limbs in all groups.

Linear Regression Analysis

There was a positive relationship between isokinetic knee extensor strength AI and CMJ concentric impulse AI in BPTB (p=0.002, r^2=0.39), HT (p=0.04, r^2=0.18) but not controls (p=0.33, r^2=0.05). No significant relationship was found between isokinetic knee extensor strength AI and CMJ eccentric deceleration impulse AI in BPTB (p=0.22, r^2=0.07), HT (p=0.05, r^2=0.18) or controls (p=0.67, r^2=0.01). Figure 3 illustrates the linear regression model for all groups.

DISCUSSION

When assessed nine months post-ACLR, athletes with a BPTB autograft demonstrated greater inter-limb impulse asymmetries than athletes with a HT autograft in the eccentric deceleration and concentric phases of the CMJ to achieve similar jump performance. BPTB athletes also had greater impulse asymmetries than controls during the concentric and landing phases of the CMJ. HT athletes showed a greater impulse asymmetry than controls during the concentric phase of the jump only. Knee extensor strength asymmetry explained 39% (BPTB) and 18% (HT) of the variation in concentric impulse asymmetry during the CMJ but no significant relationship was found in controls. Furthermore, no significant relationship was found between eccentric deceleration impulse asymmetry and knee extensor strength asymmetry in any groups.

Direction of Asymmetry

ACLR athletes chose to offload the operated side in this study. This may reflect a reduced capacity to absorb load on the ACLR side while executing the task, and results in in adaptive pattern favouring the non ACLR side.[24] It may also demonstrate a learned behaviour such as fear avoidance. Controls preferentially offloaded their non-dominant limb.

Eccentric Deceleration and Landing Phases

In this study, loading asymmetry during the eccentric deceleration and landing phases demonstrated that the athletes did not absorb energy equally on both limbs to decelerate their body.[33] These phases are often associated with the ACL injury mechanism, which occurs most commonly in the early part of eccentric phase.[34] Mean loading asymmetries of 20% were observed during the eccentric deceleration phase of the jump in BPTB cohort, which was double the asymmetry demonstrated in HT cohort (large *ES*: 0.85). In the landing phase, BPTB had a 21% asymmetry, which was significantly greater than the 12% asymmetry demonstrated by controls (moderate *ES*: 0.78). No significant difference was found in landing impulse asymmetry between BPTB and HT cohorts. The greater asymmetry measured during the eccentric deceleration phase compared to the concentric phase (moderate *ES*: 0.56) in the BPTB cohort, has previously been identified by Paterno et al.[12] as a risk for both operated and non-operated limb. Larger asymmetries were found in this study during the eccentric deceleration and landing phases of the CMJ compared to the concentric phase in BPTB athletes. As the ACL injury mechanism occurs during these higher risk eccentric phases[34] in which asymmetries are at their greatest, rehabilitation interventions should additionally target symmetry during these phases to improve outcomes.

Concentric Phase

The concentric phase of the CMJ is related to jump performance (net concentric impulse mechanically determines jump height) and assesses the athlete's ability to accelerate their CoM from a squat position to take-off during a powerful extension of the hip, knee and ankle.[29] The BPTB cohort showed a 14% loading asymmetry during the concentric phase, which was greater than the 8% and 4% asymmetry demonstrated by the HT cohort and controls respectively (large *ES*: 0.94; large *ES*: 1.84). Rehabilitation practitioners often use concentric exercises to improve jump performance after ACLR and much of the existing literature regarding RTP assessment focuses on jump or hop tests with a concentric emphasis.[35] Our findings suggest that this should be balanced with specific assessment of eccentric movements.

Isokinetic Strength Results

The BPTB cohort demonstrated a greater knee extensor strength asymmetry than the HT cohort (large *ES*=1.17) and controls (large *ES*=1.40), which is to be expected due to the influence that BPTB graft harvest has on the knee extensor mechanism. This difference concurs with previously-reported findings within a similar time-scale post-surgery.[9,13] As seen in Figure 3, two (9% of) BPTB athletes counterintuitively demonstrated greater knee extensor strength on their ACL limb than the contralateral limb, indicating ACL limb dominance (AI=-14; AI=-17%). Jordan et al. reported a similar result in a study of phase-specific asymmetries in elite skiers, with one participant out of nine demonstrating a 16% greater knee extensor strength on their ACLR than uninjured limb.[18] These findings highlight the presence of inter-subject variation in asymmetry outcome measures and may reflect a focus on unilateral exercises involving the ACL limb during individual rehabilitation programmes. In contrast to previous studies, we found no main effect of group on knee flexor strength asymmetry (although the result approached significance (p=0.053)). This may be due to the incorporation of a control group into our statistical model and hence our use of absolute asymmetry calculations, which reduce calculated differences between group means when the direction of asymmetry is modulated by group. See Table 3 for relative knee extensor and flexor isokinetic strength values for both limbs in all groups.

Influence of Quadriceps Strength on Functional Loading Asymmetries

We hypothesised that there would be a relationship between knee extensor strength asymmetries and phase-specific impulse asymmetries in the CMJ, as previous research has found a relationship between leg muscle mass and concentric impulse asymmetries in ACLR athletes.[18] A linear regression model showed that knee extensor strength asymmetry could explain 39% and 18% of the variation in concentric impulse asymmetry during the CMJ in the BPTB and the HT cohorts respectively. As a relationship was found within the ACLR athletes but not the control group, concentric strength appears to be an important focus for ACLR rehabilitation, especially with BPTB athletes. Knee extensor strength deficits are commonly reported at and beyond nine months post-surgery[9,13] and, given their relationship to functional loading deficits as demonstrated here, may warrant greater focus earlier in the rehabilitation process. In both ACLR cohorts, but particularly the HT cohort, other neuromuscular factors and rate of GRF_v development (RFD) may be contributing to concentric loading asymmetries.

We found no significant relationship between knee extensor strength asymmetry and eccentric impulse asymmetry in any group. Previous studies have found that ACLR athletes demonstrate an improvement in isokinetic knee extensor strength when managed with rehabilitation programs that include knee concentric strength exercises.[36] However, our results suggest that concentric strength asymmetry does not contribute towards loading asymmetries during the eccentric phase. This phase is when loading is greatest (Table 4) and also when the ACL rupture most frequently occurs.[34] Our findings suggest that eccentric qualities may need to be specifically targeted during rehabilitation in addition to concentric strength and the development of concentric impulse-generation qualities.

RFD is often used to assess explosive strength capabilities and muscle function after ACLR.[37] Both knee extensor and flexor isometric RFD delays have been found on the involved limb when compared to the contralateral limb in BPTB graft athletes[38]. Although there is limited literature investigating RFD during dynamic movements in ACLR athletes, it may be that eccentric RFD asymmetries are contributing towards the eccentric loading asymmetries observed here by influencing early-phase impulse. Other factors such as knee eccentric strength may also have contributed towards the eccentric impulse asymmetry, although knee eccentric extensor strength asymmetry has been found to recover more rapidly than concentric strength asymmetry post-ACLR.[39] Lower-limb inter-segmental and coordination asymmetries at the hip, knee and ankle may also be contributing towards loading asymmetries by compensating for the injured joint within and between limbs.[40] Finally, it should be noted that the GRF is not a direct measure of the force experienced by the musculoskeletal structures of the limb,[41] although it is strongly correlated to net knee extensor moment in similar tasks,[42] and tissue loading is also affected by factors such as muscle contraction and mechanical advantage. Future research should investigate other potential factors contributing to phase-specific loading asymmetries.

RTP Guidelines

There is a lack of consensus regarding acceptable asymmetries for safe RTP after ACLR. Asymmetries of <10-15% have been recommended as a framework for safe RTP during functional tests involving jumping movements,[8,10] although this is dependent on a number of factors including the movement assessed and the biomechanical variable selected for analysis.[43] The challenge of obtaining a clinically meaningful asymmetry criterion for RTP is partially due to the limited availability of normative values for different cohorts and exercises.[26] In this study we report mean normative phase-specific impulse asymmetry values of 4-12% in a healthy control group (see Figure 3). Significant differences with large effect sizes were found between ACLR athletes and controls, even when the <10-15% inter-limb asymmetry target was achieved. The <10-15% rehabilitation goal may hence be an overestimate of rehabilitation status and restoration of phase-specific impulse asymmetries to normative range may be a more appropriate and sensitive target criterion.

Methodological Considerations

No significant differences were found in IKDC scores between the BPTB and HT cohorts at the time of testing. Thus, we interpret the differences found in impulse asymmetries in this study as relating to the capacity of each limb to produce force rather than the athlete's confidence in knee function.

Future research should investigate the effect of defined exercise interventions on loading asymmetries in BPTB autograft athletes and HT autograft athletes during the rehabilitation process to restore normal levels of impulse asymmetry throughout all phases. Many rehabilitation practitioners use bilateral vertical jumps as an objective RTP test,[10] however little is known regarding whether - and how - phase-specific impulse asymmetries relate to rehabilitation outcomes. Prospective research should therefore investigate whether these differences in loading asymmetries influence outcomes such as pain-free RTP and second ACL injury (to either the operated or non-operated limb) for both graft types.

Conclusion

There was a significant influence of graft donor site on loading asymmetries during a CMJ in athletes at nine months post-ACLR, although no differences in jump height performance or subjective knee function were identified. Knee extensor strength asymmetry was greater for the BPTB than the HT cohort. This strength asymmetry partially explained concentric but not eccentric impulse asymmetries in both graft types; however, more research is needed to determine other factors contributing to loading asymmetries for each graft type. Given the results of this study, graft-specific strength deficits should be targeted during rehabilitation along with a greater focus on reducing eccentric impulse asymmetries after ACLR for both graft types.

PERSPECTIVES

This is the first study to demonstrate an effect of graft type on phase-specific impulse asymmetries and to relate these asymmetries to strength asymmetry. We found that BPTB athletes had greater inter-limb impulse asymmetries than HT in the eccentric deceleration and concentric phases of the CMJ, although similar jump heights were achieved. By showing that knee extensor strength asymmetry was a significant predictor of concentric but not eccentric impulse asymmetries in both graft types, we contribute to the understanding of strength assessment's role and limitations in explaining functional asymmetry in performance tasks. Rehabilitation practitioners commonly use concentric exercises to improve jump performance after ACLR.[35] However, we identified larger asymmetries during the eccentric deceleration phase of the CMJ than in the concentric phase in BPTB athletes, suggesting that specific targeting of eccentric movements may be beneficial during rehabilitation interventions and monitoring.

REFERENCES

1. Moses B, Orchard J, Orchard J. Systematic Review: Annual Incidence of ACL Injury and Surgery in Various Populations. *Res Sport Med*. 2012;20(3-4):157-179.
2. Kiapour AM, Murray MM. Basic science of anterior cruciate ligament injury and

repair. *Bone Jt Res*. 2014;3(2):20-31.

3. Salmon L, Russell V, Musgrove T, Pinczewski L, Refshauge K. Incidence and Risk Factors for Graft Rupture and Contralateral Rupture After Anterior Cruciate Ligament Reconstruction. *J Arthrosc Relat Surg*. 2005;21(8):948-957.
4. Pinczewski LA, Lyman J, Salmon LJ, Russell VJ, Roe J, Linklater J. A 10-Year Comparison of Anterior Cruciate Ligament Reconstructions With Hamstring Tendon and Patellar Tendon Autograft. *Am J Sports Med*. 2007;35(4):564-574.
5. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. Risk of Secondary Injury in Younger Athletes after Anterior Cruciate Ligament Reconstruction. *Am J Sports Med*. 2016;44(7):1861-1876.
6. Sajovic M, Stropnik D, Skaza K. Long-term Comparison of Semitendinosus and Gracilis Tendon Versus Patellar Tendon Autografts for Anterior Cruciate Ligament Reconstruction. *Am J Sports Med*. 2018;46(8):1800-1808.
7. Thompson SM, Salmon LJ, Waller A, Linklater J, Roe JP, Pinczewski LA. Twenty-Year Outcome of a Longitudinal Prospective Evaluation of Isolated Endoscopic Anterior Cruciate Ligament Reconstruction with Patellar Tendon or Hamstring Autograft. *Am J Sports Med*. 2016;44(12):3083-3094.
8. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: The Delaware-Oslo ACL cohort study. *Br J Sports Med*. 2016;50(13):804-808.
9. Xergia SA, Pappas E, Zampeli F, Georgiou S, Georgoulis A. Asymmetries in Functional Hop Tests, Lower Extremity Kinematics, and Isokinetic Strength Persist 6 to 9 Months Following Anterior Cruciate Ligament Reconstruction. *J Orthop Sports Phys Ther*. 2013;43(3):154-163.
10. Myer GD, Paterno M V, Ford KR, Quatman CE, Hewett TE. Rehabilitation

After Anterior Cruciate Ligament Reconstruction: Criteria-Based Progression Through the Return-to-Sport Phase. *J Orthop Sports Phys Ther*. 2006;36(6):385-402.

11. Palmieri-Smith R, Thomas AC, Wojtys EM. Maximizing Quadriceps Strength After ACL Reconstruction. *Clin Sports Med*. 2008;27(3):405-424.
12. Paterno M V, Schmitt LC, Ford KR, et al. Biomechanical Measures During Landing and Postural Stability Predict Second Anterior Cruciate Ligament Injury After Anterior Cruciate Ligament Reconstruction and Return to Sport. *Am J Sports Med*. 2010;38(10):1968-1978.
13. Xergia SA, Mcclelland JA, Kvist J, Vasiliadis H, Georgoulis A. The influence of graft choice on isokinetic muscle strength 4 – 24 months after anterior cruciate ligament reconstruction. *Knee Surgery, Sport Traumatol Arthrosc*. 2011;19(5):768-780.
14. Rosenberg TD, Franklin JL, Baldwin GN, Nelson KA. Extensor mechanism function after patellar tendon graft harvest for anterior cruciate ligament reconstruction. *Am J Sports Med*. 1992;20(5):519-526.
15. Konrath JM, Vertullo CJ, Kennedy BA, Bush HS, Barrett RS, Lloyd DG. Morphologic Characteristics and Strength of the Hamstring Muscles Remain Altered at 2 Years After Use of a Hamstring Tendon Graft in Anterior Cruciate Ligament Reconstruction. *Am J Sports Med*. 2016;44(10):2589-2598.
16. Schmitt LC, Paterno M V, Ford KR, Myer GD, Hewett TE. Strength Asymmetry and Landing Mechanics at Return to Sport after Anterior Cruciate Ligament Reconstruction. *Med Sci Sports Exerc*. 2015;47(7):1426-1434.
17. Pua Y-H, Mentiplay BF, Clark RA, Ho J-Y. Associations Among Quadriceps Strength and Rate-of-Torque Development 6 Weeks Post Anterior Cruciate Ligament Reconstruction and Future Hop and Vertical Jump Performance: A

Prospective Cohort Study. *J Orthop Sport Phys Ther*. 2017;47(11):1-24.

18. Jordan MJ, Aagaard P, Herzog W. Lower limb asymmetry in mechanical muscle function: A comparison between ski racers with and without ACL reconstruction. *Scand J Med Sci Sport*. 2015;25:301-309.

19. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *Am J Sports Med*. 2005;33(4):492-501.

20. Undheim MB, Cosgrave C, King E, et al. Isokinetic muscle strength and readiness to return to sport following anterior cruciate ligament reconstruction: is there an association ? A systematic review and a protocol recommendation. *Br J Sports Med*. 2015;49:1305-1310.

21. Hori N, Newton RU, Kawamori N, McGuigan MR, Kraemer WJ, Nosaka K. Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. *J Strength Cond Res*. 2009;23(3):874-882.

22. Webster KE, Gonzalez-Adrio R, Feller JA. Dynamic joint loading following hamstring and patellar tendon anterior cruciate ligament reconstruction. *Knee Surgery, Sport Traumatol Arthrosc*. 2004;12:15-21.

23. Mueske NM, VandenBerg CD, Pace JL, et al. Comparison of drop jump landing biomechanics and asymmetry among adolescents with hamstring, patellar and quadriceps tendon autografts for anterior cruciate ligament reconstruction. *Knee*. 2018.

24. Holsgaard-Larsen A, Jensen C, Mortensen NHM, Aagaard P. Concurrent Assessments of Lower Limb Loading Patterns, Mechanical Muscle Strength and Functional Performance in ACL-Patients — A Cross-Sectional study.

Knee. 2014;21(1):66-73.

25. Baumgart C, Hoppe MW, Freiwald J. Phase-Specific Ground Reaction Force Analyses of Bilateral and Unilateral Jumps in Patients With ACL Reconstruction. *Orthop J Sport Med*. 2017;5(6):1-9.
26. Dingenen B, Gokeler A. Optimization of the Return-to-Sport Paradigm After Anterior Cruciate Ligament Reconstruction: A Critical Step Back to Move Forward. *Sport Med*. 2017;47(8):1487-1500.
27. Hagino T, Ochiai S, Senga S, et al. Meniscal tears associated with anterior cruciate ligament injury. *Arthrosc Sport Med*. 2015;135(12):1701-1706.
28. Irrgang JJ, Anderson AF, Boland AL, et al. Development and Validation of the International Knee Documentation Committee Subjective Knee Form *. *Am J Sports Med*. 2001;29(5):600-613.
29. Linthorne NP. Analysis of Standing Vertical Jumps Using a Force Platform. *Am J Phys*. 2001;69(11):1198-1204.
30. Bishop C, Read P, Chavda S, Turner A. Asymmetries of the Lower Limb: The Calculation Conundrum in Strength Training and Conditioning. *Strength Cond J*. 2016;38(6):27-32.
31. Peters M. Footedness: Asymmetries in Foot Preference and Skill and Neuropsychological Assessment of Foot Movement. *Am Psychol Assoc*. 1988;103(2):179-192.
32. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed.; 1988.
33. Hamill J, Knutzen K, Derrick T. *Biomechanical Basis of Human Movement*. 4th ed. Lippincott Williams and Wilkins; 2014.
34. Koga H, Nakamae A, Shima Y, et al. Mechanisms for noncontact anterior cruciate ligament injuries: Knee joint kinematics in 10 injury situations from

female team handball and basketball. *Am J Sports Med*. 2010;38(11):2218-2225.

35. Wilk KE, Arrigo CA. Rehabilitation Principles of the Anterior Cruciate Ligament Reconstructed Knee: Twelve Steps for Successful Progression and Return to Play. *Clin Sports Med*. 2017;36(1):189-232.
36. Cardone C, Menegassi Z, Emygdio R. Isokinetic assessment of muscle strength following anterior cruciate ligament reconstruction. *Isokinet Exerc Sci*. 2004;12(3):173-177.
37. Aagaard P, Simonsen EB, Andersen JL, Magnusson SP, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol*. 2002;93(4):1318-1326.
38. Mirkov DM, Knezevic OM, Maffiuletti NA, Kadija M, Nedeljkovic A, Jaric S. Contralateral limb deficit after ACL-reconstruction: an analysis of early and late phase of rate of force development. *J Sports Sci*. 2017;35(5):435-440.
39. Ikeda H, Kurosawa H, Takazawa S, et al. Eccentric contraction strength of knee extensor before and after anterior cruciate ligament reconstruction. *Eur J Orthop Surg Traumatol*. 2004;14(2):107-111.
40. Roos PE, Button K, Deursen RWM Van. Motor control strategies during double leg squat following anterior cruciate ligament rupture and reconstruction: an observational study. *J Neuroeng Rehabil*. 2014;11(1):1-8.
41. Sharkey NA, Hamel AJ. A dynamic cadaver model of the stance phase of gait: performance characteristics and kinetic validation. *Clin Biomech*. 1998;13(6):420-433.
42. Nelson A, Koslakiewicz N, Almonroeder TG. Assessment of Knee Kinetic Symmetry Using Force Plate Technology. *J Sport Rehabil*. 2018;27(6):8-10.
43. Barber-Westin SD, Noyes FR. Objective criteria for return to athletics after

anterior cruciate ligament reconstruction and subsequent reinjury rates: a systematic review. *Phys Sportsmed*. 2011;39(3):100-110.