Biomechanical but not strength or performance measures differentiate male athletes who experience ACL re-injury on return to level 1 sport

Accepted version, proofs being developed

Abstract

Background

Performance measures such as strength, jump height/length and change of direction time during ACL rehabilitation have been used to determine readiness to return to play and identify those who may be at risk of re-rupture. However, athletes may reach these criteria despite ongoing biomechanical deficits when performing these tests. Combining return to play criteria with an assessment of movement through 3D biomechanics in male field sport athletes to identify risk factors for ACL re-rupture has not been explored previously.

Purpose

To prospectively examine differences in strength, jump, and change of direction (CoD) performance and movement using 3D biomechanics in a cohort of male athletes playing level 1 sports between those who re-injured their reconstructed ACL (RI) and those with no re-injury (NRI) after 2 years follow-up and examine the ability of these differences to predict re-injury.

Study Design

Case-control study

Methods

Male athletes after primary ACL reconstruction (ACLR; n = 1045) were recruited and underwent testing 9 months post-surgery, including isokinetic strength, jump and CoD performance measures, patient-reported outcomes (PRO) and 3D biomechanical analyses. Participants were followed-up after 2 years regarding ACL re-injury status (n = 38). Differences between RI and NRI groups in PRO, performance measures and 3D biomechanics on the ACLR side/symmetry between limbs were determined. The ability of these measures to predict ACL re-injury was determined through logistic regression.

Results

No differences were identified in strength and performance measures on the ACLR side or in symmetry. Biomechanical analysis indicated differences on the ACLR side primarily in the sagittal plane for the double leg drop jump (DLDJ; effect size 0.59 to 0.64) and greater asymmetry primarily in the frontal plane during unplanned CoD (effect size 0.61 to 0.69) in the RI group. While these biomechanical tests were different between groups, multivariate regression modelling demonstrated limited ability (AUC 0.67 and 0.75, respectively) to prospectively predict ACL re-injury.

Conclusion

Commonly reported return to play strength, jump, and timed CoD performance measures did not differ between RI and NRI groups. Differences in movement based on biomechanical measures during DLDJ and unplanned CoD were identified, although they had limited ability to predict re-injury. Targeting these variables during rehabilitation may reduce re-injury risk in male athletes returning to level 1 sports after ACLR.

Clinical Relevance

This study suggests strength, jump and change of direction time performance testing in isolation may be inadequate to assess readiness to RTP following ACLR. Biomechanical analysis of movement quality in performing these tests may add potentially relevant information to the assessment of ACL re-injury risk.

Key Terms

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

What is known about the subject?

Physical testing is common practice after ACLR to chart progress and determine readiness to RTP by identifying deficits which may lead to re-injury. However, recent research has reported that physical measures of strength, jump and CoD performance can recover despite ongoing biomechanical deficits after ACLR. In addition, biomechanical analysis has focused on primary ACL injury risk factors and not explored secondary ACL risk factors and their ability to predict future re-injury.

What does this study add to the existing knowledge?

This study found no differences in commonly used strength, jump and change of direction performance measures despite biomechanical differences during jump and change of direction tests in athletes who went on to suffer re-injury of the ACL after surgery. In particular, it identified differences in the sagittal plane on the ACLR side in the DLDJ and differences in asymmetry in the frontal plane during unplanned change of direction. However, these differences had limited ability to predict ACL re-injury but could be targeted during rehabilitation and RTP testing. This study adds to existing knowledge by questioning the use of clinical measures of strength, jump and CoD performance in isolation while identifying biomechanical variables that may be targeted to improve re-injury rates.

Introduction

Reducing the risk of anterior cruciate ligament (ACL) re-injury is probably the most important goal for a surgeon, athlete, and physiotherapist following ACL reconstruction (ACLR) surgery.[21, 23] Return to play (RTP) criteria have been used to mitigate the risk of re-injury, rehabilitation status before return to play (RTP). The criteria are commonly assessed using physical tests of lower limb strength, jump height/length, and timed change of direction (CoD) performance. Outcomes from theses performance tests are combined with patient-reported outcome (PRO) questionnaires to identify factors that may influence ACL re-injury risk.[9, 11, 21, 26] Recovery of symmetry of these performance measures, reported as limb symmetry index (LSI), is suggested to influence the risk of any injury to the operated knee[11] and re-injury of the re-constructed graft.[21] It has been recommended that success rates (% of group that achieve >90% LSI) should also be reported when carrying out group comparison.[43] However, passing the RTP criteria has not always shown a significantly significant association with second injury risk. Athletes have also been reported to achieve symmetrical performance during jump and CoD tests after ACLR but with asymmetrical joint mechanics.[14, 15] This suggests that assessing the movement quality through a biomechanical analysis may offer a more robust measure of physical recovery after ACLR when assessing re-injury risk than commonly used performance test batteries alone.

To date, few studies have prospectively examined biomechanical variables related to ACL re-injury risk. Paterno et al. identified several biomechanical factors predicting second ACL injury during double leg drop jump testing, including un-involved limb hip rotation moment, asymmetry of knee extension moment at initial contact, and knee valgus range of motion during landing.[35] However, both re-injury and contralateral ACL injuries were combined during the analysis, so it is unclear if the risk factors are specific to, or different between injury to either limb. Our understanding of the mechanisms that may result in re-injury may be further complicated by their inclusion of males and female subjects.[19, 40] A potential limitation to our understanding of the re-injury mechanism is that the research is restricted to the double leg drop jump, although up to 50% of ACL injuries occur during CoD manoeuvres and single-leg landing.[1] To assess the influence of patient-reported outcomes, performance measures and biomechanics on ACL re-injury, studies must control for several non-physical factors that may influence the risk of ACL re-injury and physical recovery, including time since surgery, age, level and type of sport, and graft type.[11, 21, 29, 35, 41, 46] Therefore, a combination of PRO, strength and performance measures, and 3D biomechanical analysis in both jump and CoD tests in a homogenous cohort of athletes may better identify those at increased risk of ACL re-injury.

The primary aim of this study was to examine differences in strength, jump, and timed CoD performance measures, PRO, and 3D biomechanics during jump and CoD testing in a group of male athletes aged 18–35 years returning to level 1 sports (multidirectional field sports which involve landing, pivoting or change of direction), after primary ACLR between those with ACL re-injury and a matched cohort with no re-injury after 2 years post-surgery. The secondary aim was to assess the ability of these variables to predict who would experience ACL re-injury.

Methods

Athletes were recruited into this prospective case control study from January 1, 2014 to December 31, 2016 from the caseload of two orthopaedic surgeons at the Sports Surgery Clinic, Dublin. Participants were enrolled in the study if they were diagnosed with ACL rupture, had a confirmed surgical date, and provided informed consent. Before surgery, participants completed a pre-operative questionnaire outlining their sport, mechanism of injury, and level of desired return after surgery. Male participants aged 18 to 35 years who played multidirectional field sports and intended to return to the same level of sport were included in the study. All participants underwent primary ACLR using either a bone patellar tendon bone or hamstring (gracilis/semitendinosus) graft from the ipsilateral limb. Participants who were undergoing second or subsequent ACLR, did not intend to return to level 1, or had meniscal/additional ligament repair at the time of surgery were excluded. The study was registered at clinicaltrials.gov NCT02771548 and received ethical approval from the Sports Surgery Clinic Hospital Ethics Committee (25-AFM-010).

Testing Protocol

After surgery, all participants underwent an accelerated rehabilitation protocol with weightbearing as tolerated on crutches for 2 weeks, followed by progressive blocks of strength and neuromuscular control, power and reactive strength development, and running and CoD mechanics, as physical competency and knee symptoms allowed. 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, participants took part in a physical testing protocol at approximately 9 months post-surgery. Before the testing session, all participants completed PRO: the International Knee Documentation Committee (IKDC),[13] Marx Activity Scale[25], and ACL Return to Sport after Injury questionnaire (ACL-RSI).[45] The data collection protocol took place in a 3D biomechanics laboratory and included a double leg drop jump from 30 cm, single leg drop jump from 20 cm, and 90° planned and unplanned CoD, as described elsewhere.[14, 15] In addition, single leg countermovement jump height and single leg hop for distance length were assessed to compare with previous literature.[11, 21, 30] Participants undertook a standardised warm-up: 2-minute jog, 5 bodyweight squats, and 2 submaximal and 3 maximal double leg countermovement jumps. Each participant underwent two submaximal practice trials of each movement before three valid test trial attempts (maximal effort and full-foot contact on force plate) were captured, with the mean of three trials used for analysis. Participants took a 30-s recovery between trials. Lab testing was followed by concentric isokinetic testing of the quadriceps and hamstring muscle groups of both limbs at 60°/s through 0-100° knee flexion. Peak torque/body mass was used to define the strength performance measures.[44]

Biomechanical Analysis

Joint kinematic data were collected using an eight-camera motion analysis system (Bonita-B10, Vicon, UK) capturing at 200 Hz, synchronized with two force platforms (BP400600, AMTI, Watertown, MA, USA) sampling at 1000 Hz. Motion data from 24 reflective markers (14 mm diameter) was integrated with ground reaction forces (Vicon Nexus 1.8.5), which were low-pass filtered using a fourth-order Butterworth filter (cut-off frequency: 15 Hz).[18] Participants wore their own athletic footwear. Reflective markers were secured using tape at bony landmarks on the lower limbs, pelvis, and trunk as per the adapted Plug-in-Gait marker set.[24] A custom MATLAB program (MathWorks Inc, Natick, MA, USA) was used for processing and calculating the variables analysed. The motion of the centre of mass (COM) relative to the ankle and knee joints was assessed by quantifying the distance from the COM to ankle and knee joint in all 3 planes.[15] At the joint level, in addition to the ankle, knee and hip 3D joint angles and moments, the trunk-pelvis angle in all three planes and foot-pelvis angle in the transverse plane were quantified. All kinetic variables including ground reaction force were normalized to body mass. Whole body stiffness when the body was accepting load was calculated as:

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

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 performed for the stance phase of each jump and CoD test [defined by ground reaction force (GRF) > 20 N]. Curves were normalized to 101 frames and landmark registered[37] to endecc.[28] This process aligned onset of the eccentric phase to 50% of the movement cycle across participants to ensure relevant comparison of neuromuscular characteristics between limbs and participants during continuous waveform analysis.

Performance outcomes were determined for the jump and CoD tasks. Jump height for single leg countermovement jump, double leg drop jump and single leg drop jump was calculated from ground reaction forces using the impulse-momentum theorem and jump length for single leg hop for distance was calculated as the distance from heel marker at start to landing. Time to complete the 90° CoD was recorded using speed gates (Smartspeed, Fusion Sport, Chicago, IL, 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.[14] LSI for strength and jump performance scores were calculated [(ACLR side/non-ACLR side) x 100]. Asymmetry in biomechanical variables (ASYM) was calculated as the ACLR side minus non-ACLR side.

Follow-Up

All participants were followed-up via e-mail at 1 year and 2 years post-surgery with a questionnaire recording RTP status (return to same level of sport yes/no) and identifying those who sustained re-rupture of their reconstructed ACL or rupture of their contralateral ACL. Re-injuries were also identified between these time points if participants returned to their surgeon with diagnosis of another ACL injury, with the same questionnaire regarding RTP and re-injury completed at this point. If participants did not reply to the e-mail questionnaire/return to the surgeon, they received a follow-up phone call to complete the questionnaires. For this study, all participants who re-injured their reconstructed ACL were included and placed in the ipsilateral re-injury group (RI). From the remaining participants who had returned to multidirectional field sports after ACLR and did not have ipsilateral re-injury or contralateral ACL injury (NRI) at 2 years follow-up, a cohort were selected to match to the RI group based on: mean on time from surgery to 3D biomechanical testing; time from surgery to RTP; age and graft type (Figure 1). This ensured that appropriate comparison and minimise the potential influence of other factors on ACL re-injury.

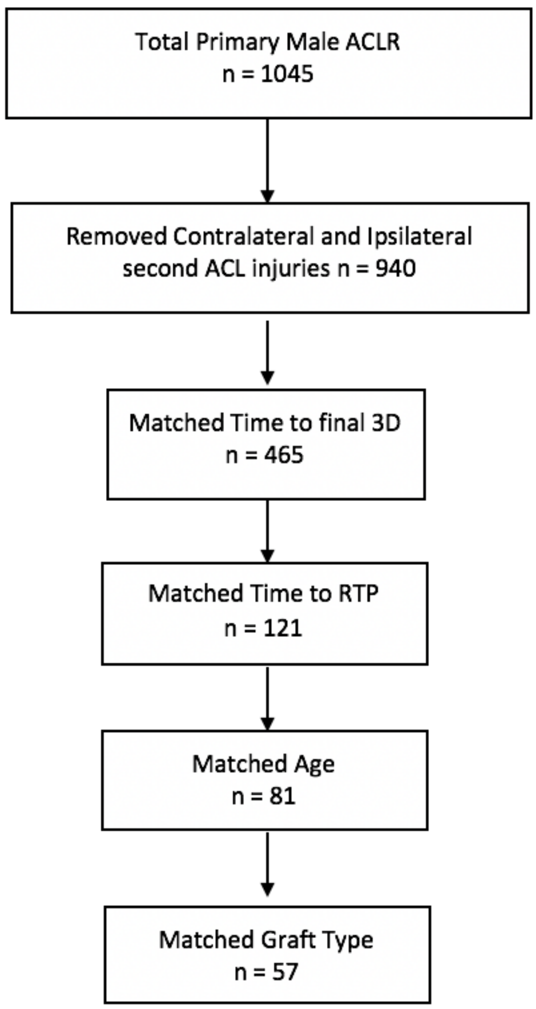

Figure 1 Flow diagram of matching process between RI and NRI groups

Statistical Analysis

Differences in PRO and strength (normalised knee flexion and extension peak torque) and performance measures (single leg countermovement jump, single leg drop jump jump height, single leg hop for distance jump length and CoD time) for the ACLR side and in LSI between RI and NRI groups were examined using Mann-Whitney U Test and independent Student's t tests respectively (Table 1).[33] Effect sizes for differences between groups were calculated and interpreted using Cohen's D (0.20 to 0.49 = small; 0.50 to 0.79 = medium; ≥0.80 = strong).[7] Success rates (percentage of group who achieved the outcome) attaining ≥90% LSI for quadriceps and hamstring strength, single leg countermovement jump and single leg drop jump height, and single leg hop for distance jump length were calculated for all groups,[42] with differences in success rates examined using chi squared test of homogeneity. Additionally, the odds ratio of participants being in the NRI compared to RI when ≥90% LSI for quadriceps, hamstring strength, single leg countermovement jump, and single leg drop jump height were calculated as well as the odds when ≥90% LSI for all five tests collectively was achieved.

Statistical parametric mapping (SPM; 1d, unpaired t-test; parametric) was used to examine differences in lower-limb biomechanics between RI and NRI groups for the ACLR limb and differences in asymmetry between limbs between groups (ACLR minus non-ACLR limb) for each biomechanical variable for double leg drop jump, single leg drop jump, and planned and unplanned 90° CoD during stance. Reported values are mean effect sizes across phases with significant differences ($p < 0.05$), excluding phases with Cohen's D < 0.50 so as to only report differences of medium effect size or larger. Graphs for biomechanical variables with differences are displayed in Appendix A.

Table 1 Summary of data points and statistical analysis

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

PRO - patient reported outcome measure; SPM - statistical parametric mapping; CoD - change of direction; ACLR - anterior cruciate ligament reconstruction; LSI - limb symmetry index; NRI - no re-injury group; ASYM - asymmetry

To assess the ability of the results to predict ACL re-injury, logistic regressions were performed using 3 predictor variables that were chosen based on the effect of the identified differences for the magnitude and symmetry analysis. Only three 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, 36] 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 RI and NRI was equal. To transform a predictor variable vector **x** (e.g.

contact time; n x m; n = 88 subjects; m = 1 feature) into z scores the following equation was used:

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

with x̄ being the average and *S* is standard deviation of the sample within **x**. During the fitting, data were balanced (using Synthetic Minority Over-sampling Technique)[6] 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 were reported. The area under the curve (AUC) was used in the RoC to classify findings (n = 0.50; poor = >0.60; fair = >0.70; good = >0.80), while the accuracy measure was compared to expected accuracy (accuracy that would have been obtained if the most frequent class had been guessed).

Results

There were 1045 male primary ACL reconstructions during the enrolment period. Re-injury of the reconstructed ACL graft was recorded in 38 participants. Of those re-injured, 3D biomechanical analysis and PRO data were recorded on 31 participants at orthopaedic follow-up (seven participants did not attend the testing session 6–9 months post-surgery), constituting the RI group. A matched cohort of 57 athletes with no ACL re-injury constituted the NRI group. Demographic and anthropometric data of both groups are reported in Table 2. The mean time (±SD) to ACL re-injury was 19.8 months (±8.4) post-surgery and 9.7 months (±8.9) post-RTP.

Table 2 Anthropometric data	RI (mean ± SD)	NRI (mean ± SD)
Subject Numbers	31	57

Graft Type (BPTB/HT)	18/13	37/20
Age (years)	21.7 (± 4.9)	22.9 (±4.1)
Mass (Kg)	82.4 (± 9.5)	81.3 (±11.8)
Height (cm)	180.3 (±6.4)	180.0 (±6)
Gaelic Football	16 (52%)	23 (40%)
Hurling	6 (19%)	14 (25%)
Soccer	5 (16%)	11 (19%)
Rugby	4 (13%)	9 (16%)
Surgery to RTP (months)	9.6 (±3.2)	9.9 (± 3.0)
Surgery to Testing (months)	9.1 (±3.1)	9.3 (± 1.2)
Surgery to Re-Injury (months)	19.8 (±8.4)	
RTP to Re-Injury (months)	9.7 (± 8.9)	

RI - re-injury group; NRI - no re-injury group; SD - standard deviation; BPTB - bone patellar tendon bone; HT - hamstring tendon; RTP - return to play

PRO scores:

No difference was detected in IKDC, ACL-RSI or Marx Activity Scale scores between groups (Table 3).

Table 3 Differences in patient reported outcome (PRO) measures

PRO	**RI**	**NRI**		
	Mean (±SD)		**p-value**	**Effect Size**
IKDC	79.3 (11.2)	83.3 (9.9)	0.12	0.31
ACL RSI	71.2 (16.2)	77.2 (15.0)	0.09	0.37
Marx	11.3 (3.5)	11.1 (3.5)	0.25	0.17

RI - re-injury group; NRI - no re-injury group; PRO – patient reported outcome; SD – standard deviation; IKDC – International Knee Documentation Committee; ACL-RSI – anterior cruciate ligament return to sport after injury

Strength and Performance Measures:

Comparison of ACLR limbs, LSI, or ≥90% LSI success rates between RI and NRI groups across all strength, jump, and CoD scores individually and combined revealed only one significant difference (Table 4) with hamstring strength, ≥90% LSI success rates significantly lower for the RI group (45%) than NRI group (69%; p = 0.020). Both groups had low success rates combined across all tests (4% RI, 2% NRI). The odds of being in the NRI group when >90% LSI was achieved for all tests was 0.49 (95% CI 0.03 to 8.15). No difference was observed for CoD performance time during planned CoD on the ACLR side (1.43 ± 0.15 s vs. 1.42 ± 0.11 s; p = 0.81) or in LSI (99.3 ± 5.0% vs. 99.3 ± 4.8%; p = 0.95) between groups. Similarly, no difference was detected in unplanned CoD performance time on the ACLR side (1.52 ± 0.12 s vs. 1.52 ± 0.09 s; p = 0.93) or in LSI (98.7 ± 4.6% vs. 98.7 ± 4.7%; p = 0.92) between groups.

Table 4 Comparison of strength and jump performance measures and ≥90% LSI success

Test	Ipsilateral Injury		Ipsilateral Matched			
		95% CI		95% CI	p-value	Effect Size
Quadriceps (N/Kg)	198 (43)	180 to 213	200 (39)	190 to 210	0.724	0.08
LSI (%)	89.4 (11.9)	85 to 94	88.1 (13.1)	85 to 92	0.652	0.10
>90% LSI success rates	52%		47%		0.644	
Hamstring (N/Kg)	122.6 (25.1)	113 to 132	127.1 (28.6)	120 to 134	0.488	0.16
LSI (%)	93 (14.4)	88 to 99	96.5 (13.9)	93 to 100	0.2745	0.24
>90% LSI success rates	45%		69%		0.022*	

SLCMJ (cm)	9.9 (2.8)	8.9 to 10.9	9.9 (2.6)	9.2 to 10.6	0.964	0.01
LSI (%)	85.4 (16.2)	79 to 91	86 (15.8)	82 to 90	0.875	0.03
>90% LSI success rates	41%		44%		0.821	
SLDJ (cm)	9.73 (2.8)	8.7 to 10.8	9.2 (2.7)	8.5 to 9.9	0.445	0.19
LSI (%)	80.1 (17.9)	73.9 to 87.8	76.3 (15.5)	72.2 to 80.3	0.224	0.28
>90% LSI success rates	25%		16%		0.287	
SLHD (cm)	148.8 (33.8)	135 to 162	142.2 (23.3)	137 to 149	0.388	0.21
LSI (%)	95.6 (14.6)	89.5 to 100	95.7 (13.7)	92.1 to 99.4	0.961	0.01
>90% LSI success rates	83%		68%		0.162	
>90% LSI success rates for all 4 tests	4%		2%		0.562	

RI - re-injury group; NRI - no re-injury group; SD - standard deviation; SLCMJ - single leg countermovement jump; SLDJ - single leg drop jump; SLHD - single leg hop for distance; CI - confidence interval; LSI – limb symmetry index; SD – standard deviation

* $p < 0.05$

Biomechanical Analysis

Biomechanical differences (% stance; effect size) on the ACLR side between RI and NRI groups are reported in Table 5 and Figure 2. In the double leg drop jump, there were medium effect size differences for knee flexion angle (9%–22%; effect size: 0.64; Figure 3), vertical distance from COM to ankle (9%–29% & 49% to 74%; d = 0.64 & 0.59) and ground contact time (d = 0.52) with more knee flexion, lower COM to ankle, and longer ground contact times in the RI group. Groups did not significantly differ for any variable within the single leg drop jump. In the planned CoD, COM was less posterior to the knee in the RI group throughout stance (0%–12%, 26%–34%, 54%–63%, 82%–93%; d = 0.66, 0.63, 0.67, 0.62).

In the unplanned CoD, there was less anterior pelvic tilt in the RI group (42%–90%; d = 0.63). The prediction model for biomechanical variables for double leg drop jump selected vertical COM distance to ankle (9-29%), knee flexion angle and ground contact time for inclusion and could predict membership of the RI group with an accuracy of 61.3% (baseline: 62.5%), sensitivity of 0.69, and specificity of 0.47 (AUC: 0.67).

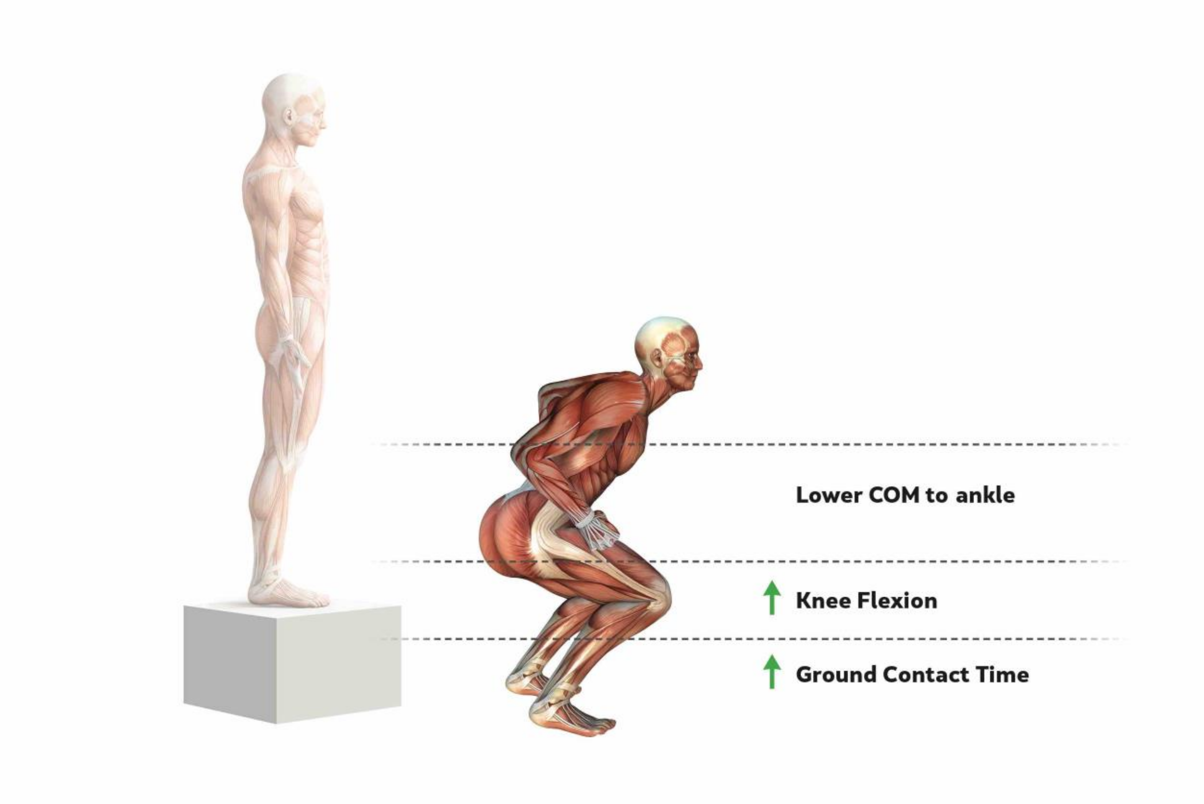

Figure 2. Biomechanical differences on ACLR side during the double leg drop jump in ACL RI group compared to NRI group illustrating longer ground contact times, greater knee flexion and lower COM to ankle on the ACLR side in the RI group.

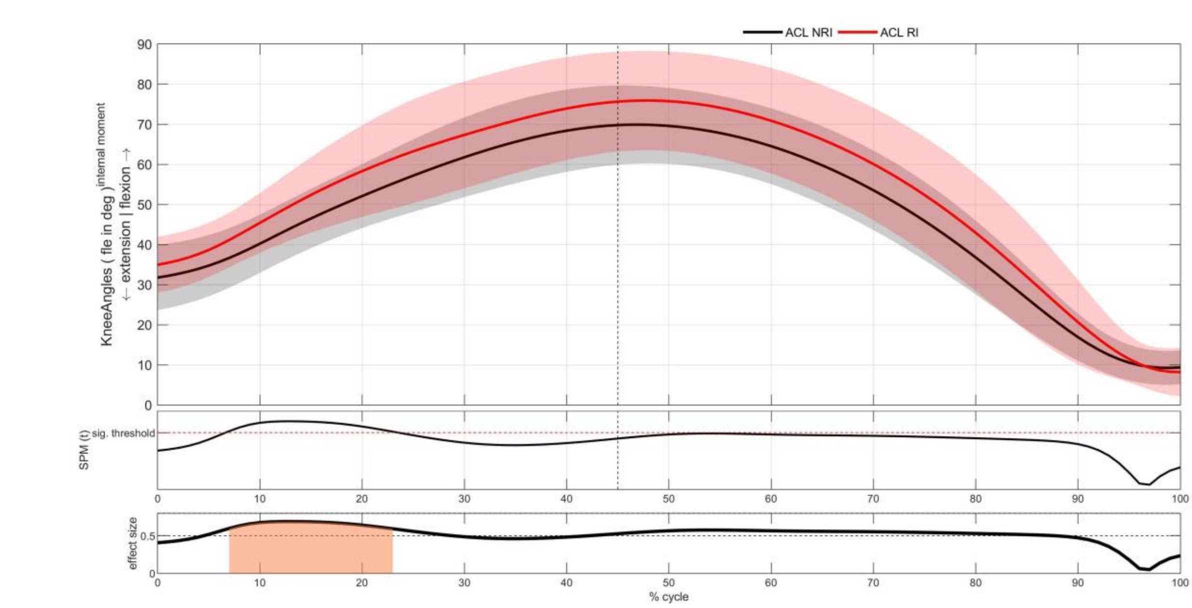

Figure 3. Difference in knee flexion angle on the ACLR side between re-injury (RI) and no re-injury (NRI) groups during double leg drop jump. Top panel illustrates mean and SD clouds for RI (red) and NRI limbs (black). Middle panel illustrates SPM{t}, the t-statistic as a function of time describing difference between the two groups. Dotted red line of the SPM curve indicates *p*<0.05 and that a significant difference exists between groups. Bottom panel illustrates effect size as a function of time, describing magnitude of the effect. Dotted black line and shaded portion indicate average Cohen's d>0.5, with orange indicating medium effect size and significant difference throughout that phase. There was less knee flexion in the RI group (9%–22%), with a medium effect size (0.64).

Table 5 Biomechanical differences on the ACLR side between RI and NRI groups

			Difference Between RI and NRI on ACLR side - D		
Variable	**Start**	**End**	**RI ACLR side (± SD)**	**95% CI**	**N**
Knee Flexion Angle (º)	9	22	52.7 (9.7)	49.0 to 56.4	
COM to Ankle Vertical (mm/BH)	9	29	0.42 (0.02)	0.41 to 0.43	
	49	74	0.40 (0.03)	0.39 to 0.41	
Ground Contact Time (sec)	n/a		0.31 (0.09)	0.27 to 0.34	
			Difference Between RI and NRI Cohort on ACLR side - P		
COM to Knee Posterior (mm)	0	12	-11.1 (60.3)	-34.1 to 11.8	
	26	34	18.9 (56.9)	-2.7 to 40.5	
	54	63	66.1 (62.2)	42.4 to 89.7	

	82	93	163 (68.4)	137.1 to 189.1
		Difference Between RI and NRI Cohort on ACLR side - Un		
Anterior Pelvic Tilt (º)	42	90	2.1 (7.0)	-0.7 to 4.8

ACLR - anterior cruciate ligament reconstruction; RI - re-injury group; NRI - no re-injury group; DLDJ - double leg drop jump; CI - confidence interval; IPSI - ipsilateral; SD - standard deviation; BH - body height; CoD - change of direction; COM – centre of mass

Differences in asymmetry between the two groups are reported in Table 6 and Figure 4. No significant differences in asymmetry were detected in the double leg drop jump, single leg drop jump and planned CoD. In the unplanned CoD significant differences in asymmetry indicated that the RI group were more asymmetrical for COM to knee (76%–90%; d = 0.69 and ankle (12%–23%; d = 0.62), with the COM more contralateral (medial) to the knee on the ACLR side. The trunk-pelvis side flexion angle was more asymmetrical in the RI group (73%–100%; d = 0.68) towards the end of the stance phase. There also was greater asymmetry in anterior pelvic tilt in the RI group (28%–99%; d = 0.69), with less anterior pelvic tilt on the ACLR side, as well as greater asymmetry in pelvic drop (9%–36%; d = 0.61), with more pelvic drop during early stance on the ACLR side. The prediction model for symmetry of biomechanical variables during unplanned CoD selected COM to knee in frontal plane, pelvic drop and trunk-pelvis side flexion for inclusion and could predict ACL re-injury with an accuracy of 67.7% (baseline: 59.7%), sensitivity of 0.65 and specificity of 0.72 (AUC: 0.75).

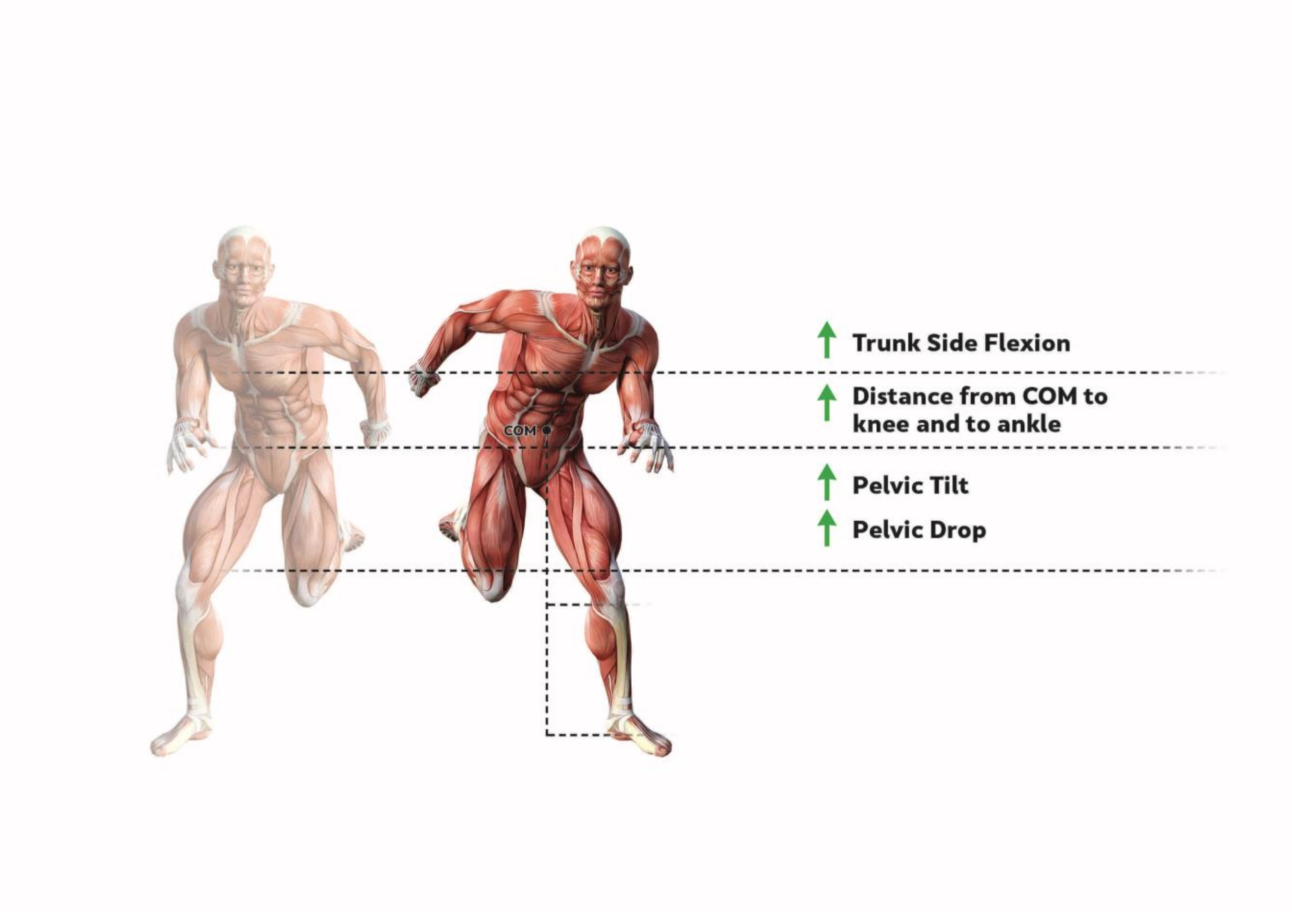

Figure 4. Biomechanical variables with greater asymmetry during the unplanned CoD in the RI group compared to NRI group illustrating greater asymmetry of trunk side flexion, distance from COM to knee and ankle in frontal plane, pelvic tilt and pelvic drop in the RI group.

Table 6 Biomechanical differences between limbs between the RI and NRI groups

	Difference Between Limbs Between RI and NRI Cohort on ACLR sid				
Variable	**Start**	**End**	**RI ACLR side (± SD)**	**95% CI**	**NR**
COM to Knee Frontal (mm)	76	90	20.1 (42.8)	3.2 to 37.1	
Anterior Pelvic Tilt (º)	28	99	-4.9 (8.8)	-1.5 to -8.4	
Trunk to Pelvis Side Flexion (º)	73	100	-4.9 (10.4)	-0.8 to -9.0	
COM to Ankle Frontal (mm)	12	23	38.8 (57.4)	16.1 to 61.6	
Contralateral Pelvic Drop (º)	9	36	6.9 (7.5)	4.0 to 9.9	

ACLR - anterior cruciate ligament reconstruction; RI - re-injury group; NRI - no re-injury group; ASYM - asymmetry; CI - confidence interval; IPSI - ipsilateral; SD - standard deviation; CoD - change of direction; COM - centre of mass

Discussion

Return to play criteria are used to determine rehabilitation status and re-injury risk after ACLR and frequently assess PRO, strength and jump/hop and CoD performance measures but movement (biomechanical) analysis is commonly absent. This study aimed to prospectively examine these combination of measures in a large cohort of male field sport athletes. This study identified differences in biomechanical measures between those who suffered re-injury and those who did not. These biomechanical differences were present in the absence of any differences between groups in commonly used and reported isokinetic strength, jump, and CoD timed performance measures, both individually and combined. Biomechanical variables from individual jump and CoD tests demonstrated limited predicative ability but highlight variables that could be targeted during rehabilitation and RTP decision-making and could be considered in future injury prediction models.

Patient Reported Outcomes

This study examined differences in PRO. There was no difference in IKDC, Marx Activity Scale or ACL-RSI score between groups, suggesting that self-reported knee function, activity levels at the time of testing or perceived readiness to RTP are not factors in re-injury risk. This is in agreement with previous research which found no difference in PRO between those that suffer subsequent knee injury and those that do not after ACLR.[11]

Performance Measures

There was no difference between ACLR limbs or in LSI for isokinetic strength of the quadriceps or hamstrings, jump height/length or CoD times individually or collectively between RI and NRI groups. There was also no difference in >90% LSI success rates for all variables, with the exception of hamstring strength testing ($p = 0.022$). This difference in hamstring strength was not evident when looking at group means, highlighting how potentially important results may be hidden in group averages.[42] When examining the >90% LSI success rates of all tests combined, there was a lower odds of being in the NRI group (0.49) but the confidence intervals were wide (0.03 to 8.15). This differs from previous findings from Kyritsis et al., who reported a 4-fold increase in re-injury risk after ACLR in those not achieving >90% LSI across strength, jump, and CoD tests. Both RI and NRI groups demonstrated ongoing deficits relating to <90% LSI threshold at the time of testing, consistent with previous studies demonstrating ongoing strength and jump deficits after ACLR at RTP.[27, 30, 39, 47] However, biomechanical deficits after ACLR have been demonstrated despite athletes passing >90% LSI criteria during jump and CoD tests.[14, 15] These results suggest that previously used performance measures of stre[21]ngth, jump, and CoD performance, on the ACLR side on in measures of symmetry (LSI), may not be sufficient to identify physical deficits that may influence risk of ACL re-injury. Additional factors may need to be considered during RTP assessment or decision-making.

Biomechanical Analysis

There were some biomechanical differences on the ACLR side and in symmetry between limbs between RI and NRI groups. In the double leg drop jump, there was increased knee flexion, lower vertical COM height to the ankle, and longer ground contact times on the ACLR side for those who experienced ACL re-injury. This suggests the RI group required longer time on the ground and more flexion/lowering of COM to absorb landing forces and then jump again during the double leg task. This longer time to absorb load may influence knee loading on RTP, resulting in higher knee and ACL load during sports-specific activities and may result in increased risk of ACL re-injury.[5, 22, 39, 47, 48] Differences in the biomechanics of planned and unplanned CoD on the ACLR side between groups demonstrated the COM being less posterior to the knee (planned) and less anterior pelvic tilt (unplanned) in the RI group. A less posterior position of the COM relative to the knee has been suggested as a method to reduce the knee extension moment required during landing and deceleration[31, 32] and knee valgus moment during CoD.[10] Combined with variables identified in the double leg drop jump, it may reflect a difference in the ability to absorb load in the sagittal plane in those who re-injure their ACL. However, given the number of biomechanical variables analysed in both CoD tests, the identification of a single variable of difference may hold little relevant information. Of note, external knee valgus moment (internal knee varus moment) and knee valgus angle were not different between groups in any test, despite this being reported as a risk factor in previous literature[11, 35] and common mechanism of ACL injury.[1, 16] This difference in findings may be due to previous analysis being mostly in female athletes, rather than male athletes, with females more likely to demonstrate dynamic knee valgus during landing[30, 38] and during ACL injury.[19] In addition, prior studies often combined ipsilateral and contralateral injuries together during analysis, which may have influenced outcomes.[11, 34, 35]

CoD tests revealed differences of symmetry in biomechanical measures between groups. In the unplanned CoD, there was greater between-limb difference for distance between the COM and knee and ankle in the frontal plane in the RI group, with distance greater (more medial) on the ACLR side. Greater step width has been suggested as a potential mechanism for ACL injury and increased knee loading, and asymmetry in strategy between limbs may increase re-injury risk in the RI group.[8, 17] However it should be noted that there was large variation in asymmetry in these variables in both groups which may be in part due to group differences but also reflect the greater variation that may exist in a more open task such as unplanned CoD. Additionally, there was greater asymmetry of ipsilateral trunk-pelvis lateral flexion and pelvic drop on the ACLR side in the RI group. Frontal plane control has been suggested as an important risk factor for ACL injury, and increased trunk sway during CoD has been demonstrated to increase knee loading and is a commonly reported mechanism during ACL injury.[1, 4, 8]

While previous research has focused on jumping mechanics, seeking to identify risk factors for ACL injury,[12, 20, 35] this study demonstrates that biomechanical analysis of both jump and CoD movements can enhance assessment of rehabilitation status to reduce ACL re-injury risk on RTP after ACLR. Biomechanical differences between groups were found despite no differences in commonly used isokinetic peak torque strength, jump, and CoD performance measures, highlighting the potential importance of examining performance and biomechanical measures after ACLR.[14, 15] Biomechanical variables for the double leg drop jump and unplanned CoD demonstrated poor predictive ability to identify those who would re-injure their ACL. Differences between those with re-injury and those without were related to the ability to absorb load during double leg drop jump and frontal plane control during unplanned CoD. Targeting these variables during rehabilitation in male athletes returning from ACLR may reduce the incidence of re-injury but may not be able to currently predict who will go on to re-injure.[3] The results of this study suggest that biomechanical variables during both jump and CoD testing may play an important role in those who will experience ACL re-injury on return to high-demand multidirectional sports and may offer more relevant information than the common strength and jump score tests previously used in isolation.

Limitations and Future Directions

Although ACL re-injury was tracked prospectively on a large number of participants, biomechanical data were not available on 7/38 subjects (18%) which may bias the results. As there is little research on prospective risk factors for ACL re-injury in male athletes, this study examined a large number of variables and tests. This increases the risk of type 1 error, although we offset this risk by setting a medium effect size threshold and only reporting variables with sufficient magnitude differences. Further, we only included male athletes, so future research should carry out similar analyses in female athletic populations to identify risk factors specific to that cohort and potential differences in risk factors for male and female athletes for ACL re-injury after ACLR. In addition, those identified biomechanical variables demonstrated limited predictive ability and have large variability in some cases. Predictive accuracy may be improved by using non-linear models, exploring alternative biomechanical measures including variability and co-ordination and including additional data that have been reported to influence ACL re-injury, such as demographic surgical and radiological data, to build a comprehensive model of factors influencing second ACL injury risk.

Conclusion

This large prospective study examined differences in both performance and biomechanical variables during jump and CoD testing to identify risk factors for ACL re-injury in male athletes. The RI group had no difference in IKDC, ACL RSI, Marx Activity Scale, or commonly used strength and performance measures at 9 month follow up. Findings demonstrate differences in biomechanical variables in the sagittal plane on ACLR side during double leg drop jump and symmetry of frontal plane control during unplanned CoD with poor predictive ability. Targeting these variables during ACL rehabilitation may reduce the risk of re-injury. Future research should combine biomechanical, surgical, and demographic data to determine if these factors are involved in ACL re-injury.

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. Bahr R. Why screening tests to predict injury do not work-and probably never will...: a critical review. *Br J Sports Med.* 2016;50(13):776-780.

4. Boden BP, Sheehan FT, Torg JS, Hewett TE. Noncontact anterior cruciate ligament injuries: mechanisms and risk factors. *J Am Acad Orthop Surg.* 2010;18(9):520-527.

5. Cerulli G, Benoit DL, Lamontagne M, Caraffa A, Liti A. In vivo anterior cruciate ligament strain behaviour during a rapid deceleration movement: case report. *Knee Surg Sports Traumatol Arthrosc.* 2003;11(5):307-311.

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

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

8. 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.

9. Dingenen B, Gokeler A. Optimization of the Return-to-Sport Paradigm After Anterior Cruciate Ligament Reconstruction: A Critical Step Back to Move Forward. *Sports Med.* 2017;47(8):1487-1500.

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. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *Br J Sports Med.* 2016;50(13):804-808.

12. 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.

13. 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.

14. King E, Richter C, Franklyn-Miller A, et al. Biomechanical but not timed performance asymmetries persist between limbs 9months after ACL reconstruction during planned and unplanned change of direction. *J Biomech.* 2018;81:93-103.

15. 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;28(12):2567-2578.

16. 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.

17. Kristianslund E, Faul O, Bahr R, Myklebust G, Krosshaug T. Sidestep cutting technique and knee abduction loading: implications for ACL prevention exercises. *Br J Sports Med.* 2014;48(9):779-783.

18. 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.

19. 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.

20. Krosshaug T, Steffen K, Kristianslund E, et al. The Vertical Drop Jump Is a Poor Screening Test for ACL Injuries in Female Elite Soccer and Handball Players: A Prospective Cohort Study of 710 Athletes. *Am J Sports Med.* 2016;44(4):874-883.

21. 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;50(15):946-951.

22. Lin CF, Gross M, Ji C, et al. A stochastic biomechanical model for risk and risk factors of non-contact anterior cruciate ligament injuries. *J Biomech.* 2009;42(4):418-423.

23. 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.

24. 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.

25. 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.

26. McPherson AL, Feller JA, Hewett TE, Webster KE. Smaller Change in Psychological Readiness to Return to Sport Is Associated With Second Anterior Cruciate Ligament Injury Among Younger Patients. *Am J Sports Med.* 2019;47(5):1209-1215.

27. Mohammadi F, Salavati M, Akhbari B, Mazaheri M, Mohsen Mir S, Etemadi Y. Comparison of functional outcome measures after ACL reconstruction in competitive soccer players: a randomized trial. *J Bone Joint Surg Am.* 2013;95(14):1271-1277.

28. Moudy S, Richter C, Strike S. Landmark registering waveform data improves the ability to predict performance measures. *J Biomech.* 2018;78:109-117.

29. Narducci E, Waltz A, Gorski K, Leppla L, Donaldson M. The clinical utility of functional performance tests within one-year post-acl reconstruction: a systematic review. *Int J Sports Phys Ther.* 2011;6(4):333-342.

30. O'Malley E, Richter C, King E, et al. Countermovement Jump and Isokinetic Dynamometry as Measures of Rehabilitation Status After Anterior Cruciate Ligament Reconstruction. *Journal of athletic training.* 2018;53(7):687-695.

31. Oberlander KD, Bruggemann GP, Hoher J, Karamanidis K. Reduced knee joint moment in ACL deficient patients at a cost of dynamic stability during landing. *J Biomech.* 2012;45(8):1387-1392.

32. Oberlander KD, Bruggemann GP, Hoher J, Karamanidis K. Altered landing mechanics in ACL-reconstructed patients. *Med Sci Sports Exerc.* 2013;45(3):506-513.

33. Pataky TC, Vanrenterghem J, Robinson MA. Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *J Biomech.* 2015;48(7):1277-1285.

34. Paterno MV, Huang B, Thomas S, Hewett TE, Schmitt LC. Clinical Factors That Predict a Second ACL Injury After ACL Reconstruction and Return to Sport: Preliminary Development of a Clinical Decision Algorithm. *Orthop J Sports Med.* 2017;5(12):2325967117745279.

35. 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.

36. 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.

37. Ramsey JO. *Functional data analysis*: John Wiley and Sons; 2006.

38. 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.

39. Schmitt LC, Paterno MV, Ford KR, Myer GD, Hewett TE. Strength Asymmetry and Landing Mechanics at Return to Sport after Anterior Cruciate Ligament Reconstruction. *Med Sci Sports Exerc.* 2015;47(7):1426-1434.

40. Sell TC, Ferris CM, Abt JP, et al. The effect of direction and reaction on the neuromuscular and biomechanical characteristics of the knee during tasks that simulate the noncontact anterior cruciate ligament injury mechanism. *Am J Sports Med.* 2006;34(1):43-54.

41. 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.

42. Thomee R, Kaplan Y, Kvist J, et al. Muscle strength and hop performance criteria prior to return to sports after ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2011;19(11):1798-1805.

43. Thomee R, Neeter C, Gustavsson A, et al. Variability in leg muscle power and hop performance after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2012;20(6):1143-1151.

44. 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.

45. 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.

46. 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.

47. Xergia SA, Pappas E, Zampeli F, Georgiou S, Georgoulis AD. Asymmetries in functional hop tests, lower extremity kinematics, and isokinetic strength persist 6 to 9 months following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther.* 2013;43(3):154-162.

48. Yu B, Garrett WE. Mechanisms of non-contact ACL injuries. *Br J Sports Med.* 2007;41 Suppl 1:i47-51.