Section II: Biomechanics and Motor Control

Movement strategy correspondence across jumping and cutting tasks after anterior cruciate ligament reconstruction

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1 **ABSTRACT**

2 There are currently a multitude of tests used to assess readiness to return to sport (RTS) following

3 anterior cruciate ligament reconstruction (ACLR). The aim of this study was to establish the extent to

4 which movement strategies transfer between three common assessment tasks to help improve design of

5 athlete testing batteries following ACLR. A cohort of 127 male patients 8-10months post-ACLR and

6 45 non-injured controls took part in the study. Three movement tasks were completed (unilateral and

7 bilateral drop jump, and 90° pre-planned cut), while ground reaction forces and three-dimensional

8 kinematics (250 Hz) were recorded. Compared to the bilateral drop jump and cut, the unilateral drop

9 jump had a higher proportion of work done at the ankle (d=0.29, $P<0.001$ and d=-1.87, $P<0.001$,

10 respectively), and a lower proportion of work done at the knee during the braking phase of the task

11 (d=0.447, $P<0.001$ and d=1.56, $P<0.001$, respectively). The ACLR group had higher peak hip moments

12 than the non-injured controls, although the proportion of work done at the ankle, knee and hip joints

13 were similar. Movement strategies were moderately and positively related at the ankle ($r_s=0.728$,

14 $P<0.001$), knee ($r_s=0.638$, $P<0.001$) and hip ($r_s=0.593$, $P<0.001$) between the unilateral and bilateral

15 drop jump, but there was no relationship at the ankle ($r_s=0.10$, $P=0.104$), knee ($r_s=0.106$, $P=0.166$) and

16 hip ($r_s=-0.019$, $P=0.808$) between the unilateral drop jump and the cut. Clinicians could therefore

17 consider omitting one of the drop jumps from assessment batteries but should include both jumping and

18 cutting tasks.

19 **K E Y W O R D S**

INTRODUCTION

Rupture of the anterior cruciate ligament (ACL) is one of the most debilitating injuries within landing, cutting and jumping-based sports[1-3]. The primary function of the ACL, particularly during landing and cutting manoeuvres, is to prevent anterior translation of the tibia relative to the femur[4]. The majority of ACL ruptures have been found to occur during non-contact events[5 6], specifically during unilateral landings, which involve sudden decelerations such as landing from a jump or planting the foot during a cutting manoeuvre[7 8]. The braking phase after initial contact with the ground is highlighted as a key phase to examine possible risk factors and mechanisms responsible for non-contact ACL injuries[5 9]. During the braking phase of unilateral stop-jump tasks, higher knee extension moments result in increased proximal tibia anterior shear forces[10]. Consequently, the use of tests to assess neuromuscular control during the braking phase to measure progress and inform the rehabilitation process prior to return to sport (RTS) is recommended[11]. However, there are currently a multitude of functional tests used to assess readiness to RTS following ACL reconstruction (ACLR) with little understanding of how the movement strategies employed by individuals change in each test. This makes it difficult for clinicians to determine the optimal testing battery to inform the readiness of patients to RTS post-ACLR.

Anterior cruciate ligament reconstruction surgery is typically followed by an extensive course of rehabilitation to restore the function of the knee. However, persistent neuromuscular alterations in lower limb joint kinetics may be observed among athletes who have undergone ACLR, which may contribute to an increase in ACL re-injury risk[12]. Negative work is performed by the lower extremity muscles to dissipate the kinetic energy gained from the descent during landing[13]. Following ACLR, lower sagittal plane energy absorption and moments at the ankle and knee, and higher sagittal plane hip moments have been reported compared to healthy controls for a bilateral vertical drop jump[14]. Differences in sagittal plane lower limb joint mechanics during drop jump tasks, in male participants, have been shown to be an important factor to distinguish between those who were likely to sustain a secondary injury following ACLR, and to those that were not [15]. The distribution of mechanical work, as well as joint moments, between the lower limb joints can be used to characterise an athlete's movement strategy for the task[13], and therefore provides an opportunity to investigate the loading strategies employed when absorbing the energy of landing across different tasks and joints. The movement strategy employed can be used to quantify an athlete's rehabilitation response when undertaking jumping, landing and cutting tasks. For example, Decker and colleagues[16] reported that while the knee contributed the greatest proportion of work done during a bilateral landing task for both ACLR patients and healthy controls, ACLR patients performed 39% less hip extensor work and 37% more plantar-flexor work than healthy controls. This may indicate that either the lower extremity compensates following ACLR to protect the involved limb or that insufficient rehabilitation has been undertaken.

57 As females are at higher risk of ACL injury than males the majority of literature has focussed on the

58 female athlete[17]. However, the incidence of ACL injuries is also high in males [18], and will possibly

59 affect more male than female athletes due to the high overall number of male athletes. Understanding

60 movement strategies employed following rehabilitation in male ACLR athletes therefore warrants

61 attention. Bilateral and unilateral tasks have been used to quantify movement strategies post ACLR in

62 order to assess the effectiveness of the rehabilitation programme. A recent study on unilateral tasks in

63 healthy male participants found that the ankle, knee and hip joints contributed similar proportions of

64 work done when landing a vertical hop (~33% each), whilst the knee joint contributed the highest

65 proportion of work done (~65%), followed by the hip and then the ankle (~24% and ~11%, respectively)

66 when landing a horizontal hop[19]. This may also be the case for a cutting manoeuvre, which has shown

67 a similar knee dominant strategy being present[20]. However, there is currently no evidence to suggest

68 whether these same movement strategies are present following ACLR. Additionally, the same task

69 performed bilaterally appears to show a different movement strategy is employed than when it is

70 performed unilaterally. For example, Yeow et al.[21] reported substantial increases in hip extensor and

71 ankle plantarflexor moments, as well as increases in proportions of work done at the hip and ankle joint

72 in a unilateral landing compared to those of a bilateral landing in healthy male participants. Furthermore,

73 in line with previous research, these authors showed that, unlike a unilateral landing, in the sagittal

74 plane the knee joint was the dominant energy dissipater during a bilateral landing [21 22]. Comparing

75 movement strategies in a selection of movement tasks typically included in post-ACLR RTS

76 assessments, in both post-ACLR and non-injured individuals, may improve the design of these

77 assessments by identifying task redundancies and hence increasing the efficiency of athlete testing, data

78 analysis and data interpretation.

79 A clearer understanding of the extent to which movement strategies transfer between bilateral and

80 unilateral tasks, and within different unilateral tasks, would help guide the design of athlete

81 biomechanical assessments and ACLR rehabilitation programme delivery. The first aim of this study

82 was to investigate the effect of task on movement strategy by examining differences in joint work

83 distribution when the same vertical drop jump task was performed bilaterally and unilaterally, and when

84 two different unilateral tasks (the unilateral drop jump and a 90° pre-planned cut) were performed. It

85 was hypothesised that the bilateral drop jump task and 90° pre-planned cut would display a knee

86 dominant strategy, whereas the unilateral drop jump would demonstrate a similar proportion of work

87 done between the ankle, knee and hip joints. A second aim was to examine the effect of group on

88 movement strategy by examining differences in joint work distribution between ACLR and non-injured

89 individuals. It was hypothesised that ACLR patients would demonstrate a reduced proportion of work

90 done at the knee, and increased proportion of work done at the hip and peak hip moments compared to

91 the non-injured controls. The final aim was to examine the level of correspondence in movement

92 strategies employed by ACLR and non-injured participants when performing a bilateral and unilateral

93 drop jump, and two different unilateral tasks (unilateral drop jump and 90° pre-planned cut). It was

94 hypothesised there would be a correlation in joint work distributions between the same task performed

95 bilaterally and unilaterally, but not between the two unilateral tasks.

96 **METHOD**

97 *Participants*

98 A total of 172 male participants between the ages of 18 and 35 years were recruited and each provided

99 written, informed consent prior to data collection to take part in the study. The ACLR group consisted

100 of 127 male participants (height: 1.81 ± 0.06 m; mass: 82.7 ± 9.3 kg) and the non-injured control group

101 consisted of 45 male participants (height: 1.82 ± 0.07 m; mass: 81.4 ± 7.8 kg). The control group were

102 matched to the ACLR cohort on limb dominance and were locally recruited from multidirectional field

103 sports teams. Ethical approval was obtained from the Sports Surgery Clinic, Dublin Hospital Ethics

104 committee.

105 To be included in the ACLR group, participants were required to be male multidirectional field sports

106 athletes, who stated an aim to return to their pre-injury level of sporting participation after surgery. All

107 participants underwent primary ACLR approximately 9 months before experimental testing (8-10

108 months inclusive). All participants underwent guided rehabilitation with their locally referred

109 physiotherapist and were reviewed by their orthopaedic surgeons at 2 weeks, 3 months, and 6-9 months

110 after surgery. Participants took part in a physical testing protocol at approximately 9 months post-

111 surgery as part of their final clinical review. All patients in the ACLR group had undergone either a

112 hamstring graft (semitendinosus and gracilis tendons) or a bone patellar tendon bone graft from the

113 ipsilateral side during surgery. Different graft types are expected to affect joint kinetics in the early and

114 mid-term postoperative phases, yet the difference in joint kinetics between graft types in the later phases

115 are negligible[23]. Participants in the non-injured control group were excluded if they had a previous

116 ACL injury, previous knee injury which required surgery, or a lower limb injury within 12 weeks of

117 testing.

118 *Experimental Procedure*

119 All testing took place at the Sports Surgery Clinic, Dublin. During one laboratory visit participants

120 undertook a standardised warmup: 2-minute jog, five body weight squats, two submaximal and three

121 maximal double-legged countermovement jumps. Participants then performed the following three

122 movement tasks (in order): a bilateral drop jump from 30 cm, a unilateral drop jump from 20 cm and a

123 90° pre-planned cut. The drop jumps and 90° pre-planned cut followed the protocols previously

124 described[24 25]. Briefly, during the drop jumps participants placed their hands on their hips and were

125 told to roll from the step and upon hitting the ground, to jump as high as they could, whilst spending as

126 little time as possible on the force plate. For the bilateral drop jump, participants began with their feet

127 approximately hip width apart and landed with one foot on each of the force plates[25]. For the pre-
128 planned cut, participants were required to start at a distance of 5 m from the force plates, run as quickly
129 as possible towards the force plates, cutting left or right whilst planting their contralateral foot on the
130 force plate, and then to accelerate away after changing direction[24]. The non-ACL reconstructed limb
131 or the dominant limb (the limb with which the participant stated that he could kick a ball the furthest
132 distance) were assessed first for each test for the ACLR patients and non-injured controls, respectively.
133 Participants completed two submaximal practice trials of each movement before test trials were
134 captured. A 30-second recovery was provided between trials. Three valid attempts (maximal effort and
135 full foot contact on force platform) were recorded for each limb.

136 *Biomechanical data*

137 All kinetic and kinematic data were collected using an eight-camera motion analysis system (200 Hz;
138 Vicon Motion Systems Ltd, Oxford, UK), synchronised with two force platforms (1000 Hz; BP400600,
139 AMTI, USA) recording 24 reflective markers (14-mm diameter) and ground reaction forces (Vicon
140 2.10.0, Oxford Metrics, UK), respectively. Participants wore their own athletic footwear and non-
141 invasive reflective markers were secured to the shoe and skin with tape based on a modified Plug-in-
142 Gait marker set[26]. The Plug-in-Gait model was used to determine kinematics and kinetics, and the
143 chord function (Vicon 2.10.0, Oxford Metrics, UK) was used to define joint centres. Only data collected
144 from the braking phase, and from the operated limb of the ACLR group were analysed. The braking
145 phase was defined as the time between initial contact (determined by the instant when the vertical
146 ground reaction force exceeded a threshold of 20 N[22]) to the frame preceding the lowest vertical
147 centre of mass (CoM) displacement. All data was processed using Vicon Nexus Software (Vicon 2.10.0,
148 Oxford Metrics, UK). Motion and force data were low-pass filtered using a fourth order zero-lag
149 Butterworth filter with a cut-off frequency of 15 Hz. Standard inverse dynamics was used to calculate
150 joint moments (reported as internal moments) at the ankle, knee and hip joints in all three planes, and
151 the instantaneous body CoM position was estimated based on segment inertial properties. Positive
152 sagittal plane internal joint moments relate to ankle plantarflexion, knee extension and hip extension.
153 All variables were calculated relative to body mass. Kinematic and kinetic analyses were carried out
154 for the first landing in the bilateral and unilateral drop jumps, and for the 90° pre-planned cut in
155 MATLAB (R2019b; MathWork, Inc, USA). Joint power was calculated to be the product of joint
156 moment and joint angular velocity. Joint work was computed as the integral of joint power over time,
157 in which negative work represented energy dissipation. The relative contribution of the hip, knee and
158 ankle work to total lower extremity joint work in the sagittal plane was calculated. Trials were excluded
159 from analysis when there was missing or invalid kinematic (missing marker) or kinetic (full contact on
160 force plate not made) data. All variables were expressed relative to body mass.

161 *Statistical Analysis*

162   Means of all three trials for each participant were computed. All data are reported as mean (M) ±

163   standard deviation (SD). Relationships and differences were investigated between the unilateral and

164   bilateral drop jump as a comparison between the same task, and between the cut and the unilateral drop

165   jump as two different unilateral tasks. For statistical analysis the Kolmogorov-Smirnov test was used

166   to test normality for all variables in each condition between groups. A Mann-Whitney test was

167   performed for independent groups on variables which were not normal, whilst a Wilcoxon test was

168   performed for dependent groups on variables which were not normal. A two-way mixed ANOVA was

169   performed on the variables which satisfied the normality and homogeneity of variance assumptions to

170   identify interactions, task effects or group effects. For significant interactions, follow up t-tests were

171   conducted on all four simple main effects. Due to the non-normality of data Spearman's correlations

172   were run to determine the relationship between the bilateral and unilateral tasks, and the two unilateral

173   tasks for proportion of work done at the ankle, knee and hip joints, and reported as negligible ($r_s < 0.3$),

174   weak ($0.3 < r_s < 0.5$), moderate ($0.5 < r_s < 0.7$), strong ($r_s > 0.7$)[27]. Cohen's *d* standardised effect size

175   was calculated and interpreted as small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$)[28]. Statistical

176   analysis was performed using SPSS Statistics (SPSS 27, IBM, Hampshire, UK). The level of

177   significance was set at $P \leq 0.05$.

178   **RESULTS**

179   **Bilateral and unilateral leg drop jump**

180   In the unilateral drop jump a higher proportion of work done was recorded at the ankle ($d=0.29$,

181    $P<0.001$) and hip ($d=0.59$, $P<0.001$) joints, and a lower proportion of work done was observed at the

182   knee ($d=0.447$, $P<0.001$) compared to the bilateral drop jump (Figure 1).

183   The unilateral drop jump recorded higher peak ankle ($d=0.90$, $P<0.001$) and hip moments ($d=-1.11$,

184    $P<0.001$) compared to the bilateral drop jump. Results revealed interactions for peak knee moment

185   between the tasks (see Table 1 for *M* and *SD's* and Table 2 for a summary of the two-way ANOVA).

186   Post-hoc T-tests showed a higher peak knee moment in the unilateral as opposed to the bilateral drop

187   jump for the ACLR group ($d=-0.22$, $P<0.001$), whilst the bilateral compared to the unilateral drop jump

188   recorded higher peak knee moments for the non-injured controls ($d=0.28$, $P<0.001$). Higher peak knee

189   moments were found in the non-injured controls for both the unilateral ($d=0.49$, $P=0.01$) and bilateral

190   ($d=0.10$, $P<0.001$) drop jump compared to the ACLR group.

191   ***FIGURE 1 HERE***

192   ***TABLE 1 HERE***

193   ***TABLE 2 HERE***

194 There was a moderate, positive correlation between the bilateral and unilateral drop jumps for the
195 proportion of work done at the ankle (r_s=0.728, P<0.001), knee (r_s=0.638, P<0.001) and hip (r_s=0.593,
196 P<0.001) joints (Figure 2a-c).

197 ***FIGURE 2 HERE***

198 Proportion of work done at the ankle, knee and hip joints, and peak ankle moment were similar between
199 groups (Figure 1). The ACLR group produced higher peak hip moments (d=0.47, P<0.001) than the
200 non-injured controls.

201 **Unilateral drop jump and cut**

202 The unilateral drop jump had a higher proportion of work done at the ankle (d=-1.87, P<0.001), and
203 lower proportions of work done at the knee (d=1.56, P<0.001) and hip (d=0.49, P<0.001) compared to
204 the cut. The cut had higher peak knee and hip moments and lower peak ankle moments than the
205 unilateral drop jump (see Table 3 and Table 4).

206 ***TABLE 3 HERE***

207 ***TABLE 4 HERE***

208 There was no correlation between the unilateral drop jump and the cut at the ankle (r_s=0.10, P=0.104),
209 knee (r_s=0.106, P=0.166) or hip (r_s=-0.019, P=0.808) joints (Figure 2d-f).

210 The ACLR group had lower peak knee moments (d=0.50, P=0.001), and higher peak hip moments (d=-
211 0.21, P=0.011) than the non-injured controls. However, peak ankle moment and proportion of work
212 done were similar between groups (see Table 3 and Table 5).

213 ***TABLE 5 HERE***

214 **DISCUSSION**

215 In support of our first hypothesis, the unilateral drop jump produced a higher proportion of work done
216 at the ankle, and lower proportion of work done at the knee compared to the cut and the bilateral drop
217 jump. A second aim was to examine the effect of group on movement strategy by examining differences
218 in joint work distribution between ACLR and non-injured individuals. The ACLR patients and non-
219 injured controls produced similar proportions of work done at the ankle, knee and hip joints, yet ACLR
220 patients produced higher peak hip moments compared to the non-injured controls. Our final aim
221 examined the level of correspondence between movement strategies employed by ACLR and non-
222 injured controls when the same vertical task was performed bilaterally and unilaterally, and when two
223 different unilateral tasks were performed. There was a moderate, positive correlation between the
224 unilateral and bilateral drop jump, but not between the unilateral drop jump and the cut.

225 Classified according to highest proportions of work done at respective joints, an ankle dominant strategy
226 was utilised for both drop jump tasks, whereas a knee dominant strategy was displayed during the cut.
227 An ankle dominant strategy has been associated with increased ankle plantarflexion via active
228 musculature contractions about the ankle, which may reduce the load on this joint[29]. It has been
229 suggested that increased ankle plantarflexion lessens the demand of muscular contractions about
230 proximal joints, thus there is decreased energy dissipation at the hip[29 30]. Compared to the bilateral
231 drop jump, the unilateral drop jump had a higher proportion of work done and peak internal
232 plantarflexion moment at the ankle, and a lower proportion of work done at the knee. In line with
233 previous research, these findings emphasise that the knee is used to a greater extent to dissipate impact
234 energy in the bilateral drop jump[31-33], whilst the ankle joint is utilised to a greater extent during the
235 unilateral drop jump[21]. Furthermore, the cut recorded higher peak internal knee extensor moments
236 and proportion of work done at the knee compared to the unilateral drop jump. In order to resist rapid
237 joint flexion by impact forces during landing, the lower extremity extensor muscles must use internally
238 generated extensor moments[32]. An internal extensor moment at the knee is produced by a quadriceps
239 contraction, which has been suggested as the primary contributor to anterior tibial shear force[34]. The
240 increased mechanical demand placed on the knee during the cut compared to the unilateral drop jump
241 shows that the cut requires greater quadriceps strength, thus potentially loading the knee to a greater
242 extent during rehabilitation.

243 In all movement tasks, the ACLR and non-injured groups had similar inter-joint work distribution but
244 different peak moments. Higher internal peak hip extensor moments and lower internal peak knee
245 extensor moments in ACLR patients compared to the non-injured group may indicate that the ACLR
246 patients have adopted a movement strategy to utilise the hip musculature to a greater extent, potentially
247 to reduce loads on the reconstructed knee[35]. The hamstring muscles act to flex the knee and extend
248 the hip[36] and a greater internal hip extensor moment denotes an increase or maintenance of hamstrings
249 muscle contraction demand. During landing, the hip extensors, in particular the gluteus maximus, work
250 eccentrically to control the femur in all three cardinal planes by decreasing the rate of hip flexion and
251 stabilising femoral adduction and internal rotation[37]. During early rehabilitation stages these slight
252 changes in movement strategy may have been consciously or subconsciously adopted to protect the
253 injured knee, and most likely represent the commonly observed knee extension strength deficits and
254 reduced capacity to produce knee extension forces, indicating that it may take longer than 9 months
255 post-ACLR to re-programme the neuromuscular system[38]. Unloading of the knee could potentially
256 be due to psychological and/or mechanical factors, thus this supports the notion that time elapsed since
257 surgery alone does not reflect the condition of the knee, and rehabilitation may still be ongoing at nine
258 months post-ACLR.

259   A moderate, positive correlation was observed between the unilateral and bilateral drop jump for
260   proportion of work done at the ankle, knee and hip joints. However, there was no correlation in the
261   proportion of work done at the ankle, knee and hip joints between the unilateral drop jump and the cut.
262   Nigg et al. [39] proposed the 'preferred movement path' concept, which may help to explain these
263   findings. The 'preferred movement path' suggests that for a given task, muscle activity ensures the
264   skeleton of an individual stays in the same movement path, however, the amplitude of this path may
265   vary depending on the differing levels of demands of the task[39]. An extension of this theory may also
266   apply on an individual level given that when the same task (drop jump) was performed bilaterally and
267   unilaterally, individuals employed the same preferred movement strategy. Conversely, both the
268   unilateral drop jump and the change-of-direction step of the cutting task are unilateral movements but
269   the different constraints, performance criteria and coordination demands of the two tasks gave rise to a
270   lack of movement strategy correspondence. Based on individuals employing similar movement
271   strategies for each type of drop jump, clinicians could consider omitting one of the drop jumps from
272   assessments if using them to help inform readiness to RTS after ACLR. Compared to both bilateral and
273   unilateral drop jumps, the unique insight gained from assessing movement strategies during a 90° pre-
274   planned cut supports the separate inclusion of this movement task in post-ACLR RTS assessments.

275   A limitation of this study is that unlike a pre-planned cut, during games cutting manoeuvres often
276   involve unanticipated movements to quickly react to external stimuli, for example avoiding another
277   player[40]. It has been proposed that a knee dominant strategy is employed in tasks that do not allow
278   an athlete to pre-plan their movement strategy[41]. Subsequently, movement strategies employed
279   during a pre-planned cut may not wholly represent those used during matches, hence it would be
280   recommended that future studies also examine unanticipated cuts. Another limitation is sex bias as only
281   males were recruited for the study. Female athletes are two to eight times more likely to tear their ACL
282   than males due to differences in intrinsic risk factors compared to their male counterparts, including but
283   not limited to anatomical differences and hormones[42]. Therefore, it would be beneficial for future
284   studies to investigate female responses during these movement tasks. As this study only examined the
285   sagittal plane, it would not be appropriate to use these findings to comment upon the effect of group or
286   task on movement strategy when examining differences in joint work distribution or moments in any
287   other plane. Future cross-sectional studies could consider non-sagittal plane joint work using marker
288   set-ups that are valid and reliable in these planes, alongside muscle strength and electromyography
289   (EMG) data. Such studies may provide valuable insights into neuromuscular control during jumps and
290   cutting manoeuvres following ACLR. Finally, the rate at which ACLR athletes returned to playing sport
291   was also not assessed. Longitudinal monitoring of ACLR athletes with an increased number of repeated
292   assessments may have been beneficial to understand whether specific movement strategies are present
293   following ACLR that are not detrimental to participating at the same sporting level prior to injury.

Perspectives

Our findings indicate a movement strategy correspondence between the bilateral and unilateral drop jump, but not between the unilateral drop jump and the cut. The bilateral and unilateral drop jump both demonstrated an ankle dominant strategy, whilst a knee dominant strategy was utilised in the cut. Due to a similar preferred movement strategy being present during bilateral and unilateral drop jumps, when assessing movement strategies following ACLR, clinicians could consider omitting one of the drop jumps from assessment batteries to avoid task redundancy. However, the 90° pre-planned cut should be included as this provides additional information using a sport-specific movement frequently encountered in training and matches. A between-group comparison found that ACLR patients adopted a knee avoidance strategy, using the hip musculature to a greater extent and reducing knee extensor muscle requirements to potentially reduce load on the reconstructed knee. Further studies are needed to understand whether the differences present are a safety mechanism employed to reduce the risk of re-injury of the ACL, or a compensatory strategy that may increase the risk of injury. Findings from this work may help improve the delivery of assessments to help inform readiness to RTS following ACLR by reducing the amount of data clinicians will need to analyse and decreasing the number of different tests athletes need to complete.

Acknowledgments

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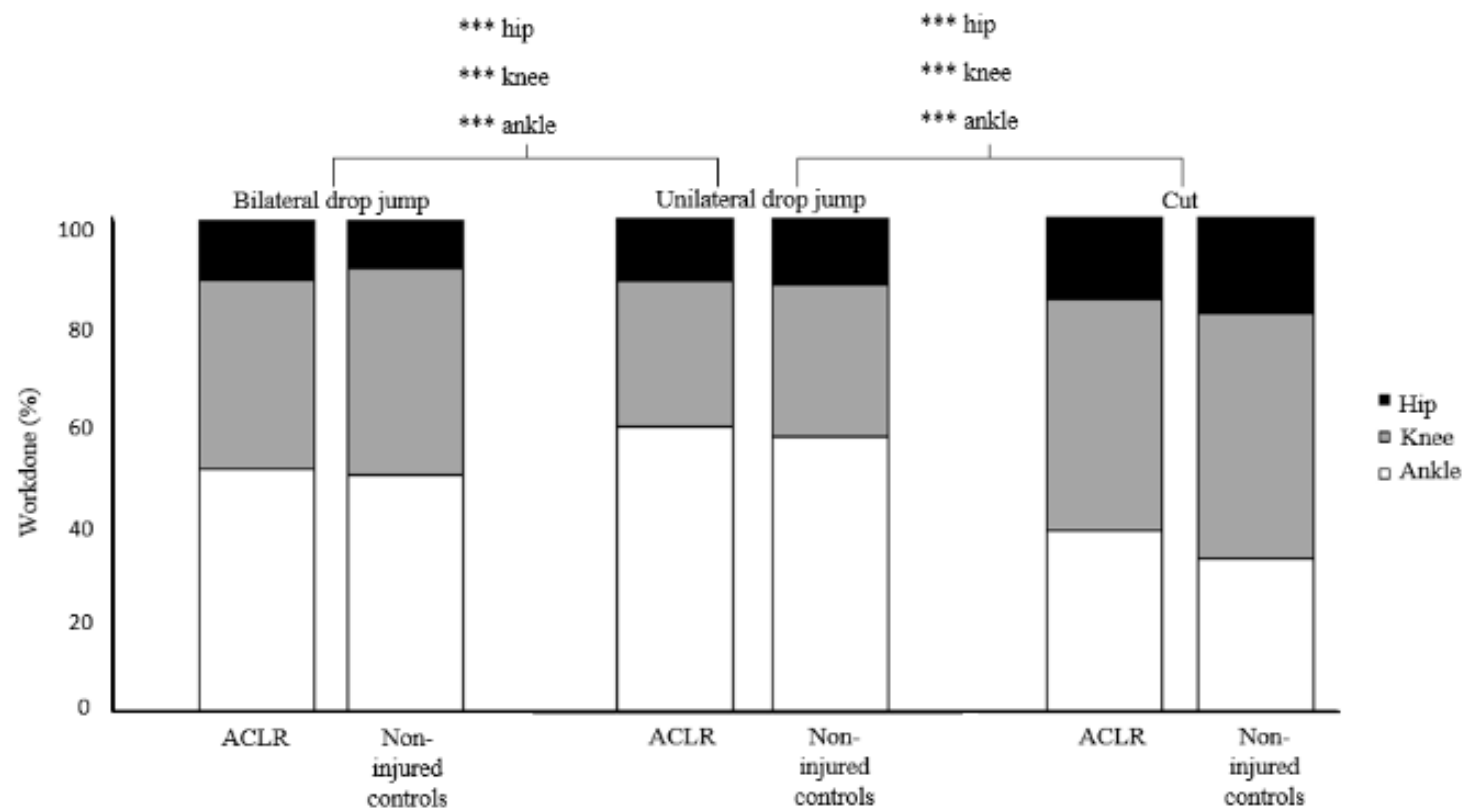424   2016;**13**(2):A1-A4

425

Figure 1. Proportion of work done at the ankle, knee and hip for ACLR patients and non-injured controls in the bilateral and unilateral drop jump, and the cut. White bars represent the ankle, grey bars represent the knee and black bars represent the hip.***$P \leq 0.001$
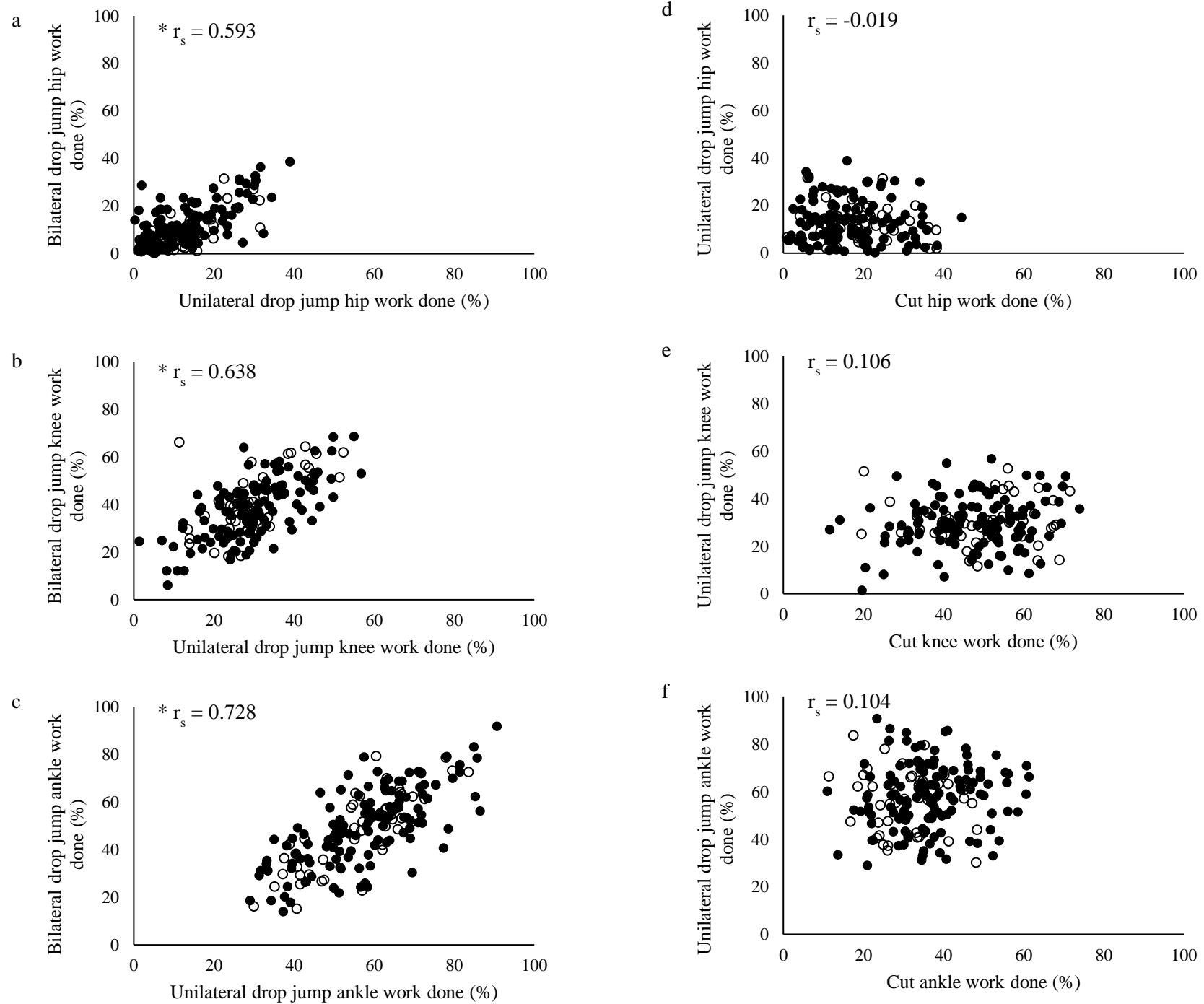
Figure 2. Correlation of proportion of work done between the unilateral and bilateral drop jump and between the cut and the unilateral drop jump at the (a and d, respectively) hip, (b and e, respectively) knee, and (c and f, respectively) ankle. *$P \leq 0.05$. Black dots represent ACLR cohort. White dots represent healthy cohort.

Table 1. Means (SD) of the biomechanical measures for each condition per group

Variable	Group	Cut	Unilateral drop jump	Bilateral drop jump
Peak hip moment ((N.m)/kg)	ACLR	-3.94 (0.95)	-3.34 (0.81)	-2.50 (0.69)
	Non-injured controls	-3.98 (1.08)	-2.89 (0.61)	-2.18 (0.56)
Peak knee moment ((N.m)/kg)	ACLR	-2.52 (0.67)	-2.35 (0.60)	-2.22 (0.58)
	Non-injured controls	-2.86 (0.59)	-2.65 (0.67)	-2.83 (0.59)
Peak ankle moment ((N.m)/kg)	ACLR	-2.07 (0.44)	-3.21 (0.68)	-2.36 (0.77)
	Non-injured controls	-1.90 (0.50)	-3.33 (0.73)	-2.78 (0.84)
Hip work done (kJ/kg)	ACLR	0.00 (0.02)	-0.02 (0.02)	-0.02 (0.02)
	Non-injured controls	0.00 (0.02)	-0.02 (0.02)	-0.01 (0.01)
Knee work done (kJ/kg)	ACLR	-0.06 (0.02)	-0.05 (0.03)	-0.05 (0.03)
	Non-injured controls	-0.06 (0.03)	-0.06 (0.02)	-0.06 (0.03)
Ankle work done (kJ/kg)	ACLR	-0.04 (0.02)	-0.10 (0.02)	-0.07 (0.02)
	Non-injured controls	-0.04 (0.01)	-0.10 (0.02)	-0.07 (0.02)
Total work done (kJ/kg)	ACLR	-0.10 (0.04)	-0.17 (0.04)	-0.14 (0.04)
	Non-injured controls	-0.09 (0.04)	-0.18 (0.03)	-0.15 (0.03)

Table 2. Summary of two-way mixed ANOVA (2x2; Condition x Group) results for each dependent variable (unilateral and bilateral drop jump)

Measure	Effect	F-value	p-value	η_p^2	Cohen's d	Follow up t-test for interaction
Peak knee moment	Interaction	14.425	**<0.001**	0.078	1. 0.486	1. **0.01**
	Task	0.305	0.582	0.002	2. 1.040	2. **0.001**
	Group	21.930	**<0.001**	0.114	3. -0.220	3. **<0.001**
					4. 0.280	4. **<0.001**
Peak ankle moment	Interaction	0.805	0.371	0.005	-	**-**
	Task	1466.183	**<0.001**	0.896	-1.023	**-**
	Group	0.145	0.704	0.001	0.322	**-**
Hip work done %	Interaction	2.656	0.105	0.015	-	**-**
	Task	243.838	**<0.001**	0.589	0.164	**-**
	Group	2.179	0.101	0.016	0.098	**-**
Knee work done %	Interaction	1.979	0.161	0.012	-	-
	Task	137.223	**<0.001**	0.447	-0.828	-
	Group	1.679	0.197	0.010	-0.188	-
Ankle work done %	Interaction	0.104	0.748	0.001	-	-
	Task	68.271	**<0.001**	0.287	0.544	-
	Group	0.387	0.535	0.002	0.097	-

Bold indicates $P \leq 0.05$. 1. Unilateral drop jump (ACLR vs non-injured controls) 2. Bilateral drop jump (ACLR vs non-injured controls) 3. ACLR (Unilateral vs bilateral) 4. Healthy (unilateral vs bilateral)

Table 3. Summary of two-way mixed ANOVA (2x2; Condition x Group) results for each dependent variable (Cut and unilateral drop jump)

Measure	Effect	F-value	p-value	η_p^2	Cohen's d	Follow up t-test for interaction
Peak knee moment	Interaction	0.032	0.654	0.001	-	-
	Task	14.850	**<0.001**	0.080	-0.275	-
	Group	10.645	**0.001**	0.059	0.504	-
Knee work done %	Interaction	0.407	0.524	0.002	-	-
	Task	119.113	**<0.001**	0.529	1.559	-
	Group	1.722	0.191	0.010	-0.135	-

Bold indicates $P \leq 0.05$.

Table 4. Summary of Wilcoxon results for Cut vs unilateral drop jump and unilateral vs bilateral drop jump (ACLR and non-injured control data combined)

Measure	Bilateral vs unilateral drop jump p-value	Z	Cohen's *d*	Unilateral drop jump vs cut p-value	Z	Cohen's *d*
Peak hip moment	**<0.001**	-10.495	-1.105	**<0.001**	-7.488	-0.825
Peak ankle moment	-	-	-	**<0.001**	-11.322	2.065
Hip work done %	-	-	-	**<0.001**	-4.172	0.494
Ankle work done %	-	-	-	**<0.001**	-10.791	-1.866

Bold indicates p ≤ 0.05

Table 5. Summary of Mann-Whitney results for ACLR vs non-injured controls (Cut and unilateral drop jump data combined, and unilateral and bilateral drop jump data combined)

Measure	ACLR vs non-injured controls (bilateral and unilateral drop jump) p-value	Mann-Whitney U	Cohen's *d*	ACLR vs non-injured controls (unilateral drop jump & cut) p-value	Mann-Whitney U	Cohen's *d*
Peak hip moment	**<0.001**	8454.5	-0.470	**0.011**	9372	-0.209
Peak ankle moment	-	-	-	0.666	11080.5	-0.026
Hip work done %	-	-	-	0.079	10008	-0.186
Ankle work done %	-	-	-	0.060	9903	0.225

Bold indicates p ≤ 0.05