

Original Articles

Drop landing between subjects post anterior cruciate ligament reconstruction and uninjured controls: A biomechanical and neuromuscular analysis

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ARTICLE INFO

Keywords:

Anterior cruciate ligament reconstruction
Drop landing
Biomechanics
Electromyography

ABSTRACT

Background: The capacity of functional testing to identify ‘at-risk’ landing strategies in return to sport evaluation has been questioned. The purpose was to evaluate if biomechanical and muscle activation patterns differ during a drop landing task in subjects post anterior cruciate ligament reconstruction against uninjured controls.

Methods: 22 subjects within two years of anterior cruciate ligament reconstruction who had returned to sport and 25 activity matched controls were recruited. Sagittal plane knee and hip biomechanics and muscle activation amplitudes were recorded during a single leg drop landing task. Discrete measures derived from waveforms were analysed using *t*-tests and Analysis of Variance models ($\alpha=0.05$).

Findings: Subjects post anterior cruciate ligament reconstruction displayed reduced knee (Effect Size = 1.2) and hip (Effect Size = 0.995) range of motion as well as reduced knee extension moments (Effect Size = 0.955) but exhibited no differences in quadriceps or hamstrings activation amplitudes versus uninjured controls.

Interpretation: Adoption of reduced knee and hip excursion or “stiffened” landing pattern despite similarities in muscle activation suggests the presence of adaptive strategies reflecting incomplete recovery despite receiving clearance for returned to sport. This suggests presence of altered patterns of movement which may place at increased risk for reinjury.

1. Introduction

Trauma to the anterior cruciate ligament (ACL) is among the most severe knee related injuries, especially to those in sports involving jump landing, cutting and pivoting (Beaulieu et al., 2021; Boden et al., 2000; Hewett et al., 2016; Krosshaug, 2005). Serving a primary stabilizing role to the knee (Beaulieu et al., 2021), injury here can result in reoccurring episodes of instability (Hewett et al., 2016) which may present challenges to resumption of regular activities (Linko et al., 2016). In North America, it is reported over 250,000 ACL injuries occur per year (Hewett et al., 2016) where ACL reconstruction (ACLR) surgery is often recommended if return to sport (RTS) is anticipated (Linko et al., 2016). As such, due to ongoing trends of ACL injury and projections of increased re-injury post ACLR (He et al., 2020; Leppänen et al., 2017), continued

investigation is needed to further our understanding in an effort to mitigate these outcomes.

There has been much advance in ACLR rehabilitation in the past 30 years (Andrade et al., 2020; Shelbourne and Nitz, 1990), however, low RTS and elevated re-injury rates continue to persist (Arderm et al., 2011; Paterno et al., 2014). Recent report suggests only 63 % return to pre-injury level of sport (Arderm et al., 2014) and for those who do return, re-injury can be as high as 24–30 % within the first two years in select cohorts (Paterno et al., 2014; Wiggins et al., 2016). Critique of late stage clinical assessment post ACLR suggest common methods employed may be incomplete in their identification of metrics essential for determining appropriateness for RTS (King et al., 2018a; King et al., 2018b). This consequence may ultimately instill a false sense of clinical certainty and ultimately puts athletes at further risk for secondary ACL injury

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<https://doi.org/10.1016/j.clinbiomech.2025.106504>

Received 23 October 2024; Accepted 22 March 2025

Available online 24 March 2025

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(Wiggins et al., 2016).

With advancement in human movement analysis, the integration of biomechanical and electromyographical (EMG) evaluation post ACLR provides a course of exploration not otherwise captured through clinical assessment. Use of kinematic and kinetic variables, such as sagittal plane range of motion (RoM) and moments, provide insight into the rehabilitation process. For example, research into single leg landings post ACLR has found lower extremity mechanics can differ from healthy participants and these adaptations have been linked to re-injury risk, despite achieving acceptable performance in clinical RTS testing (King et al., 2018a; Kotsifaki et al., 2020). Likewise, evaluation of muscular activation during single leg landings in subjects who RTS post ACLR show alternative patterns versus that of healthy participants (He et al., 2020), suggesting diverging strategies are adopted in those affected by injury.

In the evaluation of appropriateness for RTS post ACLR, evaluation of tasks such as landing from a jump are warranted. Much of the literature concentrates on re-injury prevention and evaluating load acceptance strategies during 'at-risk' movements necessary for RTS (Beaulieu et al., 2021; Hewett et al., 2016; King et al., 2018b; Krosshaug, 2005). Adaptive 'stiffening' patterns, demonstrated by a reduced RoM upon landing have been shown to illicit greater ground reaction forces (GRF) and reductions in moments at the knee and hip (Anderson et al., 2016; Beaulieu et al., 2021; Fritz et al., 2012). These combined effects have been shown to result in increased stress on passive structures at the knee and are often interpreted as risk factor for ACL (re)injury (Devita and Skelly, 1992; Hewett et al., 2016; Leppänen et al., 2017). Use of the single leg drop landing (DL) in this analysis was chosen as it has been shown to increase emphasis on the eccentric (breaking) phase, considered critical for dynamic control during landing (Devita and Skelly, 1992).

For those post ACLR, the presence of alternative landing strategies, identified through simultaneous biomechanical and neuromuscular evaluation, undetected with clinical evaluation, may be indicative of adaptive patterns that result from injury. However, analysis of both outcomes in concert are not commonly reported. Through the direct evaluation of both biomechanical and muscle activation outcomes concurrently, it is expected identification of altered 'at-risk' patterns of movement produced in response to the DL will be identified in those post ACLR cleared for RTS through clinical evaluation, when held in comparison to uninjured controls.

Thus, the purpose of this study is to evaluate RoM and peak internal extension moments (PIEM) at the hip and knee as well as mean muscle activation amplitude (MAA) of the quadriceps and hamstrings during the DL task in subjects post ACLR against activity matched, uninjured controls. It is hypothesized that individuals in the ACLR group will land using less hip and knee RoM and display lower PIEM. This reduced RoM, the hallmark of the stiffening strategy post ACLR, is often associated with greater ACL stress and remains a suspected predisposing risk factor for re-injury (Anderson et al., 2016; Vaughan et al., 1999). Reductions in PIEM are expected in the early stages of recovery post ACLR (Trigsted et al., 2018), however, as rehabilitation progresses, adaptations such as these are expected to normalize as one considers a RTS. However, evidence has found biomechanical deficits post ACLR can persist suggesting incomplete recovery where rehabilitation strategies evoked may be insufficient, despite achieving clearance in RTS assessment (Trigsted et al., 2018). Lastly, evaluation of the quadriceps and hamstrings were evaluated as they represent the primary dynamic controllers of knee responsible for movement and stability. A main group effect but absence of muscle effect of the quadriceps and hamstring are expected as this has been previously associated with the 'stiffened' landing strategy in comparison to uninjured controls. This analysis stands to aid our understanding of proposed recovery of those post ACLR within two years of surgery who have been cleared for sport through clinical evaluation. Where persistent deficits in recovery are anticipated in the ACLR group, findings are expected to emphasize the challenges that exist regarding decisions for RTS that rely on clinical performance evaluations.

2. Methods

2.1. Participants

Twenty-two subjects post ACLR surgery were recruited through two local orthopaedic surgeons. Inclusion criteria required subjects to: i) be within the ages of 18–50 years old, ii) be within two years of their ACLR surgery date, iii) having completed a course of rehabilitation, iv) have returned to activities with no restrictions, and v) returned to participating in a weight bearing sport. Twenty-five uninjured control participants (CON) were recruited by a sample of convenience through local physiotherapy clinics, community posters, and advertisement through university networks. Requirement for inclusion to this group included: i) to be within the ages of 18–30 years old and ii) to be currently participating in a weight bearing sport. All participants were required to: i) have a Tegner activity score (Briggs et al., 2009) ≥ 5 , ii) not have history of musculoskeletal injury/ disease or have undergone additional surgery to either lower extremity within the last year, iii) had no history of cardiovascular or lung conditions contraindicating physical activity, iv) had no history of neuromuscular conditions effecting sensation or strength, v) had no history of stroke and vi) were not currently pregnant. The Marx Activity Rating Scale (Cameron et al., 2015) was used to match participants based on frequency of participation in four specific activities, in particular, those associated with ACL injury (Boden et al., 2000; Hewett et al., 2016). The study received ethics approval from Nova Scotia Health (#1025162), Halifax, NS, Canada.

2.2. Lab procedures

Participants were introduced to laboratory environment and informed and written consent was obtained prior to changing into the participants own tight-fitting shorts, t-shirt and low-cut athletic shoes. Height, mass and lower limb circumferential measurements of the thigh and shank were taken followed by participants completing the Knee Osteoarthritis Outcome Score (KOOS) and ACL-Quality of Life (ACLQoL) (Al-Dadah et al., 2022; Hambly and Griva, 2010).

In preparation for the collection procedure, participants were prepared for surface EMG. Previous standard laboratory procedures (Rutherford et al., 2020) were followed that align with accepted guidelines (Hermens et al., 2000). Skin was prepared applying a light shave and cleaned using 70 % alcohol wipes. Ag/AgCl electrodes (10 mm diameter, 30 mm interelectrode distance, Red Dot 3 M Health Care, St. Paul, USA) were placed in a bipolar configuration bilaterally on lower extremity muscles including vastus lateralis (VL) and medialis (VM), rectus femoris (RF), medial (MH) and lateral (LH) hamstrings following Surface Electromyography for the Non-Invasive Assessment of Muscle Guidelines. EMG was recorded using two AMT-8™ 8 channel Bortec systems (input impedance: $> 1000 \text{ M}\Omega$, CMRR: 115 dB at 60 Hz, band-pass (10–1000 Hz) (Bortec Inc., Calgary, Canada) at a frequency of 2100 Hz with Qualysis Track Manager 2.10 (Qualysis, Gothenburg, Sweden). EMG validation was performed using specific muscle group isometric contractions, palpation and visual inspection for both electrode placement and gain adjustment.

Retro-reflective spheres on a rigid plate were positioned on the mid thoracic spine, sacrum, lateral femur, lateral tibia and forefoot using Velcro straps. Single spheres were placed on select lower extremity anatomical landmarks bilaterally. Anterior pelvic landmarks (anterior superior iliac spine) were identified virtually and defined with respect to the pelvic rigid plate. Tracking of the 3-dimensional coordinates of all reflective markers was acquired using eight Qualysis® OQU5 500 motion capture cameras and was collected at frequency of 150 Hz.

To provide adequate warm-up prior to performing the DL, all subjects participated in two clinical tests. First, subjects performed a series of single leg hop tests (single and triple hop), a recommended functional performance test in ACLR rehabilitation (Andrade et al., 2020; van Melick et al., 2016) followed by a six minute walk at their self-selected

speed on a dual-belt instrumented treadmill (R-Mill, MotekForcelink, Amsterdam, The Netherlands).

After completion of the warm-up, participants were familiarized to the DL test and were provided practice jump opportunities. A safety harness was worn during all testing. Based on a protocol by Pozzi et al (Pozzi et al., 2017), subjects were directed to perform a DL from a 30 cm high step starting from a single leg and directed to land on the same single leg, no fixed stabilization of hand position was used. The jump platform was fixed atop the stationary instrumented treadmill deck which served as the landing surface. Participants completed 10 alternating DL trials (5 left and 5 right leg landings). GRF during the landing phase were sampled from the instrumented treadmill at 2100 Hz.

To complete the data collection procedure, all retro-reflective spheres were removed, and a supine resting muscle activation trial was recorded. Following this, collection of maximum voluntary isometric contractions (MVIC) of the quadriceps and hamstrings through standardized exercises (Rutherford et al., 2020) was performed using a Humac Norm Isokinetic Dynamometer (Computer Sports Medicine Inc., USA). Flexors and extensors of the knee joint were collected at 45° of flexion. The axis of rotation of the dynamometer arm was aligned with the knee joint centre of rotation and gravity correction was performed prior to the commencement of each trial. Participants were asked to perform a maximum effort which was held for three seconds while standardized encouragement was provided. A duration of 40 s rest was provided between consecutive tests. Muscle strength was determined by obtaining the maximum torque recorded within each trial and the average of the two trials was used for statistical analysis. This DL lab protocol was modified from a version previously used in publications (Rutherford et al., 2017; Rutherford et al., 2020) which showed good reliability of hip and knee biomechanical, strength and MAA outcomes.

2.3. Data processing and analysis

Custom programs, written in MATLAB™ (The Mathworks Inc., Natick, USA, Version R2019b), were used in the processing of all data collected. Marker trajectories and GRF data were filtered using a 12 Hz low pass, 4th order zero-phase Butterworth filter to minimize potential influence of artifact during derivation of moment data during DLs (Pozzi et al., 2017). The technical and local anatomical bone embedded coordinate systems for the thoracic spine, sacrum, thigh and shank were derived from skin markers and virtual points. The method to calculate joint angles was achieved through the use of a six degrees of freedom model using Cardan rotations, as previously described by Rutherford et al (Rutherford et al., 2017), where flexion, adduction, and internal rotation are defined as positive angles. Net external moments were calculated using an inverse dynamics approach (Vaughan et al., 1999) combining GRF, kinematic and anthropometric data as well as inertial properties and were normalized to body mass (Nm/kg).

For EMG data, raw signals were corrected for resting bias, band pass filtered (10–500 Hz) using a 4th order Butterworth filter, full wave rectified, and low pass filtered using a 6 Hz 4th order Butterworth filter (Rutherford et al., 2017). Drop landing EMG data were amplitude normalized to the highest 100 ms window from the MVIC trial (%MVIC) (Rutherford et al., 2020). Motion, moment and EMG waveforms were time normalized to 100 % of the landing phase beginning at initial contact and ending 200 ms after initial contact. This time interval was chosen as it has been previously shown to capture peak moments and GRF (Devita and Skelly, 1992), reflecting the mechanical demands experienced during a DL (Sinsurin et al., 2013). Ensemble averages were calculated for all DL trials and used for further analysis.

2.4. Statistical analysis

In the analysis of the ACLR group, the surgical leg was chosen for all biomechanical and EMG outcomes and for the CON group, a random leg was selected for comparison. Sagittal plane hip and knee RoM during the

landing phase, hip and knee PIEM and mean MAA were determined from the ensemble averaged waveforms. Shapiro-Wilk's test was used to determine normality. Levene's test was used to determine equality of variance where group sample sizes did differ. Appropriate transformation practices were used for any data not meeting the above assumptions prior to statistical testing. To determine if differences existed between group means for anthropometric data, clinical outcomes (RoM, strength) or patient reported outcome measures, independent *t*-tests were used. In addition, *t*-tests were also used in the analysis of group differences in biomechanical outcomes. For EMG outcomes, a two factor repeated measures analysis of variance was used to test for between and within group differences and interactions for both the quadriceps and hamstrings. Post-hoc analysis using Bonferroni corrections were employed where significant effects were found. An alpha level was set at $\alpha = 0.05$ for all statistical outcomes. Applications of effect sizes (Cohen's *d*) were determined for biomechanical outcomes (CON – ACLR limb), where a positive effect size indicated a greater value for an uninjured participant. A previously reported guide described by Fritz et al. (<0.2 = small effect, 0.2 – 0.5 = moderate effect and 0.5 – 0.8 = large effect) (Fritz et al., 2012) was used in the interpretation of this outcome. All data were analysed using IBM SPSS Statistics (Version 28).

3. Results

Group characteristics, strength and questionnaire outcomes are shown in Table 1. The study groups of CON ($n = 25$) and ACLR ($n = 22$) encompassed 56 % and 59 % female subjects, respectively. Subjects in the ACLR group were older in age ($p < 0.001$), showed lower normalized knee extension torque ($p < 0.05$), reduced scores in all KOOS sub-scales as well as reductions in ACLQoL total score ($p < 0.05$) compared to CON. No differences were found between groups in height, mass, BMI, pain reports pre or post DL or Marx scale outcome ($p > 0.05$) or in normalized strength measures of knee flexion ($p = 0.401$).

Biomechanical and EMG outcomes for the DL are found in Table 2 and illustrated in Fig. 1. During the DL, the ACLR group showed a lower overall dynamic knee flexion RoM (8 degrees, $p < 0.001$, effect size $d = 1.2$), and hip flexion RoM (5 degrees, $p < 0.001$, effect size $d = 0.995$) compared to the CON group. Sagittal plane knee PIEM were lower in the ACLR group (0.61 Nm, $p = 0.002$, effect size $d = 0.955$) compared to the CON group, however no differences were found in sagittal plane Hip

Table 1

Mean and standard deviations of participant characteristics/ outcomes.

	Uninjured		ACLR	
	Mean	SD	Mean	SD
N	25		22	
Females (%)	56		59	
Months post-surgery			16.6	4.7
Age (years)	22*	4	33*	9
Height (m)	1.71	0.08	1.70	0.1
Mass (kg)	68.3	13.4	74.9	18.1
BMI (kg/m ²)	23.3	3.8	25.7	5.0
KOOS Symptoms	97*	7	85*	10
KOOS Pain	99*	3	92*	8
KOOS ADL	100*	1	98*	4
KOOS QoL	100*	2	70*	19
KOOS Sport Rec	98*	6	88*	10
ACLQoL Total	100*	5	76*	18*
Marx scale Total	8	4	9	4
Pain Pre DL	0	0	0	0
Pain Post DL	0	0	0	0
Torque KE (Nm/kg)	3.4*	0.95	2.8*	0.86
Torque KF (Nm/kg)	1.6	0.40	1.5	0.35

BMI=Body Mass Index, KOOS=Knee Osteoarthritis Outcome Score, ACLQoL = ACL-Quality of Life, DL = Drop Landing, KE = Knee Extension, KF = Knee Flexion.

* Indicates significant difference between groups $p < 0.05$.

Table 2

Biomechanical and EMG outcomes during drop landing.

	Uninjured	ACLR	Uninjured: ACLR		
	Mean (SD)	Mean (SD)	p value	95 % CI	d
Biomechanics					
Knee Flexion RoM (^o)	43.8 (5.9)	36.2 (6.8)	<0.001	4–11	1.200
Hip Flexion RoM (^o)	17.8 (5.6)	12.9 (3.8)	<0.001	2–8	0.995
PIEM Knee (Nm/kg)	3.3 (0.7)	2.6 (0.6)	0.002	0.2–1.0	0.955
PIEM Hip (Nm/kg)	1.3 (0.6)	1.2 (0.5)	0.630	–0.2 - 0.4	0.142
EMG	Mean %MVIC (SD)		*Muscle	p value	95 % CI
Quadriceps					
VM	68.1 (30.2)	76.8 (37.4)	VM:VL	0.634	–0.14-0.44
VL	68.2 (22.1)	67.3 (38.3)	VM: RF	<0.001	0.75–1.27
RF	47.9 (14.0)	45.0 (22.0)	VL: RF	<0.001	0.63–1.10
Hamstrings					
MH	23.1 (7.9)	26.7 (15.6)	MH: LH	0.228	–0.42-0.10
LH	22.4 (8.9)	30.9 (15.8)			

RoM = Range of Motion, PIEM = Peak Internal Extension Moment, *Muscle = Muscle main effect, VM = Vastus medialis, VL = Vastus lateralis, RF = Rectus femoris, MH = Medial hamstrings, LH = Lateral Hamstrings.

PIEM ($p > 0.05$). A significant muscle main effect for mean quadriceps % MVIC ($F(2,44) = 27.24$, $p < 0.001$, $\eta_p^2 = 0.53$), but not hamstrings ($F(1,45) = 0.18$, $p = 0.221$, $\eta_p^2 = 0.004$) was found (Table 2, Fig. 2). No significant differences in muscle activation were found between vastii muscles ($p > 0.05$) but both VL and VM yielded greater muscle activation amplitude than RF ($p < 0.05$) (Table 2). No significant main effects for group or muscle $\times$ group interactions were found ($p > 0.05$).

4. Discussion

Use of functional testing is routinely used in RTS decision-making to determine those appropriate for the physical demands of sport while attempting to mitigate re-injury risk through the identification of at-risk movement patterns (Anderson et al., 2016). However, evidence suggests visual inspection and functional measures (spatial/temporal outcomes) may fail to identify presence of ‘at-risk’ movements that can predispose to re-injury (King et al., 2018b; Kotsifaki et al., 2020). Our purpose was to identify if differences in hip and knee RoM and PIEM as well as MAA

of the quadriceps and hamstrings occur during a DL in those post ACLR cleared for RTS, a high-risk group for re-injury post ACLR (He et al., 2020), versus uninjured controls. Results identified the presence of an ‘at-risk’ stiffening strategy and a reduction in knee PIEM in the ACLR limb occurred without changes in MAA during the DL task in the ACLR group within two years of surgery. These findings confirm suspicions that persistent adaptive landing strategies may continue to exist which may reflect incomplete recovery in those cleared for RTS post ACLR. This may highlight risk factors of re-injury, not identified through conventional RTS testing methods. Despite acknowledgement of current ACLR rehabilitation frameworks abilities to identifying those likely to RTS (Schmitt et al., 2015), this should not overshadow the challenges clinicians face in identifying ‘at-risk’ patterns of movement that evade clinical testing and may contribute to the continued elevated re-injury rates post ACLR within two years of surgery (Paterno et al., 2014; Schmitt et al., 2015).

Results provided partial support for the study hypotheses where adaptations in landing were seen in individuals post ACLR who RTS. ACLR subjects landed with less hip and knee flexion RoM aligning with previous reports of a ‘stiffening’ strategy seen versus healthy controls during drop jump landing tests (Johnston et al., 2018; Lepley and Kuenze, 2018). Use of increased flexion during landing is important in the absorption of forces (Johnston et al., 2018) and forms part of the cornerstone of ACL injury prevention programs (Hewett et al., 2016). This alternative ‘stiff’ landing approach has been previously reported (Johnston et al., 2018; King et al., 2018a; Leppänen et al., 2017; Pozzi et al., 2017) and has been suggested to represent an ‘at-risk’ pattern resulting in increased joint compressive forces (Boden et al., 2000). When produced in concert with anatomic factors such as a posterior tibial slope and additional at-risk movements such as increased knee valgus (Boden et al., 2000; Withrow et al., 2006) and internal tibial rotation (Beaulieu et al., 2021) can result in elevated strain on the ACL, increasing risk for (re)injury (Beaulieu et al., 2021; Boden et al., 2000). The stiffening pattern of movement in the ACLR group represents a reduced dynamic loading strategy suggesting a reduced ability to dissipate kinetic energy (Maniar et al., 2020) and control forces imposed by ground contact during landing (Johnston et al., 2018).

Use of PIEM was included in the current analysis as it biomechanically reflects extensors muscle demand at the knee and hip to generate and control movement (Fritz et al., 2012) and represents the link between limb strength deficits and alternative landing patterns found post ACLR (Anderson et al., 2016; Fritz et al., 2012; Schmitt et al., 2015; Verniba et al., 2017). Regarding kinetic differences witnessed during the DL task, significant reductions in knee PIEM (mean difference: 0.7 Nm/kg) but not the hip (0.1 Nm/kg) were found. This finding stands in contrast to a recent meta-analysis (Johnston et al., 2018) where authors

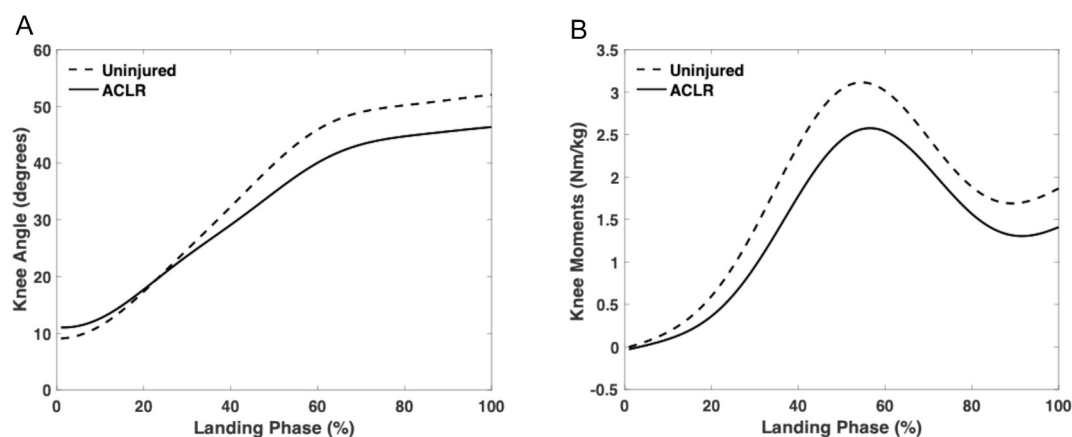


Fig. 1. Ensemble averaged waveforms normalized to 100 % of landing phase: A) Sagittal plane knee RoM B) Sagittal plane knee PIEM amplitude normalized to body mass.

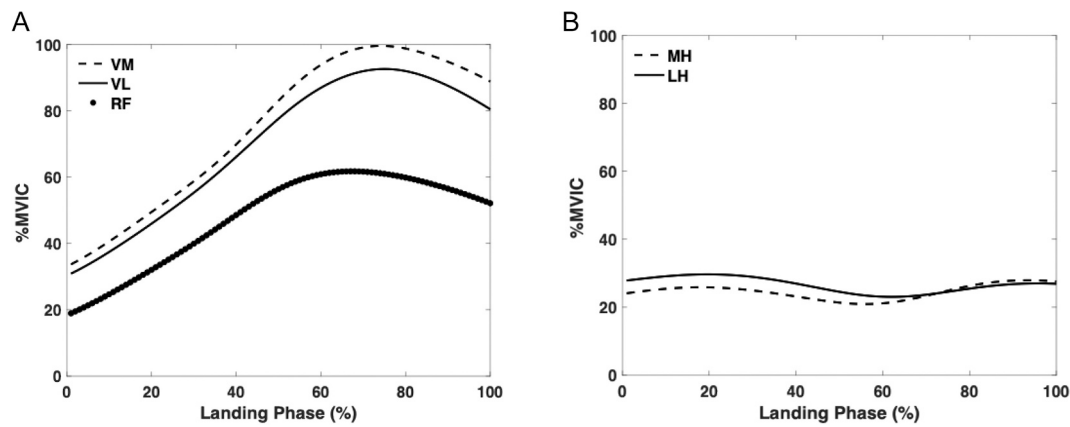


Fig. 2. Ensemble averaged electromyograms across groups (CON and ACLR) amplitude normalized to percent MVIC and time normalized to landing phase for: A) quadriceps (vastus medialis, vastus lateralis, rectus femoris) and B) hamstrings (medial hamstring, lateral hamstring).

found an overall non-significant effect in PIEM at the knee among two studies using a drop landing from a matched height (standardized mean difference (SMD) - 0.52; 95 % CI - 1.71 to 0.68) (Johnston et al., 2018). However, challenges in interpretation here relate to both the number of studies for comparison, possible influence of a same-sex subject group as well as the way landings were performed. The landing protocol used by Pozzi et al. was the framework from which the present study was derived (standard platform height 30 cm/ uncontrolled use of upper extremities during the landing phase). Here, these authors also found a significant reduction in PIEM at the knee in the ACLR group versus healthy controls (Pozzi et al., 2017). These findings however, stood in contrast with findings by Webster et al. (2011) where authors used only male participants in the analysis of DL and restricted upper limb position to hands on hips during the landing phase. In a recent study by Peebles et al., authors reported the existence of a reduced knee PIEM in females versus males during a stop jump landing task of healthy individuals (Peebles et al., 2020). Where potential sex differences in landing strategy may exist, caution in interpretation is recommended where conclusions are drawn from mixed group meta-analyses. Further, restriction in the use of the upper limbs during landing may impact one's ability to choose the desired landing strategy, increasing emphasis on the knee and possibly inflating knee moments which may otherwise be generated (Johnston et al., 2018). In a study by Lepley and Kuenze, the authors reported inconclusive findings for PIEM between ACLR and healthy groups in single leg landings (Lepley and Kuenze, 2018). Despite differences found among PIEM between groups in this study, given that conflicting evidence exists regarding the influence PIEM has during the DL task among these studies, further investigation may be warranted before a strong conclusion is drawn.

The hip PIEM was not different between groups in the current study. Given the close biomechanical relationship that exists between lower limb kinematics and kinetics during landing, a decrease in hip PIEM was expected to coincide with the reduced hip RoM seen in the ACLR group. This may have suggested a reduced muscular demand as a result of a stiffening at the hip, like that seen at the knee (Table 2). This contradiction in finding has been seen previously in a meta-analysis (Lepley and Kuenze, 2018) where investigation into drop vertical jumps between ACLR and healthy participants reported no significant differences in internal hip extension moment (Cohens d range - 0.52 to 1.41) (Lepley and Kuenze, 2018). Additionally, this finding was also seen in subjects performing a DL (Johnston et al., 2018), where no significant differences in hip PIEM were reported between groups (SMD) 0.39; 95 % CI - 1.39 to 2.17) (Johnston et al., 2018). Possible explanation for this phenomenon has been proposed wherein, during performance of a landing task, reduction of kinetic energy absorption may be expected in more proximal joints as greater amounts of energy absorption tend to be dispersed through joints more distally located nearer the body-surface

interface (Devita and Skelly, 1992). Thus, this study's findings further strengthen this trend in single leg landings witnessed across multiple studies.

In discussion of the biomechanical findings, it would be prudent to report that alternative rationalisations have been previously reported to have potential influence on biomechanical factors measured. Notably, changes found during double limb landings were hypothesized to be attributable to differences in pain, fear-avoidance or lower limb strength between groups (Lepley and Kuenze, 2018). No differences in pain experienced during the DL appeared between groups in this study however, significant differences were noticed in the ACLQoL total score, encompassing questions of fear, apprehension and confidence toward the knee, as well as normalized knee extensor strength. As the knee extensors do represent a predominant muscle group in absorption of force during landing (Malfait et al., 2016; Maniar et al., 2022), it is postulated differences in strength may partly explain differences in kinematics and kinetics during the landing phase between groups. Additionally, psychological factors may also play a part in movement strategies witnessed. Evidence of 'stiffened' landing patterns existing in those reporting greater fear of movement and reduced confidence along with reduced quadriceps strength during landing has been shown in those post ACLR (Paterno et al., 2018; Trigsted et al., 2018) and may represent those at increased risk for future injury (Paterno et al., 2018).

A main effect of quadriceps was the only significant difference found but did not result in group differences. Post-hoc testing here revealed significantly lower mean MAA in RF in comparison to VM and VL during the landing phase (mean VM = 75.4 %, mean VL = 70.1 %, mean RF 47.9 %) (Fig. 2B). It has been reported uni-articulate muscles are those primarily responsible for deceleration of the body's centre of mass during the braking phase of landing in the sagittal plane, providing an extension moment about the hip, knee and ankle, specifically, gluteus maximus, vasti muscles and soleus (Devita and Skelly, 1992; Maniar et al., 2022). Recent work by Maniar et al. further suggests bi-articulate muscles spanning the hip, knee and ankle (hamstrings, rectus femoris and gastrocnemius) play a secondary supportive role particularly in high-demand tasks such as the DL (Maniar et al., 2022). These findings concur with the muscle activation trends seen in this study (Fig. 2A,B) where a more dominate amplitude is displayed by the VM and VL in comparison to the RF. Possible explanations for disparities seen in MAA have been suggested including i) differences in muscle cross-sectional area and ii) production of antagonistic muscle actions across multiple joints. These differences may reflect smaller force producing abilities and ultimately prove counter-productive as a primary controller during the DL task, respectively (Maniar et al., 2022).

Regarding hamstring activation during the landing phase of the DL task, no main (muscle) or interaction (muscle*group) effects were found in the current study. This result led to the conclusion that no significant

differences exist in mean MAA of medial versus lateral hamstrings and between the ACLR and CON group. A similar response in hamstring activation was recently reported (Lentz et al., 2015; Paterno et al., 2018). Although reactive hamstring muscle activation was often analysed as a collective group versus differentiated by sub-group (medial versus lateral hamstring), eight of 11 studies showed no significant differences between ACLR and healthy controls in the single leg landings task.

The interactive effect between kinematics, moments and EMG in this study reveal differences in biomechanics despite similarities in MAA during the DL between groups. An increase in MAA with increased RoM may be expected during the breaking phase of landing due to elevated demand for muscular control (Maniar et al., 2022). It is speculated the reduced RoM with comparable MAA seen in the 'stiffening' strategy may reflect an increased attempt to stabilize the knee during the landing task where other traits (reduced knee extension strength/fear of movement) are present. As a result, this reduction in RoM may also explain the reduction in knee moment seen in the ACLR group. It is noteworthy to suggest a reduction in knee extension moment may reflect an attempt to lessen strain at the ACL through reduced anterior tibial translation, however this may also reflect a helpful coincidence to an otherwise 'at-risk' pattern of movement (Beaulieu et al., 2021; Devita and Skelly, 1992; Leppänen et al., 2017).

Limitations did exist in the completion of this study and warrant consideration. First, inherent differences in motor strategies can exist between subjects/trials, where differences in dominant strategy taken to perform the drop landing task (hip vs knee vs ankle) may occur. To minimize this effect, standardization of verbal instructions, provision of practice trials for familiarization, visual critique of trials and averaging of multiple DL trials was used. In the event a jump versus a drop was performed upon leaving the platform, the trial was redone to ensure DL consistency. Future work could further minimize potential for variation in DL performance through kinematic technique evaluation. Second, within the ACLR group, graft type was not controlled in this analysis which could affect interpretation. Graft types featured in the current ACLR cohort included patellar tendon, hamstring and allograft. Despite documented differences regarding healing time, strength recovery and re-rupture rate, no significant differences in RTS have been reported. Given the invasive effects surgery can have on muscle recovery, future analyses should consider potential effects graft type may have on DL movement strategies observed. Third, the use of a fixed platform height could have resulted in relative height differences for subjects performing the DL task. Alteration in platform height can create potential for variation of imposed demands and has previously shown to illicit changes in GRF, kinematics and muscle activation during the landing phase of a drop jump. The choice to standardize height in this study was made in an effort to control the vertical velocity observed among subjects (Devita and Skelly, 1992). Where no significant differences were seen between groups concerning height or mass, the influence platform height had on DL mechanics was anticipated to be minimized. Normalization of MAA in this study was obtained using %MVIC. As this method is dependent on voluntary maximal output, potential error could exist if subjects failed to elicit maximal contractility during MVIC testing. To ensure maximal effort, standardized verbal explanation of task and encouragement was given as well as real-time visual feedback of torque to reinforce maximal output. Finally, there did exist a significant difference in age between the ACLR group and uninjured controls (Table 1). Although, there currently exists a lack of consensus regarding the impact of age on sagittal plane landing mechanics in adult populations and no anthropometric differences were apparent between these groups that may influence landing mechanics, inherent differences that may coincide with physiologic aging should be considered in interpretation of these findings.

5. Conclusion

Individuals within two years of ACLR who have returned to unrestricted activity performed a DL task with less hip and knee RoM, less knee PIEM and with similar levels of knee MAA compared to a group of uninjured individuals. The adoption of a "stiffened" landing strategy suggests the possibility of incomplete recovery despite receiving clearance for RTS and may suggest evidence of altered patterns of movement which may place individuals at increased risk for reinjury.

CRedit authorship contribution statement

Chris Murphy: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Scott Landry:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Nathan Urquhart:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Catherine Coady:** Writing – review & editing, Supervision, Investigation. **Derek Rutherford:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to acknowledge Ms. Felicia Licht and Mr. Ewan Galloway for data collection support, physicians and physiotherapists for their assistance in recruitment and thank you to the participants for their time taken to conduct this research.

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