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- **1** Biomechanical but not strength or performance measures
- 2 differentiate male athletes who experience ACL re-injury on return

3 to level 1 sport

4 Accepted version, proofs being developed

5 Abstract

6 Background

7 Performance measures such as strength, jump height/length and change of direction time

8 during ACL rehabilitation have been used to determine readiness to return to play and

9 identify those who may be at risk of re-rupture. However, athletes may reach these criteria

10 despite ongoing biomechanical deficits when performing these tests. Combining return to

11 play criteria with an assessment of movement through 3D biomechanics in male field sport

12 athletes to identify risk factors for ACL re-rupture has not been explored previously.

13

14 Purpose

15 To prospectively examine differences in strength, jump, and change of direction (CoD)

16 performance and movement using 3D biomechanics in a cohort of male athletes playing level

17 1 sports between those who re-injured their reconstructed ACL (RI) and those with no re-

18 injury (NRI) after 2 years follow-up and examine the ability of these differences to predict re-

19 injury.

20

21 Study Design

22 Case-control study

23

25 N	Aethods (Methods)
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26	Male athletes after primary ACL reconstruction (ACLR; $n = 1045$) were recruited and
27	underwent testing 9 months post-surgery, including isokinetic strength, jump and CoD
28	performance measures, patient-reported outcomes (PRO) and 3D biomechanical analyses.
29	Participants were followed-up after 2 years regarding ACL re-injury status (n = 38).
30	Differences between RI and NRI groups in PRO, performance measures and 3D
31	biomechanics on the ACLR side/symmetry between limbs were determined. The ability of
32	these measures to predict ACL re-injury was determined through logistic regression.
33	
34	Results
35	No differences were identified in strength and performance measures on the ACLR side or in
36	symmetry. Biomechanical analysis indicated differences on the ACLR side primarily in the
37	sagittal plane for the double leg drop jump (DLDJ; effect size 0.59 to 0.64) and greater
38	asymmetry primarily in the frontal plane during unplanned CoD (effect size 0.61 to 0.69) in
39	the RI group. While these biomechanical tests were different between groups, multivariate
40	regression modelling demonstrated limited ability (AUC 0.67 and 0.75, respectively) to
41	prospectively predict ACL re-injury.
42	

43 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.

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51	Clinical Relevance
52	This study suggests strength, jump and change of direction time performance testing in
53	isolation may be inadequate to assess readiness to RTP following ACLR. Biomechanical
54	analysis of movement quality in performing these tests may add potentially relevant
55	information to the assessment of ACL re-injury risk.
56	
57	Key Terms
58	Anterior Cruciate Ligament Reconstruction, Return to Play, Re-injury, Biomechanics
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75 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.

82

83 What does this study add to the existing knowledge?

84 This study found no differences in commonly used strength, jump and change of direction performance measures despite biomechanical differences during jump and change of 85 86 direction tests in athletes who went on to suffer re-injury of the ACL after surgery. In 87 particular, it identified differences in the sagittal plane on the ACLR side in the DLDJ and 88 differences in asymmetry in the frontal plane during unplanned change of direction. 89 However, these differences had limited ability to predict ACL re-injury but could be targeted 90 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 91 92 identifying biomechanical variables that may be targeted to improve re-injury rates. 93 94

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- 97

98 Introduction

99 Reducing the risk of anterior cruciate ligament (ACL) re-injury is probably the most 100 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-101 102 injury, rehabilitation status before return to play (RTP). The criteria are commonly assessed 103 using physical tests of lower limb strength, jump height/length, and timed change of direction 104 (CoD) performance. Outcomes from theses performance tests are combined with patient-105 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 106 symmetry index (LSI), is suggested to influence the risk of any injury to the operated knee¹¹ 107 and re-injury of the re-constructed graft.²¹ It has been recommended that success rates (% of 108 109 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 110 111 significant association with second injury risk. Athletes have also been reported to achieve 112 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 113 114 analysis may offer a more robust measure of physical recovery after ACLR when assessing 115 re-injury risk than commonly used performance test batteries alone.

116

To date, few studies have prospectively examined biomechanical variables related to ACL reinjury 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 123 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 124 125 limitation to our understanding of the re-injury mechanism is that the research is restricted to 126 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 127 128 measures and biomechanics on ACL re-injury, studies must control for several non-physical 129 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 130 131 combination of PRO, strength and performance measures, and 3D biomechanical analysis in 132 both jump and CoD tests in a homogenous cohort of athletes may better identify those at increased risk of ACL re-injury. 133

134

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.

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143 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, 148 participants completed a pre-operative questionnaire outlining their sport, mechanism of 149 injury, and level of desired return after surgery. Male participants aged 18 to 35 years who 150 played multidirectional field sports and intended to return to the same level of sport were 151 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. 152 153 Participants who were undergoing second or subsequent ACLR, did not intend to return to 154 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 155 156 the Sports Surgery Clinic Hospital Ethics Committee (25-AFM-010).

157

158 **Testing Protocol**

159 After surgery, all participants underwent an accelerated rehabilitation protocol with 160 weightbearing as tolerated on crutches for 2 weeks, followed by progressive blocks of 161 strength and neuromuscular control, power and reactive strength development, and running 162 and CoD mechanics, as physical competency and knee symptoms allowed. Athletes were 163 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 164 orthopaedic review, participants took part in a physical testing protocol at approximately 9 165 166 months post-surgery. Before the testing session, all participants completed PRO: the International Knee Documentation Committee (IKDC),¹³ Marx Activity Scale²⁵, and ACL 167 Return to Sport after Injury questionnaire (ACL-RSI).⁴⁵ The data collection protocol took 168 169 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 170 elsewhere.^{14, 15} In addition, single leg countermovement jump height and single leg hop for 171 distance length were assessed to compare with previous literature.^{11, 21, 30} Participants 172

173 undertook a standardised warm-up: 2-minute jog, 5 bodyweight squats, and 2 submaximal 174 and 3 maximal double leg countermovement jumps. Each participant underwent two 175 submaximal practice trials of each movement before three valid test trial attempts (maximal 176 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 177 178 concentric isokinetic testing of the quadriceps and hamstring muscle groups of both limbs at 179 60°/s through 0-100° knee flexion. Peak torque/body mass was used to define the strength performance measures.⁴⁴ 180

181

182 Biomechanical Analysis

183 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, 184 185 AMTI, Watertown, MA, USA) sampling at 1000 Hz. Motion data from 24 reflective markers 186 (14 mm diameter) was integrated with ground reaction forces (Vicon Nexus 1.8.5), which 187 were low-pass filtered using a fourth-order Butterworth filter (cut-off frequency: 15 Hz).¹⁸ 188 Participants wore their own athletic footwear. Reflective markers were secured using tape at 189 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 190 191 processing and calculating the variables analysed. The motion of the centre of mass (COM) 192 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 193 194 hip 3D joint angles and moments, the trunk-pelvis angle in all three planes and foot-pelvis 195 angle in the transverse plane were quantified. All kinetic variables including ground reaction 196 force were normalized to body mass. Whole body stiffness when the body was accepting load 197 was calculated as:

stiffness (k) = delta vGRF / sqrt(delta CoMz^2)

199 where delta for both variables is from impact (the point of initial ground contact) to and end 200 of eccentric phase defined as the first instance at which COM vertical power > 0. Kinetic and 201 kinematic analysis was performed for the stance phase of each jump and CoD test [defined by 202 ground reaction force (GRF) > 20 N]. Curves were normalized to 101 frames and landmark registered³⁷ to endecc.²⁸ This process aligned onset of the eccentric phase to 50% of the 203 204 movement cycle across participants to ensure relevant comparison of neuromuscular 205 characteristics between limbs and participants during continuous waveform analysis. 206 Performance outcomes were determined for the jump and CoD tasks. Jump height for single 207 leg countermovement jump, double leg drop jump and single leg drop jump was calculated 208 from ground reaction forces using the impulse-momentum theorem and jump length for 209 single leg hop for distance was calculated as the distance from heel marker at start to landing. 210 Time to complete the 90° CoD was recorded using speed gates (Smartspeed, Fusion Sport, 211 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 212 213 performance scores were calculated [(ACLR side/non-ACLR side) x 100]. Asymmetry in 214 biomechanical variables (ASYM) was calculated as the ACLR side minus non-ACLR side. 215

216 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







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

235 Statistical Analysis

236 Differences in PRO and strength (normalised knee flexion and extension peak torque) and 237 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 238 239 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 240 interpreted using Cohen's D (0.20 to 0.49 = small; 0.50 to 0.79 = medium; $\ge 0.80 = \text{strong}$).⁷ 241 242 Success rates (percentage of group who achieved the outcome) attaining $\geq 90\%$ LSI for 243 quadriceps and hamstring strength, single leg countermovement jump and single leg drop 244 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. 245 246 Additionally, the odds ratio of participants being in the NRI compared to RI when >90% LSI 247 for quadriceps, hamstring strength, single leg countermovement jump, and single leg drop 248 jump height were calculated as well as the odds when $\geq 90\%$ LSI for all five tests collectively 249 was achieved.

250

Statistical parametric mapping (SPM; 1d, unpaired t-test; parametric) was used to examine 251 252 differences in lower-limb biomechanics between RI and NRI groups for the ACLR limb and 253 differences in asymmetry between limbs between groups (ACLR minus non-ACLR limb) for 254 each biomechanical variable for double leg drop jump, single leg drop jump, and planned and 255 unplanned 90° CoD during stance. Reported values are mean effect sizes across phases with 256 significant differences (p < 0.05), excluding phases with Cohen's D < 0.50 so as to only 257 report differences of medium effect size or larger. Graphs for biomechanical variables with differences are displayed in Appendix A. 258

262 Table 1 Summary of data points and statistical analysis

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

267	To assess the ability of the results to predict ACL re-injury, logistic regressions were
268	performed using 3 predictor variables that were chosen based on the effect of the identified
269	differences for the magnitude and symmetry analysis. Only three features were chosen to
270	achieve an input to observations ratio of 1:10 to 15, to generate a model avoiding
271	overfitting the model to the data. ^{2, 36} if a feature was multicollinear (correlation between
272	them >.70) with a higher ranked feature it was excluded and an additional lower ranked
273	feature was included. Predictor variables utilized were the average value of the phases
274	within a biomechanical waveform that differed between groups. Before fitting the logistic
275	regression predictor variables were transformed into z-scores and cohorts were balanced so
276	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:

- $z = (\mathbf{x} \bar{\mathbf{x}}) / S,$
- 280

281 with $\bar{\mathbf{x}}$ 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)⁶ so the 282 283 minority class contained the same number of observations as the majority class. To interpret 284 predictive ability of the logistic regression, receiver operating curve (RoC) and prediction 285 accuracy were reported. The area under the curve (AUC) was used in the RoC to classify 286 findings (n = 0.50; poor = >0.60; fair = >0.70; good = >0.80), while the accuracy measure 287 was compared to expected accuracy (accuracy that would have been obtained if the most 288 frequent class had been guessed).

289

290 **Results**

291 There were 1045 male primary ACL reconstructions during the enrolment period. Re-injury 292 of the reconstructed ACL graft was recorded in 38 participants. Of those re-injured, 3D 293 biomechanical analysis and PRO data were recorded on 31 participants at orthopaedic 294 follow-up (seven participants did not attend the testing session 6–9 months post-surgery), 295 constituting the RI group. A matched cohort of 57 athletes with no ACL re-injury constituted 296 the NRI group. Demographic and anthropometric data of both groups are reported in Table 2. 297 The mean time (\pm SD) to ACL re-injury was 19.8 months (\pm 8.4) post-surgery and 9.7 months 298 (±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)	

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

- 302 return to play
- 303

304 PRO scores:

305 No difference was detected in IKDC, ACL-RSI or Marx Activity Scale scores between

- 306 groups (Table 3).
- 307
- 308

309

310 Table 3 Differences in patient reported outcome (PRO) measures

PRO	RI	NRI		
	Mea	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
- 314
- 315
- 316 Strength and Performance Measures:

317	Comparison of ACLR limbs, LSI, or ≥90% LSI success rates between RI and NRI groups
318	across all strength, jump, and CoD scores individually and combined revealed only one
319	significant difference (Table 4) with hamstring strength, ≥90% LSI success rates significantly
320	lower for the RI group (45%) than NRI group (69%; $p = 0.020$). Both groups had low success
321	rates combined across all tests (4% RI, 2% NRI). The odds of being in the NRI group when
322	>90% LSI was achieved for all tests was 0.49 (95% CI 0.03 to 8.15). No difference was
323	observed for CoD performance time during planned CoD on the ACLR side (1.43 \pm 0.15 s vs.
324	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.
325	Similarly, no difference was detected in unplanned CoD performance time on the ACLR side
326	$(1.52 \pm 0.12 \text{ s vs. } 1.52 \pm 0.09 \text{ s}; p = 0.93)$ or in LSI (98.7 ± 4.6% vs. 98.7 ± 4.7%; p = 0.92)
327	between groups.

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

	Test	Ipsilater	al Injury	Ipsilatera	l Matched		
						p-	Effect
			95% CI		95% CI	value	Size
			180 to		190 to		
C	luadriceps (N/Kg)	198 (43)	213	200 (39)	210	0.724	0.08
		89.4		88.1			
	LSI (%)	(11.9)	85 to 94	(13.1)	85 to 92	0.652	0.10
>90	0% LSI success rates	52%		47%		0.644	
		122.6	113 to	127.1	120 to		
ŀ	Hamstring (N/Kg)	(25.1)	132	(28.6)	134	0.488	0.16
				96.5			
	LSI (%)	93 (14.4)	88 to 99	(13.9)	93 to 100	0.2745	0.24
>90)% LSI success rates	45%		69%		0.022*	

		8.9 to		9.2 to		
SLCMJ (cm)	9.9 (2.8)	10.9	9.9 (2.6)	10.6	0.964	0.01
	85.4					
LSI (%)	(16.2)	79 to 91	86 (15.8)	82 to 90	0.875	0.03
>90% LSI success rates	41%		44%		0.821	
		9 7 to				
SLDL (cm)	0 72 (2 8)	10 9	0 2 (2 7)	9 E to 0 0	0 4 4 5	0 10
	9.75 (2.6)	10.0 72.0 to	9.2 (2.7) 76 2	0.5 LU 9.9	0.445	0.19
	00.1 (17.0)	73.9 LU 07 0	70.5 (1E E)	72.2 LU	0 224	0.20
	(17.9)	07.0	(15.5)	60.5	0.224	0.28
>90% LSI success rates	25%		16%		0.287	
	1/12 2	135 to	117 2	137 to		
SI HD (cm)	(33.8)	162	(23.3)	1/0	0 388	0.21
SEID (CIII)	(55.8) 05.6	20 5 to	(23.3)	145 02.1 to	0.566	0.21
151 (%)	(14.6)	100	(13.7)	92.1 (U 00 /	0 961	0.01
	(14.0)	100	(13.7)	55.4	0.301	0.01
>90% LSI success rates	83%		68%		0.162	
>90% LSI success rates for all 4						
tests	4%		2%		0.562	

330 RI - re-injury group; NRI - no re-injury group; SD - standard deviation; SLCMJ - single leg countermovement jump; SLDJ - single leg drop

331 jump; SLHD - single leg hop for distance; CI - confidence interval; LSI – limb symmetry index; SD – standard deviation

332 * p < 0.05

333

334 Biomechanical Analysis

Biomechanical differences (% stance; effect size) on the ACLR side between RI and NRI

336 groups are reported in Table 5 and Figure 2. In the double leg drop jump, there were medium

337 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

- 340 times in the RI group. Groups did not significantly differ for any variable within the single
- 341 leg drop jump. In the planned CoD, COM was less posterior to the knee in the RI group
- 342 throughout stance (0%-12%, 26%-34%, 54%-63%, 82%-93%; d = 0.66, 0.63, 0.67, 0.62).

- 343 In the unplanned CoD, there was less anterior pelvic tilt in the RI group (42%-90%); d =
- 344 0.63). The prediction model for biomechanical variables for double leg drop jump selected
- 345 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:
- 347 62.5%), sensitivity of 0.69, and specificity of 0.47 (AUC: 0.67).



- 348
- 349 Figure 2. Biomechanical differences on ACLR side during the double leg drop jump in ACL RI group compared
- 350 to NRI group illustrating longer ground contact times, greater knee flexion and lower COM to ankle on the
- 351 ACLR side in the RI group.



352

353 Figure 3. Difference in knee flexion angle on the ACLR side between re-injury (RI) and no re-injury (NRI) 354 groups during double leg drop jump. Top panel illustrates mean and SD clouds for RI (red) and NRI limbs 355 (black). Middle panel illustrates $SPM{t}$, the t-statistic as a function of time describing difference between the 356 two groups. Dotted red line of the SPM curve indicates p < 0.05 and that a significant difference exists between 357 groups. Bottom panel illustrates effect size as a function of time, describing magnitude of the effect. Dotted 358 black line and shaded portion indicate average Cohen's d>0.5, with orange indicating medium effect size and 359 significant difference throughout that phase. There was less knee flexion in the RI group (9%-22%), with a 360 medium effect size (0.64).

- 361
- 362

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

			Difference Between	RI and NRI on ACLR sig	de - D
Variable	Start	End	RI ACLR side (± SD)	95% CI	1
Knee Flexion Angle (º)	9	22	52.7 (9.7)	49.0 to 56.4	
COM to Apkle 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	
		Di	fference Between RI and	NRI Cohort on ACLR sig	de - F
	0	12	-11.1 (60.3)	-34.1 to 11.8	
COM to Knee Posterior (mm)	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

-			Differ	ence Between RI and	NRI Cohort on ACLR side - Ur
-	Anterior Pelvic Tilt (º)	42	90	2.1 (7.0)	-0.7 to 4.8
L	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; I	BH - body hei	ght; CoD - ch	ange of direction; COM – centr	re of mass
	Differences in asymmetry between the two	o groups a	are report	ed in Table 6 and Fig	gure 4. No
1	significant differences in asymmetry were	detected	in the dou	uble leg drop jump, s	ingle leg
(drop jump and planned CoD. In the unplan	nned CoD	significa	nt differences in asy	mmetry
i	indicated that the RI group were more asyn	nmetrica	l for CON	I to knee (76%–90%	; d = 0.69
i	and ankle $(12\%-23\%; d = 0.62)$, with the (COM mo	re contral	ateral (medial) to the	knee on
1	the ACLR side. The trunk-pelvis side flexi	on angle	was more	e asymmetrical in the	RI group
	(73%-100%; d = 0.68) towards the end of	the stance	e phase. T	There also was greate	er
i	asymmetry in anterior pelvic tilt in the RI	group (28	3%–99%;	d = 0.69), with less a	anterior
]	pelvic tilt on the ACLR side, as well as gre	eater asyn	nmetry in	pelvic drop (9%–36	%; d =
(0.61), with more pelvic drop during early s	stance on	the ACL	R side. The predictio	n model for
1	symmetry of biomechanical variables during	ng unplar	nned CoD	selected COM to kn	ee in frontal
]	plane, pelvic drop and trunk-pelvis side fle	exion for	inclusion	and could predict A	CL re-injury
,	with an accuracy of 67.7% (baseline: 59.79	%), sensit	tivity of 0	0.65 and specificity of	f 0.72
	(AUC: 0.75).				



- 382
- 383 Figure 4. Biomechanical variables with greater asymmetry during the unplanned CoD in the RI group compared
- 384 to NRI group illustrating greater asymmetry of trunk side flexion, distance from COM to knee and ankle in
- 385 frontal plane, pelvic tilt and pelvic drop in the RI group.
- 386
- 387 Table 6 Biomechanical differences between limbs between the RI and NRI groups

	Diffe	rence Be	etween Limbs Between RI	and NRI Cohort on A	CLR sic
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	

389 ACLR - anterior cruciate ligament reconstruction; RI - re-injury group; NRI - no re-injury group; ASYM - asymmetry; CI - confidence

390 interval; IPSI - ipsilateral; SD - standard deviation; CoD - change of direction; COM - centre of mass

391 **Discussion**

392 Return to play criteria are used to determine rehabilitation status and re-injury risk after 393 ACLR and frequently assess PRO, strength and jump/hop and CoD performance measures 394 but movement (biomechanical) analysis is commonly absent. This study aimed to 395 prospectively examine these combination of measures in a large cohort of male field sport 396 athletes. This study identified differences in biomechanical measures between those who 397 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 398 399 strength, jump, and CoD timed performance measures, both individually and combined. 400 Biomechanical variables from individual jump and CoD tests demonstrated limited 401 predicative ability but highlight variables that could be targeted during rehabilitation and 402 RTP decision-making and could be considered in future injury prediction models.

403

404 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

410

411 *Performance Measures*

There was no difference between ACLR limbs or in LSI for isokinetic strength of thequadriceps or hamstrings, jump height/length or CoD times individually or collectively

414 between RI and NRI groups. There was also no difference in >90% LSI success rates for all

415 variables, with the exception of hamstring strength testing (p = 0.022). This difference in

416 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% 417 LSI success rates of all tests combined, there was a lower odds of being in the NRI group 418 419 (0.49) but the confidence intervals were wide (0.03 to 8.15). This differs from previous 420 findings from Kyritsis et al., who reported a 4-fold increase in re-injury risk after ACLR in 421 those not achieving >90% LSI across strength, jump, and CoD tests. Both RI and NRI groups 422 demonstrated ongoing deficits relating to <90% LSI threshold at the time of testing, 423 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 424 demonstrated despite athletes passing >90% LSI criteria during jump and CoD tests.^{14, 15} 425 426 These results suggest that previously used performance measures of stre²¹ngth, jump, and 427 CoD performance, on the ACLR side on in measures of symmetry (LSI), may not be 428 sufficient to identify physical deficits that may influence risk of ACL re-injury. Additional 429 factors may need to be considered during RTP assessment or decision-making.

430

431 Biomechanical Analysis

There were some biomechanical differences on the ACLR side and in symmetry between 432 433 limbs between RI and NRI groups. In the double leg drop jump, there was increased knee 434 flexion, lower vertical COM height to the ankle, and longer ground contact times on the 435 ACLR side for those who experienced ACL re-injury. This suggests the RI group required 436 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 437 438 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 439 440 of planned and unplanned CoD on the ACLR side between groups demonstrated the COM

441 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 442 method to reduce the knee extension moment required during landing and deceleration $^{31, 32}$ 443 and knee valgus moment during CoD.¹⁰ Combined with variables identified in the double leg 444 drop jump, it may reflect a difference in the ability to absorb load in the sagittal plane in 445 446 those who re-injure their ACL. However, given the number of biomechanical variables 447 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) 448 449 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} 450 This difference in findings may be due to previous analysis being mostly in female athletes, 451 452 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 453 ipsilateral and contralateral injuries together during analysis, which may have influenced 454 outcomes.11, 34, 35 455

456

CoD tests revealed differences of symmetry in biomechanical measures between groups. In 457 the unplanned CoD, there was greater between-limb difference for distance between the 458 459 COM and knee and ankle in the frontal plane in the RI group, with distance greater (more 460 medial) on the ACLR side. Greater step width has been suggested as a potential mechanism 461 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 462 463 variation in asymmetry in these variables in both groups which may be in part due to group 464 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 465

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}

470

471 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 472 473 CoD movements can enhance assessment of rehabilitation status to reduce ACL re-injury risk 474 on RTP after ACLR. Biomechanical differences between groups were found despite no 475 differences in commonly used isokinetic peak torque strength, jump, and CoD performance measures, highlighting the potential importance of examining performance and 476 biomechanical measures after ACLR.^{14, 15} Biomechanical variables for the double leg drop 477 478 jump and unplanned CoD demonstrated poor predictive ability to identify those who would 479 re-injure their ACL. Differences between those with re-injury and those without were related 480 to the ability to absorb load during double leg drop jump and frontal plane control during 481 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 482 who will go on to re-injure.³ The results of this study suggest that biomechanical variables 483 484 during both jump and CoD testing may play an important role in those who will experience 485 ACL re-injury on return to high-demand multidirectional sports and may offer more relevant 486 information than the common strength and jump score tests previously used in isolation.

487

488 Limitations and Future Directions

489 Although ACL re-injury was tracked prospectively on a large number of participants,

490 biomechanical data were not available on 7/38 subjects (18%) which may bias the results. As

491 there is little research on prospective risk factors for ACL re-injury in male athletes, this 492 study examined a large number of variables and tests. This increases the risk of type 1 error, 493 although we offset this risk by setting a medium effect size threshold and only reporting 494 variables with sufficient magnitude differences. Further, we only included male athletes, so 495 future research should carry out similar analyses in female athletic populations to identify 496 risk factors specific to that cohort and potential differences in risk factors for male and female 497 athletes for ACL re-injury after ACLR. In addition, those identified biomechanical variables 498 demonstrated limited predictive ability and have large variability in some cases. Predictive 499 accuracy may be improved by using non-linear models, exploring alternative biomechanical 500 measures including variability and co-ordination and including additional data that have been 501 reported to influence ACL re-injury, such as demographic surgical and radiological data, to 502 build a comprehensive model of factors influencing second ACL injury risk.

503

504 Conclusion

505 This large prospective study examined differences in both performance and biomechanical 506 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 507 508 commonly used strength and performance measures at 9 month follow up. Findings 509 demonstrate differences in biomechanical variables in the sagittal plane on ACLR side during 510 double leg drop jump and symmetry of frontal plane control during unplanned CoD with poor 511 predictive ability. Targeting these variables during ACL rehabilitation may reduce the risk of 512 re-injury. Future research should combine biomechanical, surgical, and demographic data to 513 determine if these factors are involved in ACL re-injury.

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