Can biomechanical testing after ACL Reconstruction identify athletes at risk for subsequent ACL injury to the contralateral uninjured limb?

Accepted version. Proofs being developed.

Abstract

Background

Athletes are twice as likely to rupture the anterior cruciate ligament (ACL) on their healthy contralateral knee after ACL reconstruction (ACLR). Although physical testing is commonly used after ACLR to assess injury risk to the operated knee, strength, jump, and change of direction performance and biomechanical measures have not been examined in those that go on to suffer contralateral ACL injury to identify factors that may be associated with injury risk.

Purpose

To prospectively examine differences in biomechanical and clinical performance measures in male athletes 9 months post ACL reconstruction (ACLR) between those who rupture their previously uninjured contralateral ACL and those who have not at 2-year follow–up and examine the ability of these differences to predict contralateral ACL injury.

Study Design

Case-control study

Methods

Accepted Proof

A cohort of male athletes returning to level-1 sports after ACLR (n = 1045) underwent isokinetic strength testing and 3D biomechanical analysis of jump and change of direction (CoD) tests 9 months post-surgery. Participants were followed-up at 2 years re-return to play or at second ACL injury. Between-group differences in patient-reported outcomes, performance measures and 3D biomechanics for the contralateral limb and asymmetry were analysed. Logistic regression was applied to determine the ability of identified differences to predict contralateral ACL injury.

Results

Of the cohort, 993 had follow up at 2 years (95%) with 67 suffering contralateral ACL injury and 38 ipsilateral injury. Male athletes who succumbed to contralateral ACL injury had lower quadriceps strength and biomechanical differences on the contralateral limb during double leg drop jump and single leg drop jump tests compared to those who did not experience an injury. Differences related primarily to deficits in sagittal plane mechanics and plyometric ability on the contralateral side. These variables could explain group membership with fair to good ability (AUC: 0.74–0.80). Patient reported outcomes, limb symmetry of clinical performance measure or biomechanical measures in CoD tasks did not differentiate those at risk for contralateral injury.

Conclusion

This study highlights the importance of sagittal plane control during drop jump tasks and the limited utility of limb symmetry in performance and biomechanical measures when assessing future contralateral ACL injury risk in male athletes. Targeting the identified differences in quadriceps strength and plyometric ability during late stage rehabilitation and testing may reduce ACL injury risk in healthy limbs in male athletes playing level-1 sports.

Accepted Proof

Clinical Relevance

This study highlights the importance of assessing the contralateral limb after ACLR and identifies biomechanical differences, in particular in the sagittal plane in drop jump tasks, that may be associated with injury to this limb. These factors could be targeted during assessment and rehabilitation with additional quadriceps strengthening and plyometric exercises after ACLR to potentially reduce the high risk of injury to the previously healthy knee.

Key Terms

Anterior Cruciate Ligament Reconstruction, Contralateral knee, Return to Play, Re-injury, Biomechanics

What is known about the subject?

ACL injury rates to the contralateral healthy knee after ACL reconstruction are twice as high as injury to the reconstructed knee. Clinical testing after ACL reconstruction has been used to assess the rehabilitation status of the operated limb and previous research has demonstrated that insufficient rehabilitation after surgery can influence re-injury rates. However, no prospective studies have examined the ability of physical testing and biomechanical analysis to identify risk factors for ACL injury to the contralateral knee.

How might it impact clinical practice in the future?

This study highlights the importance of assessing biomechanics of the contralateral limb after ACL reconstruction. No differences in patient reported outcome, and commonly used measures of symmetry of strength, jump and CoD performance were identified between those who suffered contralateral ACL injury and those that did not. The findings highlight the

Accepted Proof

importance of the sagittal plane, in particular plyometric ability and vertical stiffness which may be targeted in future assessment and rehabilitation to reduce the high rate of contralateral ACL injury.

Introduction

The primary concern after anterior cruciate ligament (ACL) reconstruction (ACLR) is minimising risk of re-rupture of the reconstructed ACL.[29, 31] Risk of re-injury to the reconstructed graft [44, 49] as well as the native ACL on the contralateral limb [51] is considerably higher than risk of ACL injury in previously un-injured healthy athletes.[40, 49, 54, 58] Further, a review of second ACL injury rates (within 5 years) reported a pooled incidence of 5.8% for injury to the ipsilateral operated limb and 11.8% for ACL injury of the contralateral limb.[59] Given this high injury rate after ACLR, identifying risk factors for ACL injury to the contralateral healthy knee that can be addressed or targeted during rehabilitation may be important for improving short and long-term outcomes for athletes.

Multiple factors have been outlined in the previous research as requiring consideration as part of the RTP process to mitigate against future injury including: time from surgery, muscle strength, clinical examination, hop testing, performance-based criteria and patient reported outcomes (PRO).[3] However the validity of these measures collectively or in isolation in identifying those that will suffer adverse outcomes is unknown.[3, 53] PRO and symmetry of clinical performance measures of isokinetic strength, jump performance, and CoD time in combination are commonly used to assess rehabilitation status after ACLR and have been suggested to influence injury risk to both knees after ACLR.[13, 29] However, these studies did not examine contralateral second knee injuries to identify risk factors specific to injury in the previously healthy knee.

Accepted Proof

Landing and change of direction (CoD) are the two most common ACL injury mechanisms.[1] Biomechanical variables during landing have been suggested to predict ACL second injury after ACLR yet CoD has not been explored. Paterno et al. identified several biomechanical factors predicting second ACL injury during double leg drop jump (DLDJ) tests, including un-involved limb hip rotation moment, asymmetry of knee extension moment at initial contact, and knee valgus range of motion during landing.[41] However this study combined male and female athletes, did not report variables specific to injury to either the ACLR or contralateral knee or examine single leg drop jump (SLDJ) even though single leg landing is a more common injury mechanism. Biomechanical differences in kinetic and kinematic variables in all three planes relating to the ankle, knee, hip and thorax to pelvis in both jump and CoD tests have been demonstrated between ACLR and contralateral limbs in male athletes 9 months after ACLR.[21, 25] These same asymmetries are greater than those in healthy, uninjured control athletes, potentially due to incomplete rehabilitation of the ACLR limb.[22] Whether these biomechanical differences in relation to greater asymmetry (insufficient rehabilitation of ACLR limb) or deficits specific to the contralateral limb influence injury risk to the contralateral knee has not been prospectively examined. Biomechanical differences have been reported despite no differences in hop and CoD performance between limbs. There were however large performance differences during the SLDJ which is a measure of plyometric ability.[21] Plyometric ability, as measured by reactive strength, refers to the capacity to absorb and then produce force, over short ground contact times, primarily using the stretch shortening cycle and thus maximising whole body stiffness. These deficits reflect an inability to absorb and produce force during landing and may reflect a relevant injury risk factor. Biomechanical differences during jump and CoD tests have been found between those who re-rupture their reconstructed ACL graft compared to those who do not, despite no

Accepted Proof

differences in clinical performance measures.(in review along with this paper) However, non-physical factors such as graft type[23] graft healing time [5], and surgeon experience [50] may influence ipsilateral graft re-rupture but are not applicable to contralateral ACL injury. Therefore, investigation of the influence of biomechanical and performance measures on risk of ACL injury to the contralateral knee is warranted.

The aim of this study was to identify differences in strength, jump, and CoD performance, PRO and landing biomechanics associated with future ACL injury to the contralateral limb and assess the ability of these differences to predict who will be injured. Our hypothesis was that there would be differences in strength and biomechanics throughout the kinetic chain during jump and CoD testing and these variables will predict contralateral injury.

Methods

Athletes were recruited into this prospective case-control study at the Sports Surgery Clinic (Dublin, Ireland) before ACLR from January 1, 2014–December 31, 2016. Before surgery, athletes completed a pre-operative questionnaire outlining their sport, mechanism of injury, and level of desired return after surgery. Males aged 18–35 years who played level-1 sports (multidirectional field sports involving landing, pivoting, and change of direction) and intended to return to the same level of sport were included in the study (n = 1045). All participants underwent primary ACLR using either a bone-patellar tendon-bone or hamstring (gracilis/semitendinosus) graft from the ipsilateral limb. Those who were undergoing second or subsequent ACLR, did not intend to return to level-1 sports, or had meniscal or additional ligament repair at the time of surgery were excluded. The study was registered at

Accepted Proof

clinicaltrials.gov (NCT02771548) and received approval from the clinics ethic committee (25-AFM-010).

Testing Protocol

After ACLR, all participants underwent a rehabilitation protocol with weight bearing as tolerated on crutches for 2 weeks, followed by progressive blocks of strength, power, and plyometric exercises, progressing to on-field running and CoD. Athletes were rehabilitated locally by their referring physiotherapist and reviewed by their orthopaedic surgeons at 2 weeks, 3 months, and 6–9 months after surgery. As part of their final orthopaedic review, athletes took part in a physical testing protocol at 9 months (range 8-10) post-surgery. Before testing, all participants completed PRO: International Knee Documentation Committee (IKDC; scaled 0-100),[20] Marx Activity Scale (scaled 0-16),[35] and ACL Return to Sport after Injury questionnaire (ACL-RSI; scaled 0-100)[56] with higher scores reflecting higher self-reported knee function, activity levels and self-reported readiness to return to sport respectively. A list of the acronyms used to describe tests and variables is outlined in Table 1.

Table 1 Acronyms used for tests and variables used

Acronym	Variable
CI	Contralateral Injury Group
NCI	No Contralateral Injury Group
PRO	Patient Reported Outcome
DLDJ	Double Leg Drop Jump
SLDJ	Single Leg Drop Jump
SLCMJ	Single Leg Countermovement Jump
SLHD	Single Leg Hop for Distance
CoD	Change of Direction
IKDC	International Knee Documentation Committee
ACL RSI	Anterior Cruciate Ligament Return to Sports after Injury
COM	Centre of Mass
LSI	Limb Symmetry Index

Accepeted Proof

Data were collected in a 3D biomechanics laboratory as part of a larger prospective research project and included a DLDJ from 30 cm, single leg drop jump (SLDJ) from 20 cm, and 90° planned and unplanned CoD,[21, 25] as well as measurement of single leg countermovement jump (SLCMJ) height and single leg hop for distance (SLHD).[13, 29, 39] Participants performed a standardised warm-up: 2-min jog, 5 bodyweight squats, and 2 submaximal and 3 maximal double leg countermovement jumps. Each participant performed two sub-maximal practice trials of each movement before three valid test trial attempts (maximal effort and full foot contact on force plate) were captured, with mean of the three trials used for analysis. A 30-second recovery was taken between trials. Lab testing was followed by concentric isokinetic testing of quadriceps and hamstring muscle groups in both limbs at 60°/s from 0-100° knee flexion, reporting peak torque/body mass.[52]

Movement mechanics data collection took place using an eight-camera motion analysis system (Bonita-B10, Vicon, UK) capturing at 200 Hz, synchronised with two force platforms (BP400600, AMTI, USA) sampling at a frequency of 1000 Hz, recording motion data from 24 reflective markers (diameter: 14 mm) and ground reaction forces (Vicon Nexus 1.8.5), which were low-pass filtered using a fourth-order Butterworth filter (cut-off frequency of 15Hz).[27] Markers were placed on the lower legs and trunk according to the adapted Plug-in-Gait and kinematic data calculated.[34] Performance measures were calculated for jump (height and length) and CoD (time) tasks. Jump height was calculated using the take-off vertical velocity derived from the vertical ground reaction force signal using the impulse-momentum theorem. Jump length was calculated as the horizontal distance from heel marker at start of the jump to landing using MATLAB (MathWorks Inc, Natick, MA, USA). Reactive strength

Accepted Proof

index was calculated for the DLDJ and SLDJ as jump height divided by ground contact time.[14] Time to complete the 90° CoD was recorded using speed gates (Smartspeed, Fusion Sport, Chicago, Illinois, USA) with a trigger gate 2 m from the start line and exit gate 2 m to the left and right of force plates to indicate end of the manoeuvre.[25]

Standard inverse dynamics analysis was used to calculate kinetic variables (reported as internal moments) at the ankle, knee, and hip. All kinetic variables were normalised to body mass. A custom MATLAB program was used for processing and calculating trunk-to-pelvis angles, and distance from center of mass (COM) to ankle and knee joint in all three planes.[24] Whole body stiffness when the body was accepting load was calculated as:

$$\text{stiffness (k)} = \text{delta vGRF} / \text{sqrt(delta CoMz} \wedge 2)$$

where delta for both variables is from impact (the point of initial ground contact) to and end of eccentric phase defined as the first instance at which COM vertical power > 0. Kinetic and kinematic analysis was carried out for the stance phase of each jump and CoD test (defined by ground reaction force [GRF] > 20 N). Curves were normalised to 101 frames and landmark-registered to when centre of mass power reached zero in the Z (vertical) axis, aligning onset of the eccentric phase to 50% of the stance phase, to ensure appropriate comparison of neuromuscular characteristics between limbs and participants during continuous waveform analysis.[36, 45] Limb symmetry index (LSI) for strength and jump performance measures was calculated as: [ACLR side/contralateral side] x 100. The magnitude of asymmetry of biomechanical variables was calculated by subtracting the contralateral limb from the ACLR limb throughout the stance phase.

Follow-Up

Accepted Proof

Participants were followed-up via e-mail to identify second ACL injuries (i.e., ACL injury confirmed on MRI to either the ACLR knee or contralateral knee) at 1 year and 2 years post-surgery using a return-to-play (RTP) questionnaire or were identified if they returned to their original surgeon with diagnosis of another ACL injury. If participants did not reply to the e-mail questionnaire, they received a follow-up phone call to complete the questionnaires. All participants who had surgery and were identified to have ACL injury to their contralateral knee, but no injury to ACLR knee, were included in the contralateral injury (CI) group (n = 67) which set the sample size for the study. A cohort of participants who had returned to multidirectional field sports after ACLR and had not experienced a second ACL injury to either knee at 2 years follow-up were assigned to the NCI (no contralateral injury) group. The NCI group was matched to the CI group mean for time from surgery to RTP, time from surgery to 3D biomechanical testing, age, and distribution of graft type (n = 60) to ensure that appropriate comparison and minimise potential influence of non-physical factors on contralateral ACL injury (Figure 1).

Figure 1. Flow diagram of matching process for CI and NCI groups.

Statistical Analysis

Differences between CI and NCI groups in LSI, PRO, isokinetic peak torque of quadriceps and hamstrings, planned and unplanned 90° CoD time, and SLDJ, SLCMJ, and SLHD jump performance on the contralateral side were examined using student's independent t-test. Effect sizes for differences between groups for each variable were calculated using Cohen's d (0.2–0.49 = small; 0.5–0.79 = medium; ≥0.8 = strong).[6] Odds ratio were calculated for subjects being in the NCI group when they had >90% LSI for quadriceps strength, hamstring

Accepted Proof

strength SLCMJ and SLDJ jump height for all five tests collectively. SPM (1d, unpaired t-test; parametric) was used to examine differences in biomechanical variables (vGRF, angles and moments at hip, knee and ankle, thorax to pelvis angles and COM to ankle and knee in all three planes) between CI and NCI groups for the contralateral limb and asymmetry between limbs (ACLR limb minus contralateral limb) between groups for each biomechanical variable for DLDJ, SLDJ, and planned and unplanned 90° CoD during stance. Mean effect size across phases with significant differences ($p < 0.05$) was reported, excluding phases with Cohen's d < 0.5. Time points and mean effect sizes with a significant difference between the two groups and mean values for each group across that phase are reported. Graphs for biomechanical variables with differences are displayed in Appendix A.

To assess the ability of the results to predict ACL re-injury, logistic regressions were performed using a maximum of 5 predictor variables that were chosen based on the largest effect sizes of the identified differences for the magnitude and symmetry analysis. Only these features were chosen to achieve an input to observations ratio of 1:10 to 15, to generate a model avoiding overfitting the model to the data.[2, 42] It should be noted that if a feature was multicollinear (correlation between them >.70) with a higher ranked feature it was excluded and an additional lower ranked feature was included. Predictor variables utilized were the average value of the phases within a biomechanical waveform that differed between groups. Before fitting the logistic regression predictor variables were transformed into z-scores and cohorts were balanced so that the sample size of CI and NCI was equal. To transform a predictor variable vector $\mathbf{x}$ (e.g. contact time; $n \times m$; $n = 88$ subjects; $m = 1$ feature) into z scores the following equation was used:

$$z = (\mathbf{x} - \bar{x}) / S,$$

Accepted Proof

with $\bar{x}$ being the average and S is standard deviation of the sample within $\mathbf{x}$. During the fitting, data were balanced (using Synthetic Minority Over-sampling Technique)[4] so the minority class contained the same number of observations as the majority class. To interpret predictive ability of the logistic regression, receiver operating curve (RoC) and prediction accuracy are reported. Area under the curve (AUC) was used to classify findings (nil = 0.50; poor > 0.60; fair > 0.70; good > 0.80), while the accuracy measure was compared to expected accuracy (accuracy if the most frequent class was guessed). A summary of the data points and statistical analysis is outlined in Table 2.

Table 2 Summary of data points and statistical analysis

Dataset	Analysis
PRO data	Mann-Whitney U Test
Strength, Jump and CoD Performance Contralateral side and LSI	Independent Student's t-test Odds Ratio CI if ≥ 90% LSI Logistic Regression
Biomechanics Contralateral side and ASYM	1D SPM independent Student's t-test Logistic Regression

PRO – patient reported outcome; CoD - change of direction; LSI - limb symmetry index, ASYM - asymmetry; SPM - statistical parametric mapping

Results

Of the 1045 male primary ACLRs, 67 contralateral ACL injuries were recorded, 38 ipsilateral ACL injuries and 52 were lost to follow up (95% follow up). Of those participants who suffered contralateral ACL injury (CI group), 3D biomechanical analysis was recorded on 55 contralateral participants (12 did not attend follow-up 3D biomechanical analysis) and was matched to 60 athletes who completed 3D biomechanical analysis but did not experience

Accepted Proof

ACL injury to either knee 2 years after surgery (NCI group). Mean time to contralateral injury was 23.3 (±9.8) months (Table 3). There was no significant difference in IKDC, ACL-RSI, or Marx Activity Scale scores between groups (Table 4).

Table 3. Anthropometric data

	CI (mean ± SD)	NCI (mean ± SD)	p-value
Subject Numbers	55	60	
Graft Type (BPTB/HT)	46/9	48/12	0.61
Age (years)	21.3 (±4.2)	21.9 (±4)	0.43
Mass (Kg)	80.7 (±10)	81.5 (±11.6)	0.69
Height (cm)	179.4 (±6.3)	180.4 (±5.6)	0.36
Surgery to RTP (months)	10.3 (±4.3)	9.7 (±2.3)	0.35
Surgery to Testing (months)	9.0 (±3.1)	9.4 (±1.2)	0.32
Surgery to Re-Injury (months)	23.3 (±9.8)		
RTP to Re-Injury (months)	13.0 (±9.5)		

CI – contralateral injury; NCI – no contralateral injury; SD – standard deviation; BPTB – bone patellar tendon bone; HT – hamstring tendon; RTP – return to play

Table 4. Patient-reported outcome (PRO) measures for the contralateral injury (CI) and no contralateral injury (NCI) groups

PRO	CI	NCI		
	Mean (±SD)		p-value	Effect Size
IKDC	79.1 (12.0)	82.4 (10.6)	0.17	0.21
ACL RSI	75.8 (17.8)	78.1 (15.3)	0.49	0.10
Marx	10.8 (3.5)	11.2 (3.2)	0.29	0.12

PRO – patient-reported outcome measure; CI – contralateral injury; NCI – no contralateral injury; SD – standard deviation; IKDC – International Knee Documentation Committee; ACL-RSI – anterior cruciate ligament return to sport after injury; Marx – Marx Activity Scale

Accepted Proof

Strength, Jump, and CoD Performance Measures

There was a significant difference with a small effect size in quadriceps peak torque on the contralateral side (effect size d = 0.39), with significantly lower strength in the CI group (Table 5). No difference was observed between groups on the contralateral side for hamstring strength, SLCMJ and SLDJ height, or SLHD distance, or for the corresponding LSI. The odds of being in the NCI group were 0.54 (95% CI: 0.02–16.39) if the athlete achieved >90% LSI across all five tests. Similarly, no differences were detected between contralateral limbs in planned CoD performance time (1.45 ± 0.12 s vs. 1.42 ± 0.08 s; $p = 0.162$) or LSI (98.9 ± 4.8% vs. 98.9 ± 4.7%; $p = 0.982$), or for the unplanned CoD (1.56 ± 0.02 s vs. 1.52 ± 0.09 s; $p = 0.206$) or LSI (98.5 ± 4.5% vs. 98.3 ± 5.3%; $p = 0.840$).

Accepted Proof

Table 5. Strength and jump performance measures (mean (±SD)) and limb symmetry index (LSI)

Test	Contralateral Injury		Contralateral Matched			
		95% CI		95% CI	p-value	Effect Size
Quadriceps (N/Kg)	216.3 (38.8)	206 to 227	231.3 (36.3)	222 to 240	0.032*	0.39
LSI (%)	80.9 (14.6)	76 to 85	84.2 (14.6)	80 to 88	0.235	0.22
>90% LSI success rates	31%		36%		0.593	
Hamstring (N/Kg)	127.3 (24.9)	120 to 134	135.7 (23.4)	130 to 142	0.063	0.34
LSI (%)	96.9 (14.5)	92.9 to 100	96.5 (10.6)	93 to 99	0.894	0.02
>90% LSI success rates	73%		73%		0.982	
SLCMJ (cm)	12.1 (2.3)	11.5 to 12.8	11.9 (2.4)	11.2 to 12.5	0.561	0.11
LSI (%)	85.8 (13.2)	82 to 90	84.4 (14.6)	81 to 88	0.627	0.09
>90% LSI success rates	40%		38%		0.792	
SLDJ (cm)	12.1 (3.2)	11.2 to 13.0	12.4 (2.7)	11.7 to 13.1	0.564	0.11
LSI (%)	78.1 (16.7)	73 to 83	74.1 (14.8)	70 to 78	0.186	0.25
>90% LSI success rates	12%		18%		0.393	
SLHD (cm)	152.3 (27.0)	144 to 160	154.9 (19.9)	150 to 160	0.562	0.11
LSI (%)	95.1 (15.5)	90 to 99	94.2 (12.4)	91 to 97	0.749	0.06
>90% LSI success rates	61%		66%		0.645	
>90% LSI success rates for all 4 tests	2%		2%		0.921	

*$p < 0.05$. CI – contralateral injury; NCI – no contralateral injury; LSI – limb symmetry index; SLCMJ – single leg countermovement jump; SLDJ – single leg drop jump; SLHD – single leg hop for distance; Cint – confidence interval; SD – standard deviation

Accepted Proof

Biomechanical Analysis

Differences on contralateral side

No significant differences were detected in joint mechanics during planned and unplanned CoD. For DLDJ, there were strong effect size differences between groups on the contralateral side for ground contact time (d = 0.83), COM vertical stiffness (d = 0.80), and COM vertical distance to the knee and ankle (both d = 0.80), with significantly longer contact times, less COM stiffness, and lower COM distances in the CI group (Table 6; Figure 2). There were medium effect size differences between groups for vertical GRF (30%–73% and 83%–99%; d = 0.74 and d = 0.78, respectively; Figure 3), with significantly lower vertical GRF through most of the stance but higher towards the end. This was reflected in lower reactive strength index in the CI group (d = 0.62).

Figure 2. Illustration of biomechanical differences on contralateral side during DLDJ in CI group (bold image) compared to NCI group (blurred image).

Figure 3. Vertical GRF on contralateral side for the CI group and matched NCI cohort during first ground contact of DLDJ. Top panel illustrates mean and SD clouds for CI group (black) and NCI group (blue). Middle panel illustrates SPM{t}, the t-statistic as a function of time describing difference between groups. Bottom panel illustrates effect size as a function of time, describing magnitude of the effect. Shaded portions of the bottom panel indicate average Cohen’s d > 0.5, with orange indicating medium effect size throughout those phases.

Several significant joint kinematic differences, primarily in the sagittal plane, were detected between CI and NCI groups, including more hip flexion (14%–95%; d = 0.76), knee flexion (14%–94%; d = 0.71), ankle dorsiflexion (69%–92%; d = 0.63), anterior pelvic tilt (43%–

Accepted Proof

88%; d = 0.61), and thorax to pelvis flexion (24%–100%; d = 0.6) in the CI group. In addition, there were several joint kinetic differences between CI and NCI groups in the sagittal plane, including lower and then greater hip extension moment (0%–6% and 62%–82%; d = 0.62 and d = 0.71, respectively), lower ankle plantar flexion moment through mid-stance and greater at end stance (24%–74% and 84%–93%; d = 0.76 and d = 0.68, respectively), and increased knee extension moment in early and late stance but lower in mid stance (3% - 7%, 17%–21%, 44%-59% and 82%–93%; d = 0.62, d = 0.60, d - 0.59 and d = 0.72, respectively) on the contralateral side in the CI group.

Outside of the sagittal plane, there was less knee valgus moment during the middle of stance followed by greater valgus moment at end of stance (42% - 62%, 84% - 94%; d = 0.60 d = 0.64). The variables selected for inclusion in the regression model included contact time, COM to ankle, hip extension moment (62-82%) and hip rotation moment (both phases identified as significantly different) and could predict membership of the CI group with an accuracy of 71.2% (baseline 53.2%), with a sensitivity of 0.83 and specificity of 0.58 (AUC = 0.80).

Accepted Proof

Table 6. Differences between groups in biomechanical variables on the contralateral side during DLDJ

Difference Between Contralateral Injury and Contralateral Matched Cohort on ACLR side - DLDJ								
Variable	**Start**	**End**	**CI non-ACLR mean (± SD)**	**95% Cint**	**NCI non-ACLR mean (± SD)**	**95% Cint**	**p - value**	**Effect Size**
Contact Time (sec)			0.34 (0.10)	0.32 to 0.37	0.27 (0.06)	0.25 to 0.29	< 0.001	0.83
COM Stiffness (N/Kg/mm)			91.2 (48.8)	77.5 to 104.9	133.5 (50.7)	120.3 to 146.7	< 0.001	0.80
COM to Ankle Vertical (mm/BH)	10	93	0.41 (0.02)	0.40 to 0.42	0.43 (0.02)	0.42 to 0.44	< 0.001	0.80
COM to Knee Vertical (mm/BH)	11	92	0.22 (0.02)	0.21 to 0.22	0.23 (0.14)	0.23 to 0.24	< 0.001	0.80
Vertical GRF (N/Kg)	30	73	18.0 (4.6)	16.7 to 19.3	21.4 (3.7)	20.4 to 22.4	< 0.001	0.74
	83	99	4.1 (1.4)	3.7 to 4.5	3.0 (0.9)	2.8 to 3.3	< 0.001	0.78
Hip Flexion Angle (º)	14	95	54.7 (12.4)	51.3 to 58.3	45.3 (9.9)	42.7 to 47.9	< 0.001	0.76
Ankle Plantarflexion Moment (Nm/Kg)	22	74	2.2 (0.7)	2.0 to 2.4	2.7 (0.6)	2.6 to 2.8	< 0.001	0.76
	84	93	0.7 (0.3)	0.6 to 0.8	0.5 (0.2)	0.4 to 0.6	0.004	0.68
Knee Flexion Angle (º)	14	94	63.8 (12.5)	60.3 to 67.4	55.6 (8.8)	53.3 to 57.9	< 0.001	0.71
Knee Extension Moment (Nm/Kg)	3	7	0.01 (0.42)	-0.12 to 0.11	-0.24 (0.26)	-0.17 to - 0.31	0.027	0.62
	17	21	1.3 (0.6)	1.1 to 1.4	0.9 (0.5)	0.8 to 1.1	0.030	0.60

Accepted Proof

	44	59	2.4 (0.8)	2.2 to 2.6	2.8 (0.6)	2.6 to 3.0	< 0.001	0.59
	82	93	0.02 (0.5)	-0.1 to 0.2	-0.4 (0.4)	-0.3 to -0.5	0.001	0.72
Hip Extension Moment (Nm/Kg)	0	6	0.5 (0.6)	0.3 to 0.6	0.8 (0.5)	0.7 to 0.9	0.005	0.62
	62	82	0.7 (0.6)	0.5 to 0.8	0.2 (0.5)	0.1 to 0.4	< 0.001	0.71
Hip External Rotation Moment (Nm/Kg)	4	8	0.03 (0.07)	0.01 to 0.04	-0.02 (0.05)	-0.03 to -0.01	0.021	0.69
	94	98	0.01 (0.05)	0 to 0.03	-0.02 (0.05)	-0.03 to 0.05	0.024	0.64
Knee Valgus Moment (Nm/Kg)	42	62	1.5 (0.6)	1.3 to 1.6	1.9 (0.7)	1.7 to 2.1	< 0.001	0.60
	84	94	0.3 (0.2)	0.2 to 0.4	0.1 (0.2)	0.1 to 0.2	0.010	0.64
Reactive Strength (cm/sec)			0.8 (0.2)	0.7 to 0.8	0.9 (0.2)	0.8 to 1.0	< 0.001	0.62
Anterior Pelvic Tilt (º)	43	88	23.7 (6.1)	22.0 to 25.4	19.8 (5.8)	18.4 to 21.4	0.009	0.61
Thorax to Pelvis Extension (º)	24	100	5.5 (7.6)	3.4 to 7.7	10.1 (5.9)	8.5 to 11.6	0.007	0.60

CI – contralateral injury; NCI – no contralateral injury; ACLR – anterior cruciate ligament reconstruction; start/end - % of gait cycle; DLDJ – double leg drop jump; BH - body height; sec - seconds; Cint – confidence interval; Contra – contralateral; SD – standard deviation; COM – center of mass ; GRF – ground reaction force; N - newton; Kg - kilogram; cm - centimetre; m - metre;

Accepted Proof

In the SLDJ, similar biomechanical differences in the sagittal plane were again evident between CI and NCI groups on the contralateral side. (Table 7; Figure 2). There was significantly less distance vertically from COM to knee (12%–83%; d = 0.73) and ankle (12%–88%; d = 0.70), longer ground contact times (d = 0.70), less COM stiffness vertically (d = 0.70), and lower reactive strength (d = 0.50) on the contralateral side in the CI group. Further, there was higher, then lower, then higher vertical GRF in the CI group (3%–11%, 32%–68%, 86%–99%; d = 0.65, d = 0.69, d= 0.63, respectively). In the sagittal plane, there was significantly increased hip flexion (14%–88%; d = 0.59), increased knee flexion (18%–24% and 64%–92%; d = 0.52 and d =0.58, respectively), increased ankle dorsiflexion (84%–88%; d = 0.52), and increased trunk on pelvis flexion (23%–43%; d = 0.50) in the CI group. In addition, there was significantly higher hip extension moment in (74%–79%; d = 0.61), increased knee extension moment in early and late stance (13% - 18%, and 83%–89%; d = 0.60 and d = 0.58, respectively; as well as reduced ankle plantarflexion moment through mid stance (22% - 63%; d = 0.61) in the CI group. In the frontal plane, there was significantly greater internal knee valgus moment (11%–15%; d = 0.58) and ipsilateral thorax on pelvis side flexion (54%–72%; d = 0.52) in the CI group. There were no differences in the transverse plane. The COM to knee, COM Stiffness, vertical GRF (3 to 11% and 33 to 68%) and hip extension moment were selected for the regression model and could predict membership of the CI group with an accuracy of 62.1% (baseline 53.2%), with a sensitivity of 0.51 and specificity of 0.75 (AUC: 0.75).

Accepted Proof

Table 7. Biomechanical differences on the contralateral side during SLDJ

Difference Between Contralateral Injury and Contralateral Matched Cohort on ACLR side - SLDJ								
Variable	**Start**	**End**	**CI non-ACLR mean (± SD)**	**95% Cint**	**NCI non-ACLR mean (± SD)**	**95% Cint**	**p - value**	**Effect Size**
COM to Knee Vertical (mm/BH)	12	84	0.24 (0.01)	0.24 to 0.25	0.25 (0.01)	0.25 to 0.26	< 0.001	0.73
Contact Time (sec)			0.39 (0.08)	0.37 to 0.41	0.33 (0.05)	0.32 to 0.35	< 0.001	0.70
COM Stiffness (N/Kg/mm)			138.3 (54.8)	122.8 to 153.6	180.1 (56.4)	165.6 to 194.7	< 0.001	0.70
COM to Ankle Vertical (mm/BH)	12	89	0.44 (0.02)	0.43 to 0.45	0.46 (0.01)	0.45 to 0.46	< 0.001	0.7
Vertical GRF (N/Kg)	3	11	9.8 (3.1)	8.9 to 10.7	8.2 (1.5)	7.8 to 8.6	0.002	0.65
	33	68	25.1 (4.5)	23.8 to 26.3	28.2 (3.9)	27.2 to 29.2	< 0.001	0.69
	87	99	4.4 (1.5)	2.3 to 6.5	3.5 (1.1)	1.7 to 5.4	< 0.001	0.63
Hip Extension Moment (Nm/Kg)	74	79	0.3 (0.7)	0.1 to 0.5	-0.2 (0.57)	-0.3 to 0	0.004	0.61
Ankle Plantarflexion Moment (Nm/Kg)	22	63	2.9 (0.6)	2.7 to 3.1	3.4 (0.7)	3.2 to 3.6	< 0.001	0.61
Knee Extension Moment (Nm/Kg)	13	18	1.0 (0.8)	0.7 to 1.3	0.5 (0.67)	0.24 to 0.77	0.020	0.60
	83	89	0.2 (0.5)	0 to 0.5	-0.1 (0.46)	-0.35 to 0.23	0.010	0.58

Accepted Proof

Hip Flexion Angle (º)	14	88	43.8 (9.2)	41.2 to 46.4	38.5 (7.0)	36.8 to 40.4	< 0.001	0.59
Knee Flexion Angle (º)	18	22	51.8 (8.9)	49.3 to 54.3	47.5 (7.1)	45.7 to 49.4	0.040	0.52
	64	92	40.7 (9.2)	38.2 to 43.3	35.5 (7.7)	33.6 to 37.5	0.003	0.58
Knee Valgus Moment (Nm/Kg)	11	15	0.9 (0.4)	0.7 to 1.0	0.7 (0.3)	0.6 to 0.8	0.030	0.58
Ankle Dorsiflexion (º)	84	88	1.3 (7.4)	-3.6 to 6.2	-2.6 (6.9)	-7.5 to 2.3	0.040	0.52
Thorax to Pelvis Side Flexion (º)	54	72	0.8 (4.9)	-0.5 to 2.2	-1.7 (4.6)	-2.9 to 4.6	0.020	0.52
Thorax to Pelvis Extension (º)	23	43	-2.5 (9.2)	-5.0 to 0.1	2.1 (8.3)	-0.1 to 4.2	0.030	0.51
Reactive Strength (cm/sec)			0.32 (0.12)	0.29 to 0.35	0.37 (0.09)	0.35 to 0.40	0.010	0.50

CI – contralateral injury; NCI – no contralateral injury; start/end - % of gait cycle; ACLR – anterior cruciate ligament reconstruction; SLDJ –single leg drop jump; BH - body height; sec - seconds; COM – center of mass ; GRF – ground reaction force; CInt – confidence interval; SD – standard deviation mm - metre;

Accepted Proof

Difference in asymmetry between groups

Differences in asymmetry of biomechanical variables between limbs between CI and NCI groups are reported in Table 8. There was no significant difference in asymmetry between groups for SLDJ or planned or unplanned CoD. In the DLDJ there was significantly greater asymmetry in the CI group for knee varus angle (91%–100%; d = 0.66), with less knee varus on the contralateral limb.

Accepted Proof

Table 8. Differences in asymmetry of biomechanical variables between groups

Difference Between Limbs Between Contralateral Injury and Contralateral Matched Cohort on ACLR side - DLDJ								
Variable	**Start**	**End**	**CONTRA ACLR side (± SD)**	**95% Cint**	**CONTRA Matched ACLR side (± SD)**	**95% Cint**	**p - value**	**Effect Size**
Knee Varus Angle (º)	91	100	1.0 (2.9)	0.9 to 1.2	-0.7 (2.1)	-0.6 to -0.8	0.03	0.66

CI – contralateral injury; NCI – no contralateral injury; ACLR – anterior cruciate ligament reconstruction; DLDJ – double leg drop jump; CInt – confidence interval; SD – standard deviation;

Accepted Proof

Discussion

This study found there were quadriceps strength and biomechanical differences primarily in the sagittal plane during plyometric tests on the contralateral side 9 months post-surgery for male athletes who experienced contralateral injury after ACLR compared to those who did not at 2 years post-reconstruction. These differences had fair to good ability to predict risk of future contralateral injury and were present despite no difference in LSI between groups and minimal biomechanical asymmetry between groups. Given the higher contralateral ACL injury rate reported in the literature, this study highlights the importance of assessing the contralateral limb and suggests tests and variables that should be targeted during rehabilitation and RTP testing that may play an important role in minimising risk of contralateral ACL injury after ACLR.

To the authors knowledge, the influence of strength and jump performance measures on contralateral ACL injury has not been investigated previously. This study demonstrated no significant difference in LSI for quadriceps and hamstring strength, jump testing, and timed CoD performance between CI and NCI groups. In addition, when combining the achievement of >90% LSI across strength and jump tests it had little influence on the odds of having a contralateral injury (OR: 0.54; 95% CI: 0.02–16.39). Further, few differences in asymmetry of biomechanical variables between groups were evident. The only asymmetry finding was increased asymmetry of knee varus angle in DLDJ at the end of stance. These limited number of findings suggest asymmetry may not be a major factor in subsequent contralateral ACL injury.

Accepted Proof

There were several differences between groups in the sagittal plane on the contralateral side during the double leg and single leg drop jump. The contralateral limb in the contralateral injury group demonstrated differences in plyometric ability and whole-body stiffness compared to the NCI group, as reflected in differences in reactive strength index (but not jump height). In both the double and single leg drop jump, there were longer ground contact times, reduced centre of mass stiffness, and greater drop of the centre of mass vertically relative to the knee and ankle in the contralateral injury group. This was accompanied by increased flexion at the hip, knee, ankle, and thorax and differences in kinetic variables in the sagittal plane with greater, then less, then greater vertical GRF, ankle plantar flexion moment and knee extension moment as well as changes in hip extension moment in the contralateral injury group. This reduction in reactive strength (driven by longer ground contact times) in combination with higher vertical GRF and higher knee extension moments early in stance may be a major contributor to excessive ACL strain and subsequent ACL injury.[12, 18, 33] Greater knee flexion, longer ground contact times, and greater drop of the centre of mass relative to the ankle during DLDJ have also been identified in male athletes who re-rupture their reconstructed knee after ACLR (King et al., in review). These results suggest that plyometric ability or whole-body stiffness may be important risk factors for ACL injury in previously uninjured knees in male athletes but also for reconstructed knees. Given that ACL rupture normally occurs in the first 40 milliseconds after ground contact,[26] greater muscular co-contraction and early rate of force development associated with increased plyometric ability [8, 30] may be important in controlling anterior tibial translation and ACL loading after ACLR. In addition, ACL injury prevention programmes that have been demonstrated to be effective in reducing ACL injury rates have all included various plyometric exercises (drop jumps, tuck jumps, bounding etc) and it may be that this component of these programmes is highly important in contributing to the reduced injury rates.[15, 32, 37]

Accepted Proof

Much of the focus during rehabilitation is to optimise recovery of quadriceps strength on the ACLR side.[39] In this study those who experienced contralateral injury had lower quadriceps strength of the contralateral limb than those that did not. Previous research has reported decrements in quadriceps strength on the contralateral side after reconstruction, and those decrements may influence second ACL injury risk.[57] Quadriceps strength accounts for ~30% of SLCMJ and SLDJ height performance,[7, 11] and its re-development after ACLR may be an important factor in developing plyometric capacity and may be an important factor to consider when minimising ACL injury risk in healthy limbs. In this study, we found no differences in CoD biomechanics between CI and NCI groups. If plyometric ability or whole body stiffness is an important measure in contralateral ACL injury risk for male athletes, it is intuitive that this would be more evident in drop jump tests rather than CoD tests, despite the fact that CoD is a common mechanism of ACL injury.[1]

Fewer differences between groups were observed in the frontal and transverse plane compared to sagittal plane of both DLDJ and SLDJ on the contralateral side. There was greater internal knee valgus moment in both tests (earlier stance in SLDJ, later stance in DLDJ) but lower through midstance in the DLDJ in the CI group. The joint moment signals demonstrated a similar pattern: higher moments earlier and later but lower moments in mid-stance in the CI group. These findings are different to previous studies in female athletes in which external knee valgus was identified as a risk factor for primary injury[17] There were lower maximum internal valgus moments in the CI group, which may reflect a reduced ability to resist external valgus moments upon more chaotic dynamic challenges on return to sport. Paterno et al reported knee valgus range of motion and hip rotation impulse as predictors of second ACL injury. This is not replicated in our study potentially due to our

Accepted Proof

focus solely on male athletes and contralateral second injuries.[41] In SLDJ, there was increased ipsilateral trunk sway over the contralateral limb in the CI group, which is a common ACL injury mechanism,[1] influences knee frontal plane loading,[9, 10] and, in combination with knee valgus movement, is a risk factor for non-contact knee injuries.[16] That a greater number of variables indicated differences in the sagittal than in the frontal plane in this male cohort compared to previous research may be due to the difference gender/sex of our participants. Females are more likely to demonstrate dynamic knee valgus during landing [38, 48] and during ACL injury mechanism.[28] Cumulatively our findings add new literature suggesting physical risk factors for ACL injury may be different between sexes and may require differential approaches to assessment and analysis to achieve sex specificity for ACL injury risk.

The biomechanical variables identified had fair to good ability to predict CI group membership for DLDJ and SLDJ, therefore targeting these variables during rehabilitation and RTP testing may reduce risk of ACL injury. Higher levels of sensitivity vs. specificity are important for ACLR given the severe consequences of second injury. Lower specificity also reflects previous research demonstrating that as many as 20% of healthy athletes are classified as having the same movement strategies as those who have undergone ACLR,[46] suggesting that movement alone does not account for all risk related to ACLR injury.

Limitations

As no previous literature examined biomechanical risk factors for contralateral ACL injury, this study examined variables throughout the kinetic chain in several jump and CoD tests. Although this may increase risk of “over-analysis” or finding differences that are not relevant to the outcome, inclusion of only medium and large effect size differences attempted to

Accepted Proof

identify only those differences of largest magnitude to highlight variables of greatest clinical and research interest despite multiple analyses. We performed multiple comparisons, and one could argue that a multiple comparisons correction should have implemented to reduce the type 1 error. However, as the type I error decreases, the chance of type II errors increases.[19, 43, 47, 55] Our approach to modelling and resultant conclusions were based on P values in combination with effect sizes, and differences with weak effects were excluded to decrease the type 1 error. Although a strength of the study is that it was carried out on a homogenous cohort (male field sports athletes), findings may not be directly extrapolated to other populations. Therefore, future research with similar analyses in female athletic populations is needed to identify risk factors specific to that cohort as well as potential differences in risk factors for male and female athletes for additional ACL injury after ACLR. In addition, future research verifying the ability of the findings to predict the risk of contralateral ACL injury in a different group of athletes would be valuable to re-enforce the generalisability of the findings. Although the 2 year cut-off for second injury was selected as a threshold for the control NCI group the average time for contralateral injury in the CI group was 23.3 months ± 9.8 meaning many of the injuries happened after the selected threshold and raising the potential for injury in the NCI group after selection. However all on further follow up of the NCI group none had suffered injury at a minimum of 3.5 years post-surgery. To improve on the model, other biomechanical measures such as variability and coordination and resistance to fatigue could be included to assess if they are factors which may lead to contralateral injury. These can be used in combination with anthropometric, surgical, and radiological data which can influence ACL injury to build a comprehensive model of factors influencing second ACL injury risk. Finally, intervention studies are needed to examine the most effective way to change variables identified during rehabilitation and the influence of this on subsequent contralateral ACL injury.

Accepted Proof

Conclusion

This study highlights that biomechanical analysis of the contralateral limb at 9 months after ACLR could identify movement differences between those who go on to experience a contralateral ACL rupture and those who do not. These variables had a fair to good ability to predict contralateral injury and would not have been identified by evaluating only clinical performance measures. Findings demonstrate lower quadriceps strength, sagittal plane control, and plyometric ability on the contralateral limb in those who experienced subsequent contralateral ACL injury. These was no difference in LSI in performance measures and minimal differences in asymmetry of biomechanical variables. Therefore, this study highlights several factors that may be used in future analysis to model prediction of second ACL injury and target during rehabilitation to reduce contralateral ACL injury after ACLR.

Accepted Proof

References

1. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc.* 2009;17(7):705-729.

2. Babyak MA. What you see may not be what you get: a brief, nontechnical introduction to overfitting in regression-type models. *Psychosom Med.* 2004;66(3):411-421.

3. Burgi CR, Peters S, Ardern CL, et al. Which criteria are used to clear patients to return to sport after primary ACL reconstruction? A scoping review. *Br J Sports Med.* 2019;53(18):1154-1161.

4. Chawla N, Bowyer K, Hall L, Kegelmeyer W. SMOTE: Synthetic Minority Over-sampling Technique. *J. Artif. Intell. Res. (JAIR).* 2002;16:321-357.

5. Claes S, Verdonk P, Forsyth R, Bellemans J. The "ligamentization" process in anterior cruciate ligament reconstruction: what happens to the human graft? A systematic review of the literature. *Am J Sports Med.* 2011;39(11):2476-2483.

6. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*; 1988.

7. Crotty ND, K.; King, E.; Cafferkey., N; McFadden, C; Falvey, E. The Relationship Between Isokinetic Knee Strength and Single- Leg Drop Jump Testing Following Anterior Cruciate Ligament Reconstruction. Paper presented at: Faculty of Sports and Exercise Medicine Annual Conference, 2019; Dublin.

8. de Villarreal ES, Izquierdo M, Gonzalez-Badillo JJ. Enhancing jump performance after combined vs. maximal power, heavy-resistance, and plyometric training alone. *J Strength Cond Res.* 2011;25(12):3274-3281.
9. Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ. Changing sidestep cutting technique reduces knee valgus loading. *Am J Sports Med.* 2009;37(11):2194-2200.
10. Donnelly CJ, Lloyd DG, Elliott BC, Reinbolt JA. Optimizing whole-body kinematics to minimize valgus knee loading during sidestepping: implications for ACL injury risk. *J Biomech.* 2012;45(8):1491-1497.
11. Fischer F, Blank C, Dünnwald T, et al. Isokinetic Extension Strength Is Associated With Single-Leg Vertical Jump Height. *Orthopaedic Journal of Sports Medicine.* 2017;5(11):2325967117736766.
12. Fleming BC, Renstrom PA, Beynnon BD, et al. The effect of weightbearing and external loading on anterior cruciate ligament strain. *J Biomech.* 2001;34(2):163-170.
13. 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.
14. Healy R, Smyth C, Kenny IC, Harrison AJ. Influence of Reactive and Maximum Strength Indicators on Sprint Performance. *J Strength Cond Res.* 2019;33(11):3039-3048.
15. Hewett TE, Lindenfeld Tn Fau - Riccobene JV, Riccobene Jv Fau - Noyes FR, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. (0363-5465 (Print)).
16. Hewett TE, Myer GD. The mechanistic connection between the trunk, hip, knee, and anterior cruciate ligament injury. *Exerc Sport Sci Rev.* 2011;39(4):161-166.
17. 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.
18. Hirokawa S, Solomonow M, Lu Y, Lou ZP, D'Ambrosia R. Anterior-posterior and rotational displacement of the tibia elicited by quadriceps contraction. *Am J Sports Med.* 1992;20(3):299-306.
19. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc.* 2009;41(1):3-13.
20. 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.
21. King E, Richter C, Franklyn-Miller A, et al. Whole-body biomechanical differences between limbs exist 9 months after ACL reconstruction across jump/landing tasks. *Scand J Med Sci Sports.* 2018.
22. King E, Richter C, Franklyn-Miller A, Wadey R, Moran R, Strike S. Back to Normal Symmetry? Biomechanical Variables Remain More Asymmetrical Than Normal During Jump and Change-of-Direction Testing 9 Months After Anterior Cruciate Ligament Reconstruction. *Am J Sports Med.* 2019;47(5):1175-1185.
23. King E, Richter C, Jackson M, et al. Factors Influencing Return to Play and Second Anterior Cruciate Ligament Injury Rates in Level 1 Athletes After Primary Anterior Cruciate Ligament Reconstruction: 2-Year Follow-up on 1432 Reconstructions at a Single Center. *Am J Sports Med.* 2020:363546519900170.
24. King E. RC, Franklyn-Miller A., Daniels K., Wadey R., Moran R., Strike S. . Whole body biomechanical differences between limbs persist 9 months after ACL reconstruction across jump/landing tasks. *Scandinavian Journal or Sports Medicine and Science (in review).* 2017.

Accepted Proof

25. King E. RC, Franklyn-Miller A., Daniels K., Wadey R., Moran R., Strike S. . Biomechanical but not timed performance asymmetries persist between limbs 9 months after ACL reconstruction during planned and unplanned change of direction. . *Journal of Biomechanics (In Press).* 2018.

26. 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.

27. Kristianslund E, Krosshaug T, van den Bogert AJ. Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *J Biomech.* 2012;45(4):666-671.

28. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med.* 2007;35(3):359-367.

29. Kyritsis P, Bahr R, Landreau P, Miladi R, Witvrouw E. Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. *Br J Sports Med.* 2016.

30. Kyrolainen H, Avela J, McBride JM, et al. Effects of power training on muscle structure and neuromuscular performance. *Scand J Med Sci Sports.* 2005;15(1):58-64.

31. Lynch AD, Logerstedt DS, Grindem H, et al. Consensus criteria for defining 'successful outcome' after ACL injury and reconstruction: a Delaware-Oslo ACL cohort investigation. *Br J Sports Med.* 2015;49(5):335-342.

32. Mandelbaum BR, Silvers Hj Fau - Watanabe DS, Watanabe Ds Fau - Knarr JF, et al. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. (0363-5465 (Print)).

33. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res.* 1995;13(6):930-935.

34. Marshall BM, Franklyn-Miller AD, King EA, Moran KA, Strike SC, Falvey EC. Biomechanical factors associated with time to complete a change of direction cutting maneuver. *J Strength Cond Res.* 2014;28(10):2845-2851.

35. Marx RG, Stump TJ, Jones EC, Wickiewicz TL, Warren RF. Development and evaluation of an activity rating scale for disorders of the knee. *Am J Sports Med.* 2001;29(2):213-218.

36. Moudy S, Richter C, Strike S. Landmark registering waveform data improves the ability to predict performance measures. *J Biomech.* 2018.

37. Myklebust G, Engebretsen L Fau - Braekken IH, Braekken Ih Fau - Skjølberg A, Skjølberg A Fau - Olsen O-E, Olsen Oe Fau - Bahr R, Bahr R. Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. (1050-642X (Print)).

38. Norcross MF, Lewek MD, Padua DA, Shultz SJ, Weinhold PS, Blackburn JT. Lower extremity energy absorption and biomechanics during landing, part I: sagittal-plane energy absorption analyses. *J Athl Train.* 2013;48(6):748-756.

39. O'Malley E. RC, King E., Moran R., Strike S., Moran K. and Franklyn-Miller A. . Countermovement jump and isokinetic dynamometry as measures of rehabilitation status following anterior cruciate ligament reconstruction. *Journal of Athletic Training, In Press.* 2017.

40. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med.* 2012;22(2):116-121.

Accepted Proof

41. Paterno MV, 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.

42. Peduzzi P, Concato J, Kemper E, Holford TR, Feinstein AR. A simulation study of the number of events per variable in logistic regression analysis. *J Clin Epidemiol.* 1996;49(12):1373-1379.

43. Perneger TV. What's wrong with Bonferroni adjustments. *Bmj.* 1998;316(7139):1236-1238.

44. 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: a controlled, prospective trial. *Am J Sports Med.* 2007;35(4):564-574.

45. Ramsey J. *Functional data analysis.* : John Wiley and Sons; 2006.

46. Richter C, King E, Strike S, Franklyn-Miller A. Objective classification and scoring of movement deficiencies in patients with anterior cruciate ligament reconstruction. *PLoS One.* 2019;14(7):e0206024.

47. Rothman KJ. No adjustments are needed for multiple comparisons. *Epidemiology.* 1990;1(1):43-46.

48. Russell KA, Palmieri RM, Zinder SM, Ingersoll CD. Sex differences in valgus knee angle during a single-leg drop jump. *J Athl Train.* 2006;41(2):166-171.

49. 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. *Arthroscopy.* 2005;21(8):948-957.

50. Schairer WW, Marx RG, Dempsey B, Ge Y, Lyman S. The Relation Between Volume of ACL Reconstruction and Future Knee Surgery. *Orthopaedic Journal of Sports Medicine.* 2017;5(7 suppl6):2325967117S2325900298.

51. Sward P, Kostogiannis I, Roos H. Risk factors for a contralateral anterior cruciate ligament injury. *Knee Surg Sports Traumatol Arthrosc.* 2010;18(3):277-291.

52. 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(20):1305-1310.

53. van Melick N, van Cingel RE, Brooijmans F, et al. Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. *Br J Sports Med.* 2016;50(24):1506-1515.

54. Walden M, Hagglund M, Magnusson H, Ekstrand J. Anterior cruciate ligament injury in elite football: a prospective three-cohort study. *Knee Surg Sports Traumatol Arthrosc.* 2011;19(1):11-19.

55. Wasserstein RL, Lazar NA. The ASA Statement on p-Values: Context, Process, and Purpose. *The American Statistician.* 2016;70(2):129-133.

56. Webster KE, Feller JA, Lambros C. Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery. *Phys Ther Sport.* 2008;9(1):9-15.

57. Wellsandt E, Failla MJ, Snyder-Mackler L. Limb Symmetry Indexes Can Overestimate Knee Function After Anterior Cruciate Ligament Injury. *J Orthop Sports Phys Ther.* 2017;47(5):334-338.

Accepted Proof

58. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. Risk of Secondary Injury in Younger Athletes After Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-analysis. *Am J Sports Med.* 2016.

59. Wright RW, Magnussen RA, Dunn WR, Spindler KP. Ipsilateral graft and contralateral ACL rupture at five years or more following ACL reconstruction: a systematic review. *J Bone Joint Surg Am.* 2011;93(12):1159-1165.

Accepted Proof