Biomechanical asymmetries differ between autograft types during unplanned change of direction after ACL reconstruction

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ABSTRACT

Nine months after anterior cruciate ligament (ACL) reconstruction, athletes who undergo surgery using a bone-patellar-tendon-bone (BPTB) autograft demonstrate higher loading asymmetries during vertical jumping than those with a hamstring tendon (HT) autograft. These asymmetries may transfer into sporting movements with a greater ACL injury risk. The aim of this study was to compare between-limb asymmetries in knee mechanics and task performance during an unplanned 90° change-of-direction (CoD) task in male field sport athletes reconstructed with BPTB or HT autografts. Seventy-eight male multidirectional field sport athletes with either a BPTB (n=39) or HT (n=39) autograft completed maximal unplanned CoD trials in a three-dimensional motion capture laboratory at approximately nine months post-surgery. A mixed model 2x2 ANOVA (autograft type x limb) was used to compare variables related to ACL injury risk (e.g. internal knee moments) and performance (e.g. completion time) between autografts and limbs. Statistical parametric mapping was used for a waveform comparison throughout stance, supplemented with a discrete point analyses of peak knee moments and performance variables. Interaction effects were found at the knee joint, with BPTB demonstrating greater asymmetries than HT in knee extension moment ($p<0.001$); resultant ground reaction force ($p<0.001$); peak knee external rotation moment ($p=0.04$); and knee adduction ($p=0.05$), medial rotation ($p<0.001$) and flexion ($p<0.001$) angles. No differences were found between autografts for any performance variable. BPTB demonstrated greater lower-limb biomechanical asymmetries than HT during CoD, which may influence knee loading and longer-term outcomes and should thus be targeted during rehabilitation prior to return to play.

Key words: Anterior cruciate ligament, bone-patellar tendon-bone autograft, hamstring autograft, asymmetry, statistical parametric mapping, rehabilitation.

INTRODUCTION

Anterior cruciate ligament (ACL) rupture is a severe knee injury with an incidence proportion for amateur athletes of up to 1.6% per year in multi-directional field sports such as soccer and rugby.[1] The most common treatment for ACL rupture is surgical reconstruction (ACLR) using either a bone-patellar-tendon-bone (BPTB) or hamstring tendon (HT) autograft.[3] Prospective studies have reported high ACL second injury rates of up to 42% for the operated and the contralateral non-operated limb combined.[5,6,8,10,12] Autograft type appears to influence the likelihood of a subsequent ACL rupture, with BPTB demonstrating higher contralateral limb second injury rates than HT but similar or lower ACLR limb re-injury rates.[5,7,9,11]

Strength, jumping and landing metrics show that athletes who have undergone ACLR demonstrate deficits on the operated limb relative to both the contralateral limb and to healthy controls.[13,14] Research has shown that biomechanical differences are present between BPTB and HT athletes post-surgery in lower-limb strength, walking, hopping and jumping.[14–18] BPTB demonstrate greater knee extensor strength deficits and lower knee flexor strength deficits than HT, most-likely related to the insult caused by the graft harvesting procedure.[17] These strength differences between autograft types translate into loading (impulse) asymmetries during different phases of the countermovement jump: BPTB were found to demonstrate greater eccentric deceleration and concentric impulse asymmetries than HT, and to offload their ACLR limb by increasing the load on their contralateral limb.[14] The authors suggested that this may contribute to the previously-reported differences in contralateral re-injury rates between autograft types.[5,7,9,11] To improve the strength of this evidence-base assessing walking, hopping and jumping, further research is needed to compare knee loading asymmetries between autografts during more challenging and ecologically relevant manoeuvres such as change of direction (CoD).

CoD is a key skill in multi-directional field sports and is the most common task in which a non-contact ACL injury is observed, responsible for up to 50% of such injuries.[19] Video analysis studies examining the CoD injury mechanism have associated positions of dynamic knee valgus and large knee moments (in the transverse and frontal plane) with ACL injury.[20] Dynamic knee valgus is a combination of adduction and medial rotation at the hip, abduction and external rotation at the knee, and eversion at the ankle.[21] This motion, integrated with a large ground reaction force (GRF), long knee moment arm,[21] and an extended leg posture,[22] increases the anterior tibial translation, external knee abduction and external rotation moments and thus the load on the ACL.[23,24] Therefore, when assessing ACL re-injury risk during CoD, it is important to assess these variables during rehabilitation after ACLR.

Previous studies have often focused on the first 20% of CoD stance, as this early deceleration phase is when the majority of non-contact ACL injuries have been reported to occur.[25] During this phase, both female and male athletes with ACLR using either a BPTB or HT autograft show a greater peak internal knee adduction moment on the ACLR limb than controls.[26,27] However, important information on CoD biomechanics throughout stance may have been missed due to the use of only discrete point zero-dimensional (0D; e.g. peak knee abduction moment) analyses and the analysis of only CoD manoeuvres examining direction change during stance on the ACLR limb. This is particularly pertinent for between-graft comparisons given the differences that were previously identified in the propulsive phase of the countermovement jump.[14] King et al.[28] used a full waveform analysis (i.e. analysis including the full time-series curve for the relevant variable) to demonstrate that between-limb asymmetries in key variables associated with risk factors and rehabilitation outcomes, such as knee abduction and internal rotation moments, are present across different phases of stance during maximal unplanned CoD nine months after ACLR using either autograft type. However, no differences in completion time for the entire CoD task (measured using speed gates) were found between the limbs. These findings highlight the importance assessing entire waveforms during high-risk movement patterns after ACLR and suggest that rehabilitation status may be overestimated by sole reliance on recovery of symmetry of peak knee moments and timed performance. Nevertheless, it is of importance to assess 0D and 1D in parallel to capture important information on the maximum forces, moments and angles at joints, as well as entire biomechanical movement patterns and timings respectively.

It is unknown whether kinematic and kinetic asymmetries in maximal multiplanar movements such as CoD are affected by autograft type. This information could be used by rehabilitation practitioners to tailor their interventions to be specific to autograft type to optimise rehabilitation and outcomes post ACLR. Therefore, the aim of this study was to compare between-limb asymmetries in knee mechanics and timed performance during an unplanned 90° CoD task in male field sport athletes reconstructed with BPTB or HT autografts, nine months post-surgery. We hypothesised that BPTB would demonstrate larger biomechanical asymmetries than HT at the knee joint during the unplanned CoD manoeuvre.

METHODS

Participants

This cross-sectional study was completed using the caseload of ACLR patients from two orthopaedic knee consultants at Sports Surgery Clinic, Dublin, Ireland, between 2014 and 2018. Participants were recruited onto the ACL research program prior to ACLR surgery. Seventy-eight male amateur to semi-professional field sport (e.g. soccer, rugby, Gaelic football) athletes with ACLR (Table 1) using either a BPTB (n=39) or HT autograft (semitendinosus and gracilis; n=39) harvested from the ipsilateral limb were included in the analysis. Surgical procedures for both autograft types were as described in King et al.[29] An *a priori* power analysis (G*Power, version 3.1.9.2, Düsseldorf, Germany) indicated a required minimum sample size of 23 in each group to achieve 80% statistical power with an alpha level of 0.05. A Cohen's *d* effect size of 0.85 was chosen for the power analysis,[30] based on previous differences identified between the two autograft types in jump impulse asymmetries.[14] Inclusion criteria were male, multidirectional field sport athletes (i.e. Gaelic football, hurling, soccer, rugby) aged between 18–35 years with the intention to RTP at the same level of participation as prior to the injury. Participants were excluded if they had concomitant multiple ligament reconstructions or a previous ACLR on either limb. Participants were retrospectively selected, with all eligible HT athletes with complete datasets (i.e. no trials with incomplete force platform contacts; n=39) matched to an eligible BPTB athlete based on concurrent meniscal repair (yes/no), injury mechanism (contact or non-contact), RTP status (yes/no), International Knee Documentation Committee subjective knee function questionnaire (IKDC) score and body mass. The required information regarding meniscal repair status, injury mechanism and RTP status was extracted from surgical records and a pre-testing questionnaire completed by all participants.

Participants completed a biomechanical testing session between eight and ten months post-ACLR. Rehabilitation was not standardised between surgery and testing; however, participants received rehabilitation guidance from clinicians at the study centre immediately after surgery and during clinical reviews at approximately three and six months after ACLR. Participants gave informed written consent prior to testing and the study received ethical approval from the University of Bath's Research Ethics Approval Committee for Health (MSES 18/19-012) and the Sports Surgery Clinic Hospital Ethics Committee (25-AFM-010).

Protocol

Height and body mass were measured, then participants were prepared with markers attached to the anatomical bony landmarks of the lower-limbs, pelvis and trunk according to a modified Plug-in-Gait model.[31] Participants wore their own athletic footwear. Prior to testing, participants completed a warm-up that consisted of a two-minute overground jog (at a self-selected speed), five body weight squats, two submaximal and three maximal countermovement jumps. The CoD was preceded by a battery of exercises (three trials of a double and single leg drop jump, single leg hop for distance and a hurdle hop) used for the patient's clinical assessment and as part of multiple broader research studies.[14,28,29,32,33] The experimental set-up for the 90° unplanned CoD manoeuvre is displayed in Figure 1. Sharper turns (90° vs. 45°) are associated with greater mechanical loading and thus would be expected to be more representative of re-injury risk[2] which are frequently performed in field-sports such as soccer.[4] An unplanned rather than planned CoD task was selected due to its greater ecological validity to the multidirectional field sports the athletes participated in.[34] In accordance with the methods described by King et al.[28], a Smartspeed system (Fusion Sport, Chicago, Illinois, USA) was used to cue participants in the direction of the turn and to record CoD task completion times. The CoD was timed from the trigger gate to the exit gate (Figure 1). Participants were instructed to complete the CoD manoeuvre as quickly as possible without decelerating before the exit gate after the turn. Once the participant passed the trigger gate, the left or right exit gate automatically flashed, signalling to the participant to turn in that direction off their outside leg (i.e. planting the right leg to turn to the left). The direction of the turn was randomly assigned and continued until three successful trials were captured on each limb (up to a maximum of ten trials before the participant was excluded), following three initial familiarisation trials. After the physical testing, participants completed the IKDC questionnaire to assess subjective knee function (Table 1).[35]

Data collection and processing

A twelve-camera three-dimensional (3D) motion capture system (200 Hz; Bonita-B10, Vicon, UK), synchronised (Vicon Nexus 1.8.5) with two force platforms (1000 Hz BP400600, AMTI, USA) were used to record 3D trajectories of 28 reflective markers (14 mm diameter) and GRFs. Marker trajectories and force data were low-pass filtered using a fourth-order zero-lag Butterworth filter with a cut off frequency of 15 Hz.[36] Visual 3D software (version 6.03, C-Motion, Maryland, USA) was used to create a lower-body and trunk model from the static trial and to calculate model-based computations (joint angles, internal joint moments and the position of the body centre of mass [CoM]). Ground contact time (stance) was defined as the time-period when vertical GRF was >20 N.

The angle of the CoD manoeuvre was quantified using the change in heading angle (CoM deflection angle) and pelvis rotation angle from initial contact to foot-off (Figure 2). CoD angle is known to affect knee joint kinetics[37,38] and is often reduced when athletes with ACLR turn off their reconstructed limb,[39] so this quantification enables any non-equivalence in the completed task to be identified. Approach and exit velocities were calculated as the resultant horizontal CoM velocity at initial contact and toe off on the force platform respectively. Resultant horizontal CoM velocity was calculated during the entire penultimate stride before foot contact with the force platform, to show a deceleration profile for both autografts during the penultimate step prior to CoD.[40] A standard inverse dynamics approach was used to calculate internal knee moments. Mean values from the three successful trials for each limb were used for analysis. All kinetic variables were expressed relative to body mass.

Statistical Analyses

Continuous waveform data for joint angles, joint moments, penultimate stride horizontal CoM velocity and resultant GRF were temporally normalized from 0 to 100% of stance. The open-source spm1d MATLAB package (www.spm1d.org v0.4.7; run on MATLAB vR2019b, MathWorks Inc, Massachusetts, USA) was then used to identify regions of differences between waveforms using one-dimensional statistical parametric mapping (SPM).[41] If differences were found across >5% of stance, the start and end points (% of stance) of the period over which the significant difference was observed were reported alongside mean values during that phase.

Statistical analyses of discrete point 0D data (mean values for each participant's three CoD trials) comprising CoM approach and exit velocities, CoD completion time, contact time, change in heading and pelvis rotation angles, and peak joint moments were conducted using IBM SPSS Statistics version 25 (IBM, New York, USA).

2x2 mixed-model analysis of variance (ANOVA) models with factors autograft type (BPTB/HT) and limb (ACLR/non-ACLR) were used for all 0D and 1D comparisons. In the analysis of knee moments, the discrete point and SPM analyses measured complementary but different information. The discrete point analysis determined whether differences were present at the point of peak knee moment, whereas the SPM analysis examined potential differences throughout the entire stance phase to give a more complete biomechanical profile. Any significant interaction effect represents a difference in between-limb asymmetry between the autograft types. Significance was accepted at α<0.05. We did not adjust for multiple comparisons because a relatively small number of pre-planned comparisons were made within each model. This would be expected to increase the likelihood of a 'false positive', which we attempt to mitigate by not interpreting transient (<5%) significant clusters in the SPM analysis.

RESULTS

Knee joint moments

Knee moments in the frontal, transverse and sagittal plane throughout stance are displayed for both autograft types (BPTB and HT) and limbs (ACLR and non-ACLR) in Figure 3. In the sagittal plane, the 1D SPM analysis showed an interaction effect in knee extension moment from 10–88% of stance ($p<0.001$), with BPTB displaying a greater between-limb asymmetry than HT (inferred from Figure 3C). A main effect of autograft type for sagittal plane moment was found, with BPTB demonstrating a lower moment than HT from 21-63% of stance ($p<0.001$) on the ACLR side. Additionally, a main effect of limb was found for knee extension moment from 10–84% of stance, with the non-ACLR limb showing a greater moment ($p<0.001$) than the ACLR limb. These findings are supported through the 0D discrete point analysis, as an interaction effect representing greater asymmetry in BPTB ($F(1, 78)= 24.30$, $p<0.001$), a main effect of autograft type ($F(1, 78)=13.94$, $p<0.001$) and a main effect of limb ($F\ (1,78)=90.38$, $p<0.001$) were found for peak knee extension moment (Table 2).

In the frontal plane, no significant interaction effect (autograft type x limb) and no main effects of autograft type or limb were found for knee adduction moment using SPM analysis (Figure 3A). However, as shown in Table 2, the 0D discrete point analysis identified differences between limbs in peak knee adduction moment, with a higher peak frontal plane moment on the non-ACLR than ACLR limb ($F\ (1,78)=6.14$, $p=0.02$).

In the transverse plane, an interaction effect was found from 83 – 89% of stance for knee internal rotation moment ($p=0.03$), with HT showing a larger asymmetry than BPTB (Figure 3B). No main effect of autograft or limb (as the difference occurred over

<5% of stance) was identified. The 0D discrete point analysis identified an interaction effect in peak transverse plane moment showing that BPTB displayed a greater asymmetry than HT ($F(1, 78)=4.32$, $p=0.04$), and a greater external rotation moment was exhibited on the non-ACLR limb ($F(1,78)=7.86$, $p=0.01$) (Table 2).

Knee joint angles

Knee joint angle comparisons throughout stance are displayed in Table 3. An interaction effect was found from 18–36% and 44-88% of stance in medial rotation angle; as well as from 7-89% of stance in extension angle (Table 3). These interaction effects were driven by BPTB showing higher between-limb asymmetries in knee joint angles in the sagittal and transverse planes than HT (Appendix A). However, no significant interaction effect occurred in knee adduction angle. No main effect of autograft type was found in any of the analysed planes (Table 3, Appendix A). A main effect of limb was found in all knee joint angles measured during the reported phases of stance (Table 3). The most pronounced differences were in the sagittal plane from 10-79% of stance, with the ACLR limb displaying lower levels of knee flexion.

Performance

Figure 4 shows the performance related variables: CoD completion time, contact time, approach velocity, change in heading angle and change in pelvis rotation angle. No significant interaction effects or main effects of autograft type were found for any performance variable. A main effect of limb was found for change in heading angle ($F(1,78)=6.67$, $p=0.01$), with change in heading angle being slightly lower (mean difference of only 2.3°) when athletes changed direction on their ACLR than on their non-ACLR limb (62.5±7.2° vs. 64.8±7.0°).

Resultant GRFs during stance for both autograft types and limbs are displayed in Figure 5. BPTB produced a lower resultant GRF than HT from 29-46% of stance (p<0.001). A main effect of limb was found between 3-8% (p=0.03), 22-42% (p<0.001) and 59 - 76% (p<0.001) of stance, with the ACLR limb producing less resultant GRF than the non-ACLR limb. No significant main effects or interaction effects were found throughout the penultimate stride in horizontal CoM velocity (Appendix B).

DISCUSSION

As hypothesised, athletes with a BPTB autograft demonstrated a more asymmetrical biomechanical profile at the knee joint when compared to athletes with a HT autograft, particularly in the sagittal plane, while achieving a similar CoD performance. Athletes with BPTB autografts exhibited a lower knee extension moment and resultant GRF than HT when changing direction off their ACLR limb, and also exhibited greater between-limb asymmetries in medial rotation and extension knee angles, knee extension moment and peak internal rotation moment during specific phases of stance during the CoD manoeuvre. These findings suggest that autograft type should be carefully considered by practitioners during rehabilitation: BPTB autografts are likely to require more emphasis on reducing biomechanical between-limb asymmetries and increasing the capacity of the ACLR limb to produce an eccentric knee extension moment during the CoD step prior to RTP.

Knee joint biomechanics

The ACLR limb knee joint was more extended than the contralateral limb knee joint throughout the majority of stance in BPTB (Table 3, Appendix A). An extended knee angle during CoD stance has previously been identified as a potential risk factor for ACL injury.[19] This is largely attributed to the increased loading on the ACL resulting from anterior shear and non-sagittal joint loads when the knee is in a more extended position.[24] Therefore, the greater knee extension displayed by BPTB on the ACLR limb during CoD would be expected to increase their susceptibility to ACL re-injury (although the lower re-rupture rates reported for BPTB autografts suggest that other factors are able to compensate[9,29]).

When changing direction off the ACLR limb, knee extension moment was lower for BPTB than for HT from 21% to 63% of stance. This outcome was hypothesised due to previous research showing greater loading asymmetries during jump tasks in BPTB than HT.[14] Lower knee extension moments during hopping tasks have been previously associated with the larger quadriceps strength deficits on the ACLR limb in athletes reconstructed with BPTB than HT nine months post-surgery.[13] This is supported by evidence from King et al.[28], who also found a lower knee extension moment on the ACLR limb during 90° CoD. This analysis included both autograft types in the between-limb comparison,[28] so the identified difference was likely driven primarily by BPTB and less so by HT, as supported by the interaction effect in the current study (Figure 3C). Also in accordance with King et al.[28], a main effect of limb was found for knee joint angles in all three planes of motion, which is representative of altered CoD kinematics when athletes with ACLR turn off either limb. Greater biomechanical asymmetries during sporting manoeuvres may increase the risk of ACL injury, especially when they are present during early stance phase, as this is the period in which ACL ruptures most frequently occur.[25,26]

The identified interaction effects highlight the larger asymmetries in knee adduction, medial rotation and extension angles for BPTB during particular phases of stance (Table 3). These differences in asymmetries between autograft types translated into joint moment asymmetry differences in knee external rotation and extension moments only, with no significant effect identified for knee adduction moment. We observed an interaction effect (autograft x limb) in peak knee external rotation moment CoD (Table 2). This peak fell within the initial 20% of stance in which ACL injuries are thought to be most likely to occur,[25] and is a variable related to increased strain on the ACL.[42] BPTB autografts demonstrated a reduced load on their ACLR limb and an increased load on their contralateral limb. Moments were measured in each plane of motion in isolation, but the combination of greater load on the contralateral limb as measured by peak knee adduction moment and peak external rotation moment in BPTB may increase the load on the ACL and contribute to the higher contralateral limb re-rupture rate observed in this cohort.

CoD performance

Considering the large knee extension moment and force production deficit found in BPTB, it is interesting to note that no differences were detected in CoD performance asymmetry (Figure 4). Studies assessing athletes with ACLR during jumping tasks have reported BPTB to demonstrate reduced capacity of the quadriceps muscle on the ACLR limb during the eccentric deceleration and concentric phases in comparison to HT.[14] In the current study, this was shown to translate into CoD force production, with BPTB generating a lower resultant GRF than HT (Figure 5). Despite these deficits, BPTB achieve a similar performance outcome to HT, meaning that alternative neuromuscular compensation strategies must be adopted by this cohort when turning off their ACLR limb. Many factors contribute towards CoD task performance[23] so BPTB may be mechanically compensating proximally and distally to the knee joint to perform the task.

The penultimate step before CoD can be used to assist with CoM deceleration to reduce the requirement for deceleration during the CoD step. When athletes with ACLR change direction off their ACLR limb they often demonstrate increased load on the contralateral limb during the penultimate step as an offloading mechanism for the ACLR limb during the turning step, and *vice versa* when stepping off the contralateral limb.[43] However, no main effects or interaction effects were found throughout the CoM velocity waveforms during the penultimate step prior to CoD. Braking patterns and magnitudes thus appear to be similar for both limbs and autografts. This finding does not support the supposition that athletes with ACLR decelerate more during the penultimate step (using the contralateral limb) in an attempt to offload their ACLR limb for the turning step.

Limitations and suggestions for future research

Alternative musculoskeletal models are likely to offer greater suitability for high-speed dynamic movements such as CoD, as the Plug-in Gait model was originally designed to be used for the clinical analysis of walking.[44] The model is relatively sensitive to marker placement,[33] which can affect the reliability of the calculated kinematic and kinetic variables (particularly in the transverse and frontal plane). The Plug-in Gait model also uses a direct kinematics modelling approach, which only enables the segments to move freely about three rotational DoF, with the three translational DoF being constrained.[44] Disregarding translations at the knee is a potential limitation of this study and many others in the field, since translations such as anterior tibial shear on the femur has been related to high ACL strains and injury risk.[45] However, a previous study comparing direct kinematic and inverse kinematic modelling approaches for kinematic and kinetic CoD data found no difference in the classification of athlete ACL injury risk.[44] Additionally, the methodology of the study (including the modelling approach) was identical for HT and BPTB so errors would be expected to be systematic and unlikely to influence our overall conclusions.

We identified differences between athletes reconstructed with BPTB than HT in CoD biomechanics when variables proposed to be associated with ACL injury risk such as joint angles and moments were studied in isolation. Further work is required to examine the extent to which biomechanical between-limb asymmetries are clinically relevant to both performance and ACL second injury risk (in both the ACLR and non-ACLR limbs), as well as work attempting to determine what rehabilitation practitioners should be targeting with their athletes regarding biomechanical asymmetry during CoD. It has previously been shown that the non-ACLR limb can also exhibit deficits after ACLR surgery, potentially as a result of bilateral detraining and/or neural inhibition.[16,46,47] It is therefore important to consider these asymmetry metrics alongside the absolute values recorded on each limb, ideally by comparison to appropriate matched controls or pre-injury baseline data. As the knee joint was the predominant focus of this study, additional research is needed to examine other joints such as the hip and the ankle to determine whether BPTB are compensating at proximal or distal joints. Future research could attempt to assess the biomechanics of lower-limb segments from a coordination variability perspective, such as examining joint coupling angles at the knee joint which are more directly related to high ACL loads. Athletes post-ACLR demonstrate greater coordination variability in these joint couplings than controls during CoD, which has been suggested to increase ACL re-injury risk.[48] Therefore, this alternative approach may give additional insight into biomechanical differences between athletes reconstructed with BPTB and with HT during CoD, and how these differences may influence outcomes and re-injury rates.

Only male athletes were included in this study. Multiple sex differences in ACL injury incidence and risk factors have previously been reported,[49] so our findings cannot necessarily be extrapolated to female athletes. Establishing the extent to which autograft type also affects post-ACLR mechanics in females should be a focus for future work. Our sample did not include elite/professional level athletes, for which different outcomes may be observed. Standardised footwear was not provided for the testing session so there was some variation in the athletic footwear worn by the participants, and rehabilitation was not standardised across participants for logistical reasons (the majority lived some distance from the study centre so underwent rehabilitation under the guidance of their own local practitioner). These factors may have introduced additional uncontrolled effects on biomechanical outcome measures but are unlikely to have systematically influenced the between-group comparisons. Finally, we tested participants only at maximum effort and at a single CoD target angle (90°). Both CoD angle and approach speed are known to affect joint mechanics,[21,23,38] so a complete understanding of the effect of autograft type on CoD biomechanics would require additional investigation at multiple controlled angles and speeds.

Practical applications

It has been widely established that BPTB athletes have greater quadriceps strength deficits and lower hamstring strength deficits than HT,[14,17] as well as biomechanical differences during movements such as walking, hopping and jumping.[14–16,50] However, little was previously known about biomechanical differences between athletes reconstructed with BPTB and with HT autografts during unplanned CoD after ACLR, despite the fact that this type of task is commonly incorporated into return to play testing batteries[51] and is a common mechanism of injury. Our findings suggest that rehabilitation requirements specific to each autograft type should be carefully considered on an individualised level when prescribing exercises targeting CoD biomechanics after ACLR. BPTB are likely to require more emphasis on reducing kinematic between-limb asymmetries and increasing the ACLR limb's capacity to utilise the knee extensor complex to decelerate the CoM when changing direction. This may improve outcomes relating to pain, re-injury and sporting performance after return to play.

PERSPECTIVES

Previous studies have revealed differences between athletes with BPTB and HT autografts in whole-body loading asymmetries during the eccentric deceleration and concentric phases of a jumping task.[14] This was the first study to examine differences in knee mechanics between athletes with BPTB and HT autografts during a more ecologically valid task associated with high ACL injury risk task - unplanned CoD - around the time of RTP. Biomechanical differences between BPTB and HT athletes were found to be present during CoD, with BPTB showing greater between-limb asymmetries than HT in knee angles and moments despite no differences being found in CoD performance. Change of direction tasks are commonly used within testing batteries and in RTP decision-making, so our findings suggest that clinicians and rehabilitation practitioners should be aware that autograft types are likely to differ in CoD biomechanics and that BPTB athletes may require more specific rehabilitation targeted towards reducing inter-limb asymmetries in order to ensure a safe return to play.

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TABLES

Table 1: Participant characteristics

Characteristic	BPTB (n=39)	HT (n=39)
Age (years)	23.4 ± 4.4	23.1 ± 3.4
Height (cm)	181.8 ± 6.4	178.5 ± 4.9
Mass (kg)	83.8 ± 7.2	82.5 ± 8.9
Injured during CoD % [n]	51 [20]	54 [21]
Concurrent meniscal repair % [n]	18 [7]	13 [5]
Dominant ACLR % [n]	67 [26]	69 [27]
RTP at the time of testing % [n]	33 [13]	38 [15]
Time of testing post-ACLR (mon)	9.24 ± 0.38	9.03 ± 0.23
IKDC score (0-100)	84 ± 7	86 ± 7

Dominance was defined as preferred kicking limb. BPTB = Bone-patellar-tendon-bone autograft. HT = Hamstring tendon autograft. RTP = Return to play. IKDC = International Knee Documentation Committee questionnaire. CoD = Change of Direction. Continuous data are presented as mean ± SD.

Table 2: Peak internal joint moments including statistical comparisons

Variable	Direction	BPTB (n=39)		HT (n=39)		2x2 ANOVA
		ACL	Non-ACLR	ACL	Non-ACLR	
Knee moment (Nm/kg)	Adduction	1.08 ± 0.42	1.30 ± 0.49	1.09 ± 0.42	1.14 ± 0.39	†
	Internal rotation	-0.52 ± 0.20	-0.67 ± 0.27	-0.59 ± 0.24	-0.61 ± 0.23	† §
	Extension	1.86 ± 0.50	2.82 ± 0.63	2.60 ± 0.58	2.90 ± 0.55	***†††§§§

Data expressed as means ± SD. *** = Significant main effect of autograft type at $P < 0.001$. † = Significant main effect of limb at $P < 0.05$. ††† = Significant main effect of limb at $P < 0.001$. § = Significant autograft x limb interaction effect at $P < 0.05$. §§§ = Significant autograft x limb interaction effect at $P < 0.001$. BPTB = Bone-patellar-tendon-bone autograft. HT = Hamstring tendon autograft.

Table 3: Knee joint angle differences between ACLR and non-ACLR limbs and autograft x limb interaction effects during the Change of Direction (CoD) manoeuvre

Variable	Direction	Main effect of limb				Interaction effect	
		% Stance	ACLR	Non-ACLR	P	% Stance	P
Knee angle (°)	Adduction	23 - 32	-3.93 ± 9.23	-6.93 ± 8.83	**0.03**	n.s	n.s
	Medial rotation	18 - 33	22.84 ± 9.32	26.82 ± 10.85	**0.03**	18 - 36	**0.02**
		46 - 74	24.77 ± 9.28	27.82 ± 10.66	**0.005**	44 - 88	**<0.001**
	Extension	10 -79	-57.12 ± 7.48	-61.76 ± 7.38	**<0.001**	7 - 89	**<0.001**

Data represents the mean ± SD during the time-period of significant difference as identified by the Statistical Parametric Mapping (SPM) analysis. There were no significant differences identified between BPTB and HT for knee joint angle in any plane. N = 78 (39 in each group).

FIGURES

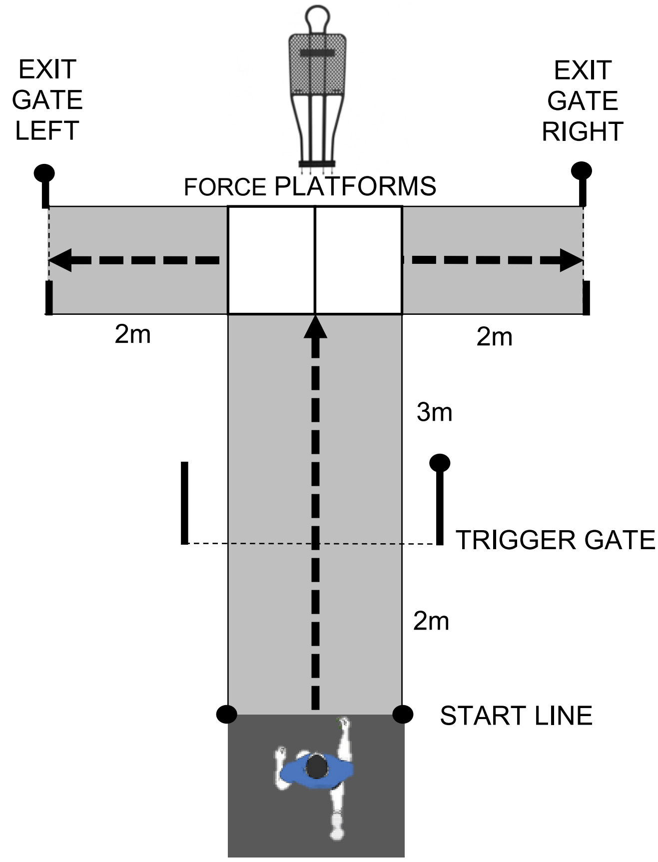


Figure 1: The dimensions for the unplanned change of direction manouvre.

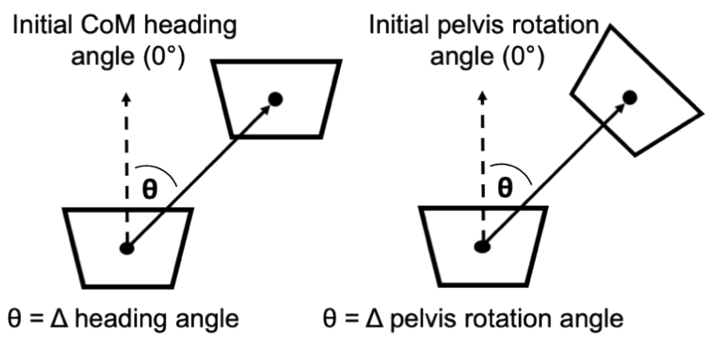


Figure 2: Variables defining CoM (Centre of Mass) deflection (left) and pelvis rotation (right).

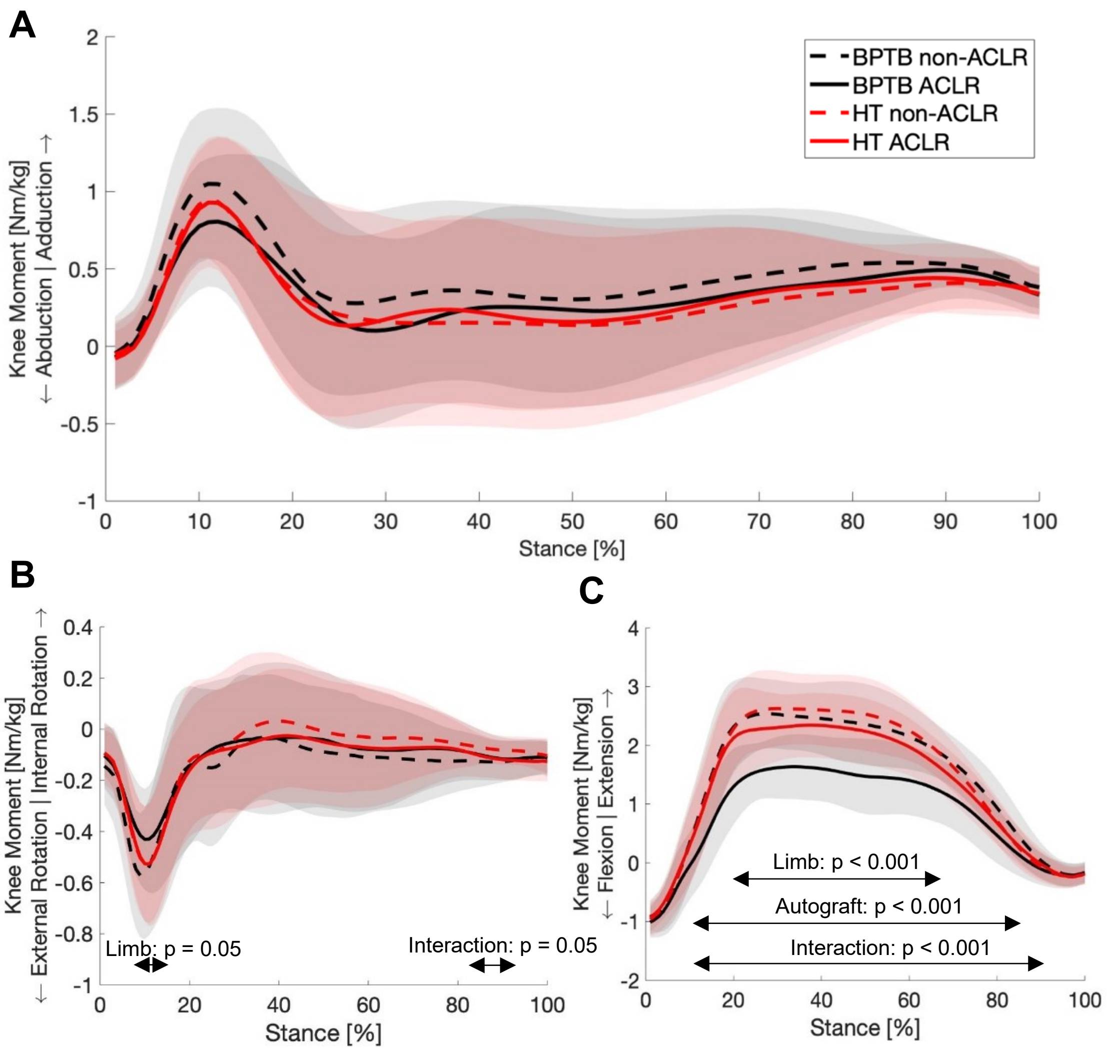


Figure 3: Internal knee moments in the frontal (A), transverse (B) and sagittal (C) plane. All data were normalised to 100% of stance. The curves demonstrate the mean moment. The grey and red shaded areas represent SD for BPTB and HT respectively. BPTB = Bone-patellar-tendon-bone autograft. HT = Hamstring tendon autograft. N = 78 (39 in each group).

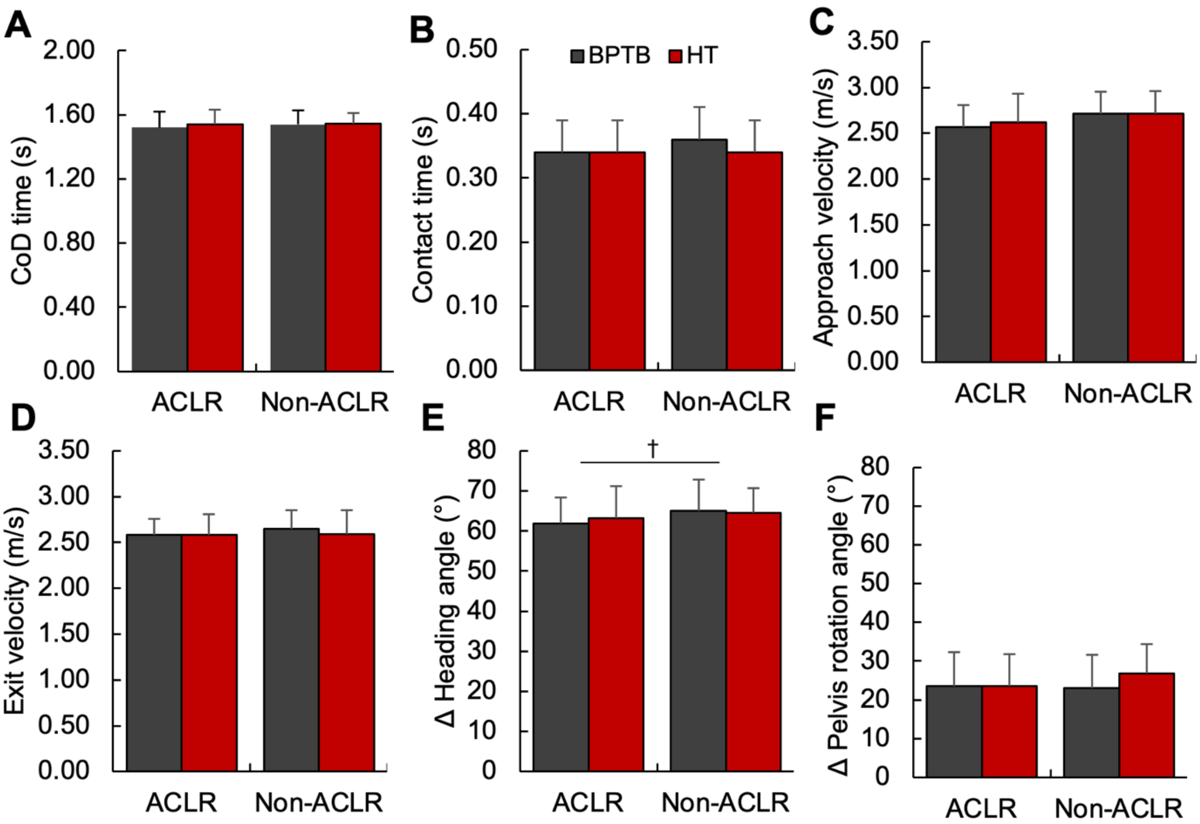


Figure 4: CoD performance measures for BPTB (red) and HT (black). Data represent mean ± SD. † = Significant between-limb main effect at $P<0.05$. No main effect of autograft type or interaction effect were found. N = 78 (39 in each group). A = CoD time; B = contact time; C = approach velocity; D = exit velocity; E = Δ heading angle; F = Δ pelvis rotation angle. BPTB = Bone-patellar-tendon-bone autograft. HT = Hamstring tendon autograft.

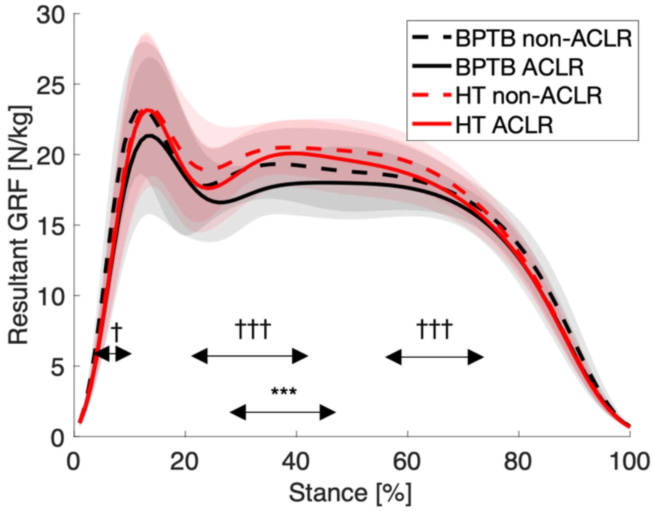


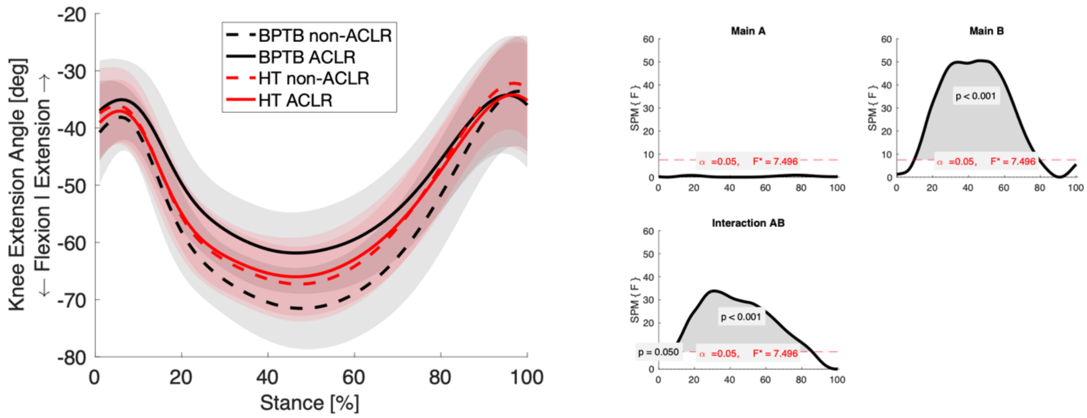
Figure 5: Resultant GRF normalised to 100% of stance. The curves demonstrate the mean GRF. The grey and red shaded areas represent SD for BPTB and HT respectively. BPTB = Bone-patellar-tendon-bone autograft. HT = Hamstring tendon autograft. *** = Significant main effect of autograft type at $P < 0.001$. † = Significant main effect of limb at $P < 0.05$. ††† = Significant main effect of limb at $P < 0.001$. N = 78 (39 in each group).

APPENDICES

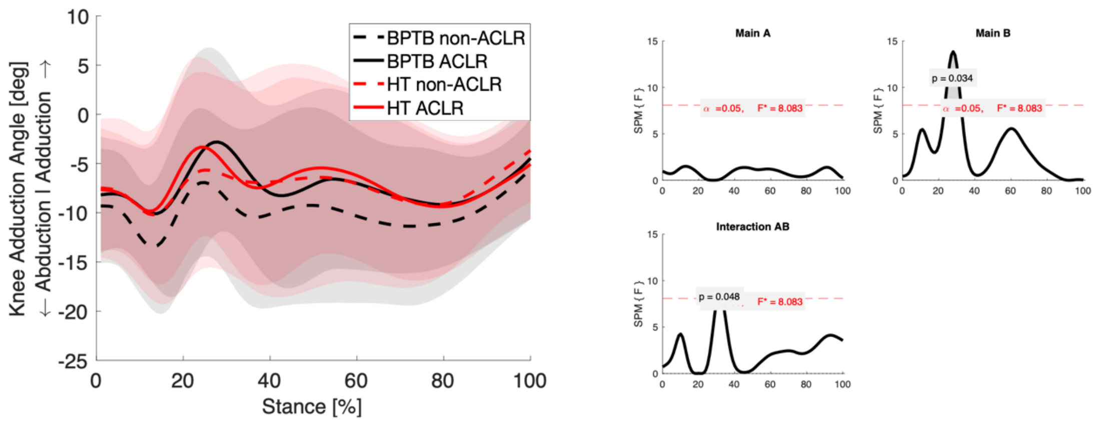
The following appendices show the continuous waveforms for variables that are only shown in tables within the main text, or that do not reach significance in 'Main A' (factor = autograft type), 'Main B' (factor = limb), or 'Interaction AB' (interaction between autograft type and limb).

Appendix A: Knee joint angles including SPM comparisons

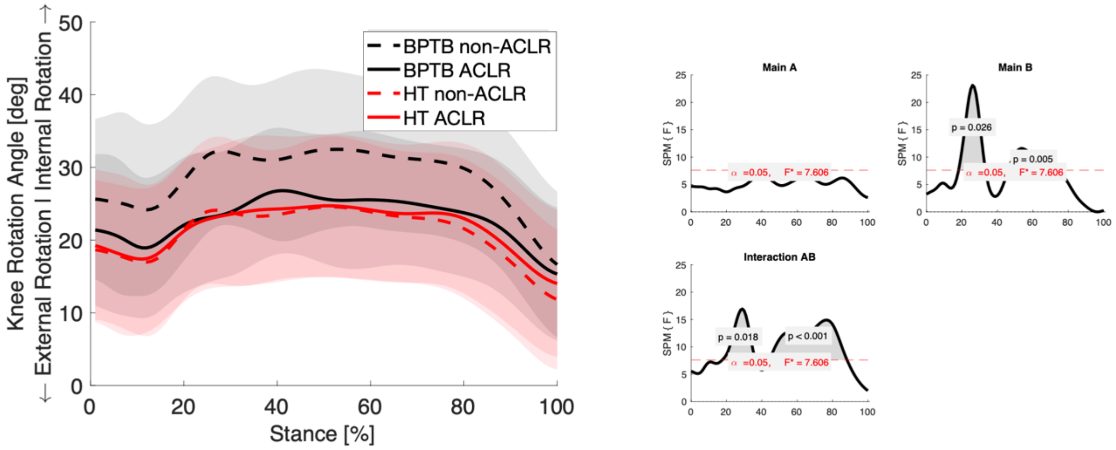
Knee flexion angle



Knee adduction angle



Knee rotation angle



Appendix B: Penultimate stride horizontal CoM velocity including SPM comparisons