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

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Funding: This study was supported by the Sports Surgery Clinic, Ireland, and Knowledge Economy Skills Scholarships 2 (KESS2) which is an All Wales higher level skills initiative led by Bangor University on behalf of the HE sectors in Wales. KESS2 is part funded by the Welsh Government's European Social Fund (ESF) competitiveness programme for East Wales.

Holly S.R. Jones: No conflict of interest.

Isabel S Moore: No conflict of interest.

Enda King: No conflict of interest.

Victoria Stiles: No conflict of interest.

Luca Laudani: No conflict of interest.

Molly McCarthy Ryan: No conflict of interest.

Ciarán McFadden: No conflict of interest.

Katherine A.J. Daniels: No conflict of interest.

ABSTRACT

There are currently a multitude of tests used to assess readiness to return to sport (RTS) following anterior cruciate ligament reconstruction (ACLR). The aim of this study was to establish the extent to which movement strategies transfer between three common assessment tasks to help improve design of athlete testing batteries following ACLR. A cohort of 127 male patients 8-10months post-ACLR and 45 non-injured controls took part in the study. Three movement tasks were completed (unilateral and bilateral drop jump, and 90° pre-planned cut), while ground reaction forces and three-dimensional kinematics (250 Hz) were recorded. Compared to the bilateral drop jump and cut, the unilateral drop jump had a higher proportion of work done at the ankle (d=0.29, $P<0.001$ and d=-1.87, $P<0.001$, respectively), and a lower proportion of work done at the knee during the braking phase of the task (d=0.447, $P<0.001$ and d=1.56, $P<0.001$, respectively). The ACLR group had higher peak hip moments than the non-injured controls, although the proportion of work done at the ankle, knee and hip joints were similar. Movement strategies were moderately and positively related at the ankle ($r_s=0.728$, $P<0.001$), knee ($r_s=0.638$, $P<0.001$) and hip ($r_s=0.593$, $P<0.001$) between the unilateral and bilateral 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 hip ($r_s=-0.019$, $P=0.808$) between the unilateral drop jump and the cut. Clinicians could therefore consider omitting one of the drop jumps from assessment batteries but should include both jumping and cutting tasks.

K E Y W O R D S

ACL, movement strategies, rehabilitation, mechanical work, RTS

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.

As females are at higher risk of ACL injury than males the majority of literature has focussed on the female athlete[17]. However, the incidence of ACL injuries is also high in males [18], and will possibly affect more male than female athletes due to the high overall number of male athletes. Understanding movement strategies employed following rehabilitation in male ACLR athletes therefore warrants attention. Bilateral and unilateral tasks have been used to quantify movement strategies post ACLR in order to assess the effectiveness of the rehabilitation programme. A recent study on unilateral tasks in healthy male participants found that the ankle, knee and hip joints contributed similar proportions of work done when landing a vertical hop (~33% each), whilst the knee joint contributed the highest proportion of work done (~65%), followed by the hip and then the ankle (~24% and ~11%, respectively) when landing a horizontal hop[19]. This may also be the case for a cutting manoeuvre, which has shown a similar knee dominant strategy being present[20]. However, there is currently no evidence to suggest whether these same movement strategies are present following ACLR. Additionally, the same task performed bilaterally appears to show a different movement strategy is employed than when it is performed unilaterally. For example, Yeow et al.[21] reported substantial increases in hip extensor and ankle plantarflexor moments, as well as increases in proportions of work done at the hip and ankle joint in a unilateral landing compared to those of a bilateral landing in healthy male participants. Furthermore, in line with previous research, these authors showed that, unlike a unilateral landing, in the sagittal plane the knee joint was the dominant energy dissipater during a bilateral landing [21 22]. Comparing movement strategies in a selection of movement tasks typically included in post-ACLR RTS assessments, in both post-ACLR and non-injured individuals, may improve the design of these assessments by identifying task redundancies and hence increasing the efficiency of athlete testing, data analysis and data interpretation.

A clearer understanding of the extent to which movement strategies transfer between bilateral and unilateral tasks, and within different unilateral tasks, would help guide the design of athlete biomechanical assessments and ACLR rehabilitation programme delivery. The first aim of this study was to investigate the effect of task on movement strategy by examining differences in joint work distribution when the same vertical drop jump task was performed bilaterally and unilaterally, and when two different unilateral tasks (the unilateral drop jump and a 90° pre-planned cut) were performed. It was hypothesised that the bilateral drop jump task and 90° pre-planned cut would display a knee dominant strategy, whereas the unilateral drop jump would demonstrate a similar proportion of work done between the ankle, knee and hip joints. A second aim was to examine the effect of group on movement strategy by examining differences in joint work distribution between ACLR and non-injured individuals. It was hypothesised that ACLR patients would demonstrate a reduced proportion of work done at the knee, and increased proportion of work done at the hip and peak hip moments compared to the non-injured controls. The final aim was to examine the level of correspondence in movement strategies employed by ACLR and non-injured participants when performing a bilateral and unilateral drop jump, and two different unilateral tasks (unilateral drop jump and 90° pre-planned cut). It was hypothesised there would be a correlation in joint work distributions between the same task performed bilaterally and unilaterally, but not between the two unilateral tasks.

METHOD

Participants

A total of 172 male participants between the ages of 18 and 35 years were recruited and each provided written, informed consent prior to data collection to take part in the study. The ACLR group consisted of 127 male participants (height: 1.81 ± 0.06 m; mass: 82.7 ± 9.3 kg) and the non-injured control group consisted of 45 male participants (height: 1.82 ± 0.07 m; mass: 81.4 ± 7.8 kg). The control group were matched to the ACLR cohort on limb dominance and were locally recruited from multidirectional field sports teams. Ethical approval was obtained from the Sports Surgery Clinic, Dublin Hospital Ethics committee.

To be included in the ACLR group, participants were required to be male multidirectional field sports athletes, who stated an aim to return to their pre-injury level of sporting participation after surgery. All participants underwent primary ACLR approximately 9 months before experimental testing (8-10 months inclusive). All participants underwent guided rehabilitation with their locally referred physiotherapist and were reviewed by their orthopaedic surgeons at 2 weeks, 3 months, and 6-9 months after surgery. Participants took part in a physical testing protocol at approximately 9 months post-surgery as part of their final clinical review. All patients in the ACLR group had undergone either a hamstring graft (semitendinosus and gracilis tendons) or a bone patellar tendon bone graft from the ipsilateral side during surgery. Different graft types are expected to affect joint kinetics in the early and mid-term postoperative phases, yet the difference in joint kinetics between graft types in the later phases are negligible[23]. Participants in the non-injured control group were excluded if they had a previous ACL injury, previous knee injury which required surgery, or a lower limb injury within 12 weeks of testing.

Experimental Procedure

All testing took place at the Sports Surgery Clinic, Dublin. During one laboratory visit participants undertook a standardised warmup: 2-minute jog, five body weight squats, two submaximal and three maximal double-legged countermovement jumps. Participants then performed the following three movement tasks (in order): a bilateral drop jump from 30 cm, a unilateral drop jump from 20 cm and a 90° pre-planned cut. The drop jumps and 90° pre-planned cut followed the protocols previously described[24 25]. Briefly, during the drop jumps participants placed their hands on their hips and were told to roll from the step and upon hitting the ground, to jump as high as they could, whilst spending as little time as possible on the force plate. For the bilateral drop jump, participants began with their feet approximately hip width apart and landed with one foot on each of the force plates[25]. For the pre-planned cut, participants were required to start at a distance of 5 m from the force plates, run as quickly as possible towards the force plates, cutting left or right whilst planting their contralateral foot on the force plate, and then to accelerate away after changing direction[24]. The non-ACL reconstructed limb or the dominant limb (the limb with which the participant stated that he could kick a ball the furthest distance) were assessed first for each test for the ACLR patients and non-injured controls, respectively. Participants completed two submaximal practice trials of each movement before test trials were captured. A 30-second recovery was provided between trials. Three valid attempts (maximal effort and full foot contact on force platform) were recorded for each limb.

Biomechanical data

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

Statistical Analysis

Means of all three trials for each participant were computed. All data are reported as mean (M) ± standard deviation (SD). Relationships and differences were investigated between the unilateral and bilateral drop jump as a comparison between the same task, and between the cut and the unilateral drop jump as two different unilateral tasks. For statistical analysis the Kolmogorov-Smirnov test was used to test normality for all variables in each condition between groups. A Mann-Whitney test was performed for independent groups on variables which were not normal, whilst a Wilcoxon test was performed for dependent groups on variables which were not normal. A two-way mixed ANOVA was performed on the variables which satisfied the normality and homogeneity of variance assumptions to identify interactions, task effects or group effects. For significant interactions, follow up t-tests were conducted on all four simple main effects. Due to the non-normality of data Spearman's correlations were run to determine the relationship between the bilateral and unilateral tasks, and the two unilateral tasks for proportion of work done at the ankle, knee and hip joints, and reported as negligible (r_s <0.3), 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 was calculated and interpreted as small (*d* = 0.2), medium (*d* = 0.5), and large (*d* = 0.8)[28]. Statistical analysis was performed using SPSS Statistics (SPSS 27, IBM, Hampshire, UK). The level of significance was set at *P*≤0.05.

RESULTS

Bilateral and unilateral leg drop jump

In the unilateral drop jump a higher proportion of work done was recorded at the ankle (*d*=0.29, *P*<0.001) and hip (*d*=0.59, *P*<0.001) joints, and a lower proportion of work done was observed at the knee (*d*=0.447, *P*<0.001) compared to the bilateral drop jump (Figure 1).

The unilateral drop jump recorded higher peak ankle (*d*=0.90, *P*<0.001) and hip moments (*d*=-1.11, *P*<0.001) compared to the bilateral drop jump. Results revealed interactions for peak knee moment between the tasks (see Table 1 for *M* and *SD's* and Table 2 for a summary of the two-way ANOVA). Post-hoc T-tests showed a higher peak knee moment in the unilateral as opposed to the bilateral drop jump for the ACLR group (*d*=-0.22, *P*<0.001), whilst the bilateral compared to the unilateral drop jump recorded higher peak knee moments for the non-injured controls (*d*=0.28, *P*<0.001). Higher peak knee moments were found in the non-injured controls for both the unilateral (*d*=0.49, *P*=0.01) and bilateral (*d*=0.10, *P*<0.001) drop jump compared to the ACLR group.

FIGURE 1 HERE

TABLE 1 HERE

TABLE 2 HERE

There was a moderate, positive correlation between the bilateral and unilateral drop jumps for the 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, *P*<0.001) joints (Figure 2a-c).

FIGURE 2 HERE

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

Unilateral drop jump and cut

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

TABLE 3 HERE

TABLE 4 HERE

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

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

TABLE 5 HERE

DISCUSSION

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

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

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

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

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

The authors would like to acknowledge the Biomechanics team at Sports Surgery Clinic for assistance with data collection and processing. The authors would also like to thank Dr Hans Von Lieres Und Wilkau and Ms Rebecca Straker for their critical comments on earlier versions of the manuscript.

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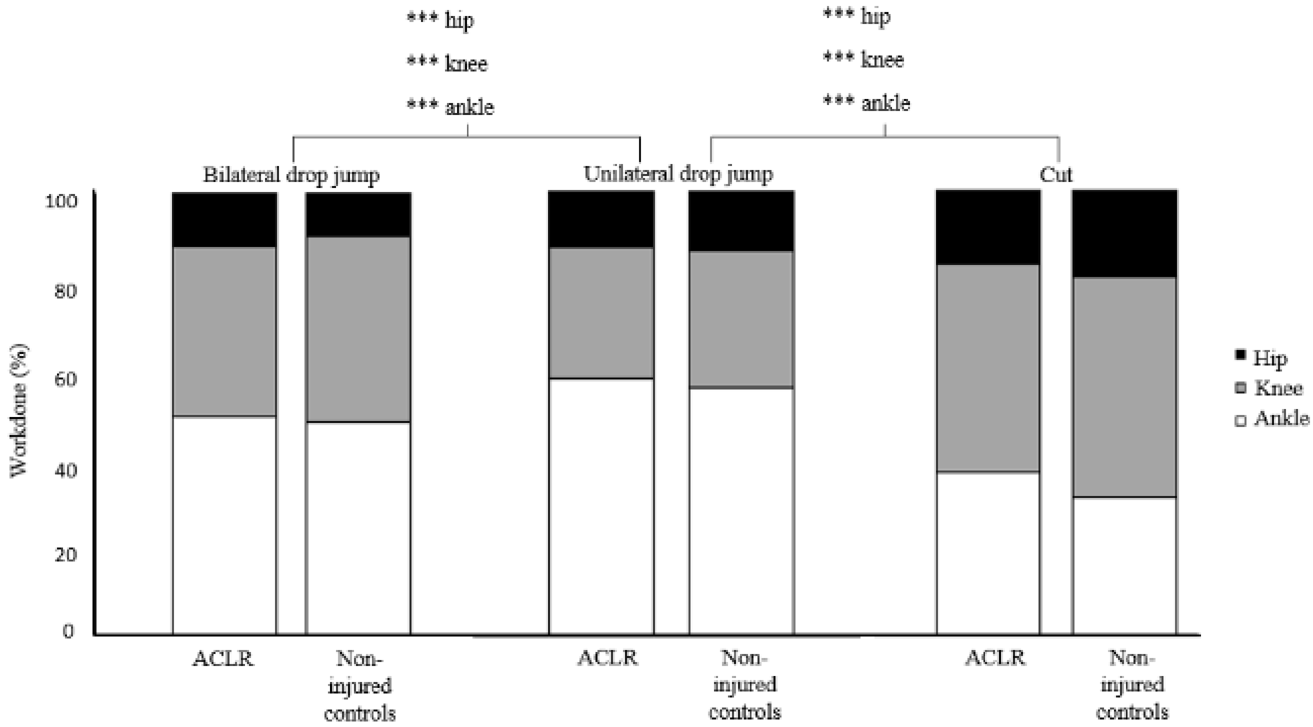

Figure 1. Proportion of work done at the ankle, knee and hip for ACLR patients and non-injured controls in the bilateral and unilateral drop jump, and the cut. White bars represent the ankle, grey bars represent the knee and black bars represent the hip.****P*≤0.001

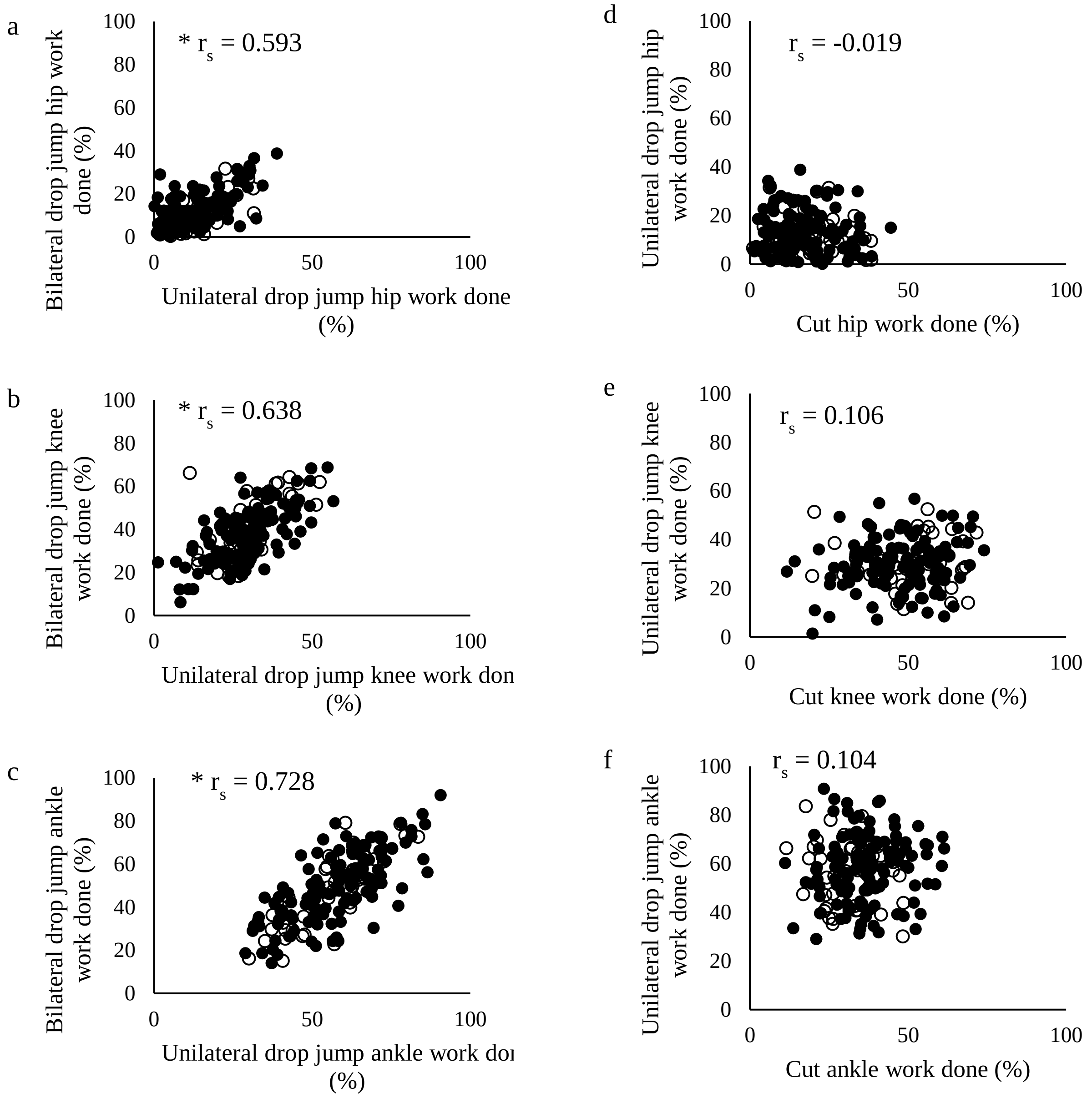

Figure 2. Correlation of proportion of work done between the unilateral and bilateral drop jump and between the cut and the unilateral drop jump at the (a and d, respectively) hip, (b and e, respectively) knee, and (c and f, respectively) ankle. *$P \leq 0.05$. Black dots represent ACLR cohort. White 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 healthy 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 $p \leq 0.05$

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

Measure	ACLR vs Healthy (bilateral and unilateral drop jump) p-value	Mann-Whitney U	Cohen's *d*	ACLR vs Healthy (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 $p \leq 0.05$