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Differences in vertical and lower-limb joint stiffness in RTS assessments between ACLR patients and non-injured controls

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ABSTRACT

The aim of this study was to establish alterations in vertical and lower-limb joint stiffness following anterior cruciate ligament reconstruction (ACLR). 127 male patients 8–10 months post-ACLR and 45 non-injured controls performed unilateral and bilateral drop jumps, and cutting, while ground reaction forces (GRFs) and 3D kinematics were recorded. Stiffness and changes in vertical GRF were lower in ACLR patients during bilateral drop jumps compared to non-injured controls. ACLR patients also displayed lower knee stiffness in the bilateral drop jumps (d=-0.91, $p < 0.001$ and $d = 0.53$, $p < 0.001$, respectively) and cutting (d=-0.85, $p < 0.001$ and $d = 0.19$, p=0.040, respectively). In the unilateral drop jump, there were no differences in ankle, knee, or hip stiffness between groups, yet ACLR patients displayed smaller changes in knee moments (d=-0.63, $p < 0.001$) and decreased knee range of motion (d=0.44, p=0.013). During the bilateral drop jump, ACLR patients displayed lower ankle stiffness (d=0.46, p=0.003) and smaller ankle moment changes (d=0.48, p=0.006), compared to controls. Hence, joint level analysis provides practitioners with a more detailed insight into an athlete's movement strategy following ACLR than whole body analysis. Range of motion, change in moment, and stiffness of the knee joint especially, can help practitioners to assess fitness for return-to-sport in ACLR patients.

KEYWORDS
ACL reconstruction; joint analysis; rehabilitation; return to sport; stiffness

Introduction

Following an anterior cruciate ligament (ACL) rupture, multi-directional field sport athletes aiming to return to their preinjury level of sport typically undergo ACL reconstruction (ACLR) surgery. Even after an extensive course of rehabilitation to restore the function of the knee following ACLR surgery, alterations in lower limb joint kinematics and kinetics can still be observed in movements included in return to sports (RTS) assessments, which may contribute to an increase in subsequent ACL injury risk (Jones et al., 2022 Johnston et al., 2018; Paterno et al., 2012). Differences in kinematics and kinetics have been found 9 months post-ACLR during bilateral and unilateral drop jumps and planned 90° cutting tasks in the ACLR limb, compared to both the healthy limb and non-injured controls (Gokeler et al., 2010, King et al., 2018a; King et al., 2018b; King et al., 2019).

Vertical stiffness has been shown to be lower in athletes who went on to sustain a contralateral ACL injury within 2 years compared to those that did not (King et al., 2021). Hence, vertical stiffness may be a risk factor for ACL injury. Vertical stiffness is the resistance of the body to undergo vertical displacement when a ground reaction force (GRF) is applied (Butler et al., 2003). Therefore, a larger vertical displacement of the body's centre of mass (CoM) and/or a smaller GRF results in a lower vertical stiffness. Following ACLR, a greater joint motion (resulting in larger vertical CoM displacement) may indicate reduced dynamic joint stability, which could increase the risk of injuries to soft-tissues, such as the ACL (Shelbourne et al., 2022; Williams et al., 2001, 2004). Additionally, smaller vertical GRFs have been found in the ACLR limb compared to the uninvolved limb and non-injured controls (Paterno et al., 2007, 2011). Smaller peak vertical GRFs have been associated with heightened co-activation of the quadriceps and hamstrings (Blackburn et al., 2019). Following ACLR, it has been proposed that this heightened co-activation may be a compensatory motor strategy to alleviate perceived instability (Rudolph et al., 2001) and may imply the athlete is not ready to RTS. Larger vertical CoM displacements and smaller GRFs would result in lower vertical stiffness in ACLR patients, which may contribute to an increased risk of second ACL injury. Given that vertical stiffness is partly regulated by modifying lower limb joint stiffness, primarily in the sagittal plane (Serpell et al., 2012; Serpell et al., 2016), joint level analysis may provide practitioners with a more accurate insight of an athlete's ACL injury risk as opposed to whole-body analysis.

The stiffness of a joint is influenced by the interaction between joint moments and range of motion (RoM) (Davis et al., 1996; Dixon et al., 2010). Underlying this, joint stiffness is modulated through various neuromuscular and kinematic

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This article has been corrected with minor changes. These changes do not impact the academic content of the article.

factors, including muscle strength (Oh & Lee, 2022), muscle (co-)activation strategies (Kosaka et al., 2023; Verheul et al., 2017), ability to rapidly produce joint moments (Brightwell et al., 2023), and kinematic movement strategies (Padua et al., 2005). Rather than investigating joint stiffness itself, previous research has primarily focused on the individual components for calculating joint stiffness (i.e., joint moments and RoM) that may be altered following ACLR. Compared to non-injured controls, ACLR patients have been found to have greater ankle RoM throughout the braking phase of a drop landing (Decker et al., 2002) as well as lower mean sagittal plane ankle and knee moments, and higher hip moments during a bilateral vertical drop jump (Brightwell et al., 2023; Mueske et al., 2018). This would result in ACLR patients displaying lower ankle and knee stiffness and higher hip stiffness compared to non-injured controls. Therefore, differences in ankle, knee and hip stiffness may be important variables for practitioners to measure in RTS assessments.

A clearer understanding of how vertical- and lower limb joint-stiffness interact and differ in post-ACLR athletes in movements typically performed in RTS assessments (a bilateral and unilateral drop jump and a cut) may help practitioners identify the readiness of athletes to RTS and potentially identify deficits that should be targeted earlier and more consistently throughout rehabilitation. Therefore, the first aim of this study was to investigate differences in vertical stiffness between ACLR patients and non-injured controls. The second aim was to examine how ankle, knee, and hip stiffness differ between ACLR patients and non-injured controls. It was hypothesised that (1) ACLR patients would display lower vertical stiffness, (2) ACLR patients would demonstrate lower sagittal plane ankle and knee moments and higher ankle RoM and hip moments compared to non-injured controls, resulting in ACLR patients displaying lower ankle and knee stiffness and higher hip stiffness.

Methods

Participants and experimental procedure

A total of 172 male multidirectional field-sport athletes (e.g., football, rugby) participated in the study. Participants included 127 ACLR patients (height: 1.81 ± 0.06 m; mass: 82.7 ± 9.3 kg) and 45 non-injured controls (height: 1.82 ± 0.07 m; mass: 81.4 ± 7.8 kg). Participation criteria for ACLR patients were that athletes had to be aged between 18 and 35 years, had undergone either a hamstring graft (semitendinosus and gracilis tendons) or a bone patellar tendon bone graft from the ipsilateral side, had to be between 8 and 10 months post-surgery at the time of testing, and had to have stated an aim to return to their pre-injury level of sporting participation after surgery. All ACLR patients 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. Controls had to be aged between 18 and 35 years, have never had a previous ACL injury or other knee injury which required surgery, or a lower limb injury within 12 weeks of testing. The control group was matched to the ACLR cohort on limb dominance.

All participants visited the laboratory once, completing three movement tasks as part of a clinical testing battery: a bilateral drop jump (from 30 cm box), a unilateral drop jump (from 20 cm box) and a maximal effort 90° pre-planned cut. The drop jumps and cut were performed in line with previously described protocols (King et al., 2018a; King et al., 2018b). Briefly, for the drop jumps participants placed their hands on their hips and were instructed to step from a box 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 jumps, participants started with their feet approximately hip width apart and landed with one foot on each of the force plates (King et al., 2018b). 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 either left or right at a 90° angle whilst planting their contralateral foot on the force plate, and then to accelerate away after changing direction (King et al., 2018a). Participants completed two submaximal practice trials of each movement before trials were recorded. 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. Ethical approval was obtained from the Sports Surgery Clinic, Dublin Hospital Ethics Committee (approval reference code: 25-AFM-010) and each athlete provided written informed consent prior to participating.

Biomechanical data collection

Kinetic and kinematic data were collected using an eight-camera motion capture system (200 hz; Vicon Motion Systems Ltd), synchronised with two force platforms (1000 hz; BP400600, AMTI) recording 24 reflective markers (14-mm diameter) and GRFs, respectively. Reflective markers were secured to the body with tape based on a modified Plug-in-Gait marker set in which the head and arm markers were removed and the trunk segment was modelled as a single upper body combined segment (Marshall et al., 2014). The modified Plug-in-Gait model was used to determine kinematics and kinetics. Only data collected from the sagittal plane during the braking phase for the first landing in the bilateral and unilateral drop jumps, and for the 90° pre-planned cut, and from the operated limb of the ACLR group were analysed. The limb selected for analysis in the control group was block randomised based on the ratio of dominant to non-dominant limb ACLRs.

Data analysis

The braking phase was defined as the time between initial contact (the frame vertical GRF exceeded 20 N) to the frame preceding the lowest vertical CoM displacement. All data were processed using Vicon Nexus software (Vicon 2.10.0, Oxford Metrics). Motion and force data were low-pass filtered using a fourth-order zero-lag Butterworth filter with a cut-off frequency of 15 hz (Kristianslund et al., 2012). Kinematic and kinetic analyses were carried out in MATLAB (R2019b; MathWork, Inc). Standard inverse dynamics procedures were used to calculate net internal joint moments at the ankle, knee and hip joints in the sagittal plane and the instantaneous body

CoM position was estimated based on Dempster's segment inertial properties (Dempster, 1955). The GRFs and joint moments were normalised to body mass. Change in vertical GRF and vertical CoM displacement were calculated as the magnitude of change from initial contact to lowest vertical CoM displacement. Vertical stiffness was calculated as ratio of change in GRF to vertical CoM displacement. Change in sagittal plane ankle, knee, and hip joint moments, and joint RoM were calculated as the magnitude of change from initial contact to lowest vertical CoM displacement. Joint stiffness was determined as the ratio of change in sagittal plane joint moments to joint RoM.

Statistical analysis

Means ± SD of all three trials for each participant were computed. For statistical analysis, the Kolmogorov–Smirnov test and Levene's test were used to test for normality and homogeneity of variance, respectively, for all variables in each condition between groups. A Mann–Whitney test was performed for variables that were found to violate the assumptions of normality and homogeneity of variance, and an independent samples t-test was performed otherwise. Cohen's *d* standardised effect size was calculated and interpreted as negligible ($d < 0.2$), small ($0.2 \le d < 0.5$), medium ($0.5 \le d < 0.8$), and large ($d \ge 0.8$) (Cohen, 2013). Statistical analysis was performed using SPSS Statistics (SPSS 27, IBM). The level of significance was set at $p \le 0.05$.

Results

Bilateral drop jump

The ACLR patients displayed lower vertical stiffness ($p = 0.012$, $d = 0.44$; Figure 1(c)), and smaller knee and ankle stiffness ($p < 0.001$, $d = 0.53$ and $p = 0.003$, $d = 0.46$, respectively; Figure 2(c)) compared to controls. Additionally, the ACLR patients demonstrated smaller changes in vertical GRFs ($p = 0.001$, $d = 0.61$; Figure 1(b)) and smaller changes in knee and ankle moments ($p < 0.001$, $d = -0.91$ and $p = 0.006$, $d = 0.48$, respectively; Figure 2(b)).

Unilateral drop jump

For the unilateral drop jump, the ACLR patients had smaller magnitudes of change in knee moment ($p < 0.001$, $d = -0.63$) and decreased knee RoM ($p = 0.013$, $d = 0.44$) compared to controls (Figure 2(e-f)).

Cut

During the cut, the ACLR patients had a lower knee stiffness ($p = 0.040$, $d = 0.19$; Figure 2(i)) compared to controls. Furthermore, the ACLR patients displayed a respective smaller and greater change in knee ($p < 0.001$, $d = -0.85$) and ankle ($p = 0.044$, $d = 0.38$) moment than the controls (Figure 2(h)).

Discussion and implications

The aim of this study was twofold. Firstly, to investigate differences in vertical stiffness between ACLR patients and non-injured controls in RTS assessments. Secondly, to examine how ankle, knee and hip stiffness differ between ACLR patients and non-injured controls. It was hypothesised that (1) ACLR patients would display lower vertical stiffness, (2) ACLR patients would demonstrate lower sagittal plane ankle and knee moments and higher ankle RoM and hip moments compared to non-injured controls, resulting in ACLR patients displaying lower ankle and knee stiffness and higher hip stiffness. The results showed that in ACLR patients, vertical stiffness was reduced during bilateral drop jumps, and that the range of motion, change in moment, and stiffness of the knee joint especially, were most prominently affected.

In partial support of the first hypothesis, vertical stiffness was lower in ACLR patients during the bilateral drop jump due to smaller changes in vertical GRFs. However, no differences were observed between groups for change in vertical GRF or vertical stiffness for either the unilateral drop jump or the cut. This could imply that interlimb compensations have occurred during the bilateral drop jump, whereas unilateral movements (the unilateral drop jump and cut) do not allow for such compensations. Unilateral landings are more challenging than bilateral landings due to the narrower base of support and increased muscle forces required to absorb the impact of landing on only one lower limb (Pappas et al., 2007; Smith et al., 2012) and provide a more specific assessment of each limbs landing mechanics compared to bilateral landings. Intra-limb compensations may have occurred in the unilateral movements to reduce load on the reconstructed knee (Maestroni et al., 2021). As such, unilateral movements may be more appropriate to assess the landing mechanics of each lower limb, and joint level analysis may offer practitioners a more detailed insight into an athlete's movement strategy than a whole-body analysis.

In support of the second hypothesis, ACLR patients displayed smaller changes in knee moments during the braking phase in all movements with medium to large effect sizes. This aligns with previous research (King et al., 2018a; Lewek et al., 2002; Schmitt et al., 2015) and may negatively influence the ability of the knee to adequately attenuate force. Smaller changes in knee moments following ACLR likely indicate a compensatory movement strategy to unload the knee joint, which may be due to weakness in the knee extensor muscles (e.g., quadriceps), decreased neuromuscular control, or reluctance to bear weight on the reconstructed knee (Schmitt et al., 2015). Persistent quadriceps weakness, reduced peak moments, and the subsequent diminished ability to attenuate load on the ACLR limb may form a particular factor of interest for practitioners to identify increased risk of re-injury to the knee joint for ACLR patients returning to sport (Brightwell et al., 2023; Rice et al., 2010). However, quadriceps muscle strength is typically targeted during conventional ACL rehabilitation programs. It is, therefore, unlikely that quadricep weakness alone is the sole cause of the knee moment deficits observed in the ACLR patients (Shi et al., 2019).

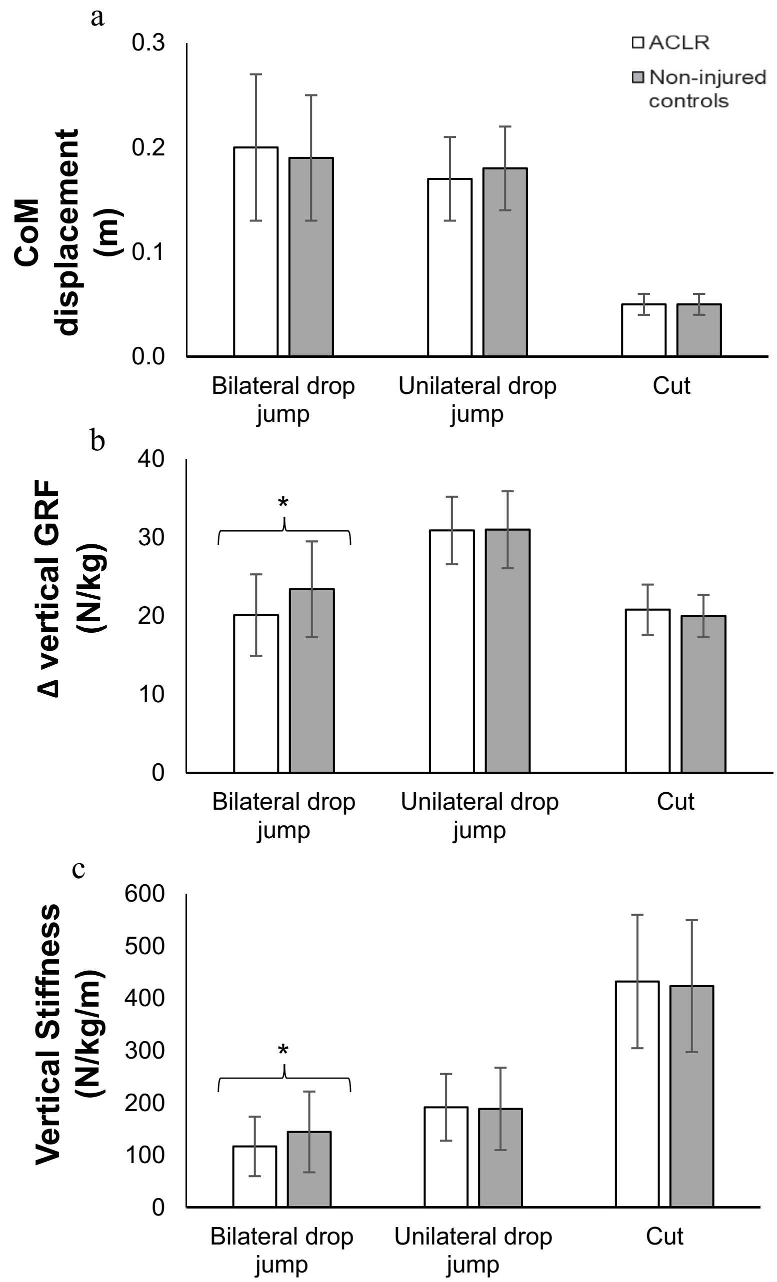

Figure 1. Between group comparisons of the (a) vertical CoM displacement, (b) change in vertical GRF and (c) vertical stiffness for the bilateral drop jump, unilateral drop jump, and 90° pre-planned cut. White bars represent ACLR patients. Grey bars represent non-injured controls. *$p \le 0.05$. CoM = centre of mass; GRF = ground reaction force; ACLR = anterior cruciate ligament reconstruction; Δ = change in.

Neuromuscular changes such as reduced knee extensor muscle activation or increased knee flexor muscle co-activation may also explain the smaller changes in knee moments in ACLR patients (Gokeler et al., 2010; Smeets et al., 2020). In ACLR patients, reduced peak quadriceps muscle activity and a delay in quadriceps muscle onset time have been observed compared to non-injured controls, resulting in decreased knee flexion moments (Burland et al., 2020). Furthermore, increased co-activation of the hamstring muscles may be a protective mechanism to limit anterior tibial translation and increase knee stability during dynamic tasks (Friemert et al., 2010; Pamukoff et al., 2017). Conversely, a key aspect of rehabilitation following ACLR is also focussed on restoring hamstring function (Buckthorpe, 2019; Buckthorpe et al., 2020). A combination of reduced knee extensor strength and activity and increased knee flexor co-activation likely results in the smaller changes in ACLR patients in knee moments observed in this study, which may contribute to an increase in subsequent ACL injury risk. Additionally, imbalances in the hamstring:quadricep strength ratio can elevate the risk of an athlete sustaining a hamstring injury (Croisier et al., 2008). Rehabilitation programmes predominantly focus on quadriceps and hamstring strengthening exercises, suggesting these exercises alone are ineffective at targeting biomechanical deficits following ACLR. Practitioners should, therefore, also consider strategies targeting neuromuscular deficits, such as using

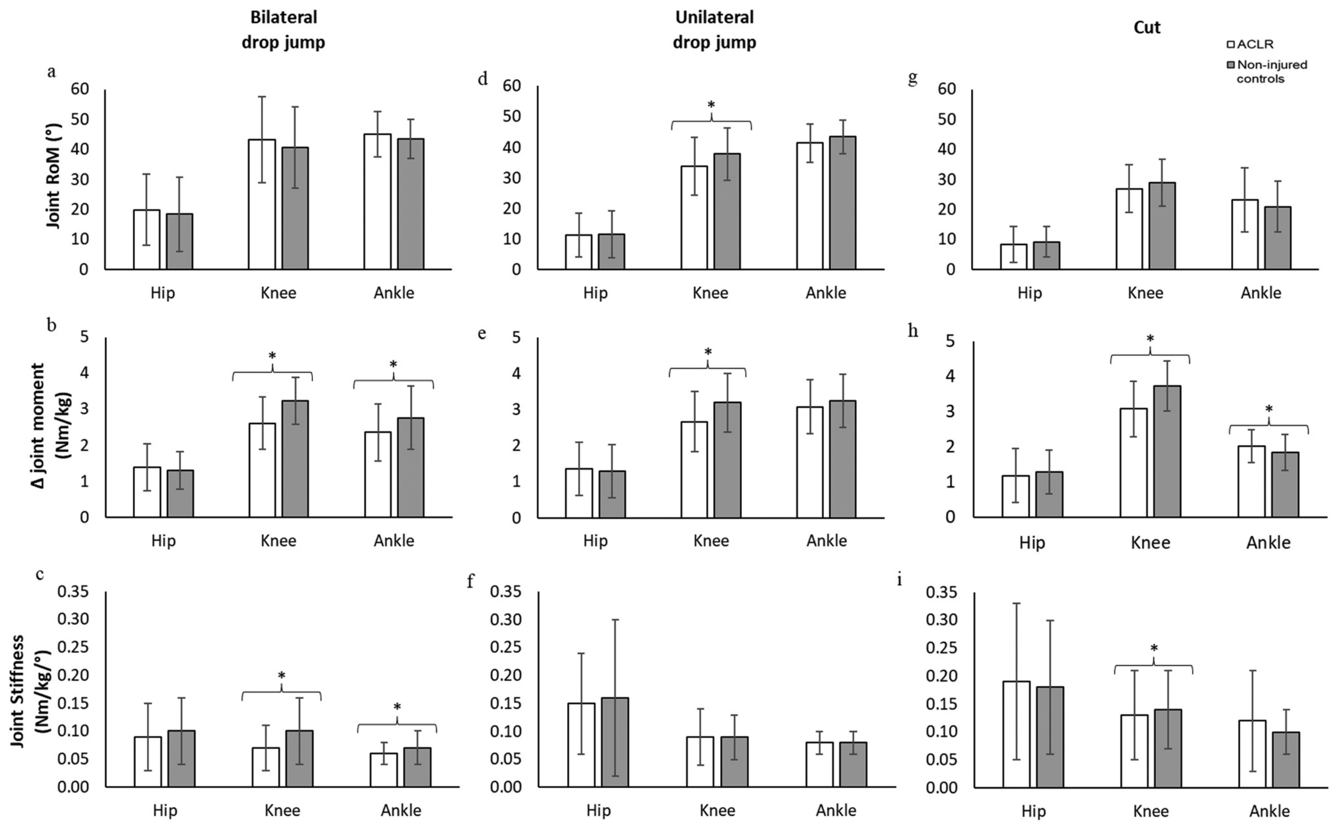

Figure 2. Group comparisons of the joint RoM, Δ joint moment and joint stiffness for the (a-c) bilateral drop jump, (d-f) unilateral drop jump, and (g-i) 90° pre-planned cut. White bars represent ACLR patients. Grey bars represent non-injured controls. *$p \leq 0.05$. RoM = range of motion; Δ = change in; ACLR = anterior cruciate ligament reconstruction.

motor learning strategies (e.g., differential learning (Gokeler et al., 2019; Schöllhorn et al., 2012)) to improve quadricep activation patterns (e.g., measured from electromyography or using musculoskeletal modelling) that may allow ACLR patients to more effectively attenuate the forces experienced when landing. Variations of a bilateral drop jump (e.g., landing on toes, keeping arms across chest when jumping, closing one eye), changing the environment (e.g., performing the bilateral drop jump in the dark or with noise from audience in a stadium) and the athlete performing the exercise in a fatigued state are just a few examples of how differential learning can be applied to practicing a bilateral drop jump that may lead to the emergence of more effective neural activity and movement strategies to execute the task (Gokeler et al., 2019).

Due to smaller changes in knee moments, a lower knee stiffness was found in the ACLR patients during the bilateral drop jump (medium effect size) and cut (negligible effect size). A lower knee stiffness in the ACLR patients may indicate a movement strategy compensation to protect the involved limb or that insufficient rehabilitation has been undertaken. During the cut, a significant but negligible effect size was reported, which warrants the need for further investigations into whether lower knee stiffness is a compensatory strategy following ACLR or if it reflects insufficient rehabilitation and should, therefore, be targeted earlier and more consistently throughout rehabilitation. Although this study was retrospective in nature, a prospective study may provide better clarity on whether knee stiffness is a risk factor for ACL injury. Conversely, during the unilateral drop jump, ACLR patients displayed significantly smaller changes in knee moment, as well as reduced knee RoM. Lower knee RoM during unilateral rebounds are often referred to as stiffer landings (Johnston et al., 2018b), but our findings show joint level and vertical stiffness to be unaffected. Characterising the type of landing using only knee RoM, therefore, appears to be too simplistic and inaccurate. Thus, using knee RoM to characterise landing stiffness should be approached with caution.

Due to smaller changes in ankle moments during the bilateral drop jump, a lower ankle stiffness was observed in the ACLR patients compared to controls. This aligns with previous research whereby ankle moments were lower in ACLR patients compared to non-injured controls during a bilateral drop jump (Mueske et al., 2018). Decreased ankle plantar flexor moments may increase the demand of the knee extensor muscles to aid with shock absorption (Shimokochi et al., 2009). Yet, in the bilateral drop jump, lower internal knee extensor moments were observed as well as reduced ankle plantar flexor moments in the ACLR patients. This could potentially indicate that during the bilateral drop jump the ACLR patients shifted the demand of landing on to their uninvolved limb (interlimb compensation), which may increase their risk of sustaining a contralateral ACL injury. This shift towards the uninvolved limb is supported by recent evidence showing a reduced energy absorption ability in the ACLR knee during landing from a jump (Brightwell et al., 2023). Future research may wish to consider comparing lower limb joint moments between the ACL reconstructed limb to the uninvolved limb to understand compensatory movement strategy adjustments in more detail. However, comparing the ACL reconstructed limb to the uninvolved limb ignores the likelihood that bilateral deficits are present following ACLR (Kline et al., 2015); thus, between limb comparisons, post-ACLR should be interpreted with caution.

A limitation of this study was that joint stiffness was defined using a simplistic model as the ratio of joint moments to joint RoM (Farley et al., 1998), which fails to account for multiple components within the multi-joint system (e.g., degrees of freedom, tendons, ligaments, bones, etc.). Joint stiffness is influenced by both active (e.g., muscles) and passive (e.g., ligaments) elements (Dixon et al., 2010; Wojtys et al., 2003). A combination of both passive and active elements in similar proportions is required to resist external loads. If active joint stiffness is reduced, however, a greater proportion of the load must be borne by passive structures (Wojtys et al., 2003). Passive joint stiffness can be measured using an isokinetic dynamometer. Subtracting passive joint stiffness as a function of joint angle from the total joint stiffness to obtain the active joint stiffness, which is accounted for by muscular activity, could be useful for practitioners to understand the differences in active and passive joint stiffness ratios in ACLR patients that increase the load on the ACL, and thus, resulting in increased ACL injury risk. Secondly, a retrospective cohort design was utilized in this study. Ideally, a prospective cohort design should be used to quantify differences in biomechanical variables that would more accurately reflect injury risk factors. However, prospective studies are time-consuming and expensive, with no certainty that an injury will occur. Thirdly, the data in our study did not allow for a detailed analysis of rehabilitation status and its correlation with biomechanical characteristics. Although the ACLR patients were all between 8 and 10 months post-surgery, no specifics on, e.g., physical activity or acute/chronic pain levels, were available. Future work may focus on the biomechanical variables of interest determined in this study, in relation to quantified rehabilitation parameters. Finally, we did not account for the influence of graft type. Lower knee flexion moments have been found in ACLR patients who have undergone a bone patellar tendon bone graft compared to a hamstring graft; however, both graft types have lower knee flexion moments compared to controls (Mueske et al., 2018). Whilst the magnitude of differences between ACLR patients and non-injured controls may alter slightly if graft types are controlled for, the general direction of the differences would be expected to remain unchanged.

Conclusion

This study found that joint level analysis may offer practitioners a better insight into an athlete's movement strategies during RTS assessments as opposed to whole body analysis. The knee joint especially showed the strongest significant effects across all movements and variables. Compared to non-injured controls, ACLR patients displayed reduced knee moments during all movements typically performed in practitioner assessments of ACL injury risk. This resulted in lower knee stiffness being observed during the bilateral drop jump and cut. However, during the unilateral drop jump, there were no differences between ACLR patients and controls in knee stiffness as the ACLR patients displayed smaller changes in knee moments as well as reduced knee RoM. Overall, these findings highlight differences between ACLR patients and non-injured controls in knee RoM, moment and stiffness. These differences may be a safety mechanism employed to reduce the risk of second ACL injury or a compensatory strategy that may increase the risk of second injury. To determine if knee RoM, moment and stiffness are associated with ACL injury risk, future research should assess these variables by means of a prospective study.

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References

Blackburn, T., Pietrosimone, B., Goodwin, J. S., Johnston, C., & Spang, J. T. (2019). Co-activation during gait following anterior cruciate ligament reconstruction. *Clinical Biomechanics*, *67*, 153–159. https://doi.org/10.1016/j.clinbiomech.2019.05.010

Brightwell, B. D., Samaan, M. A., Johnson, D., & Noehren, B. (2023). Dynamic knee joint stiffness during bilateral lower extremity landing 6 months after ACL reconstruction. *The Knee*, *42*, 73–81. https://doi.org/10.1016/j.knee.2023.02.017

Buckthorpe, M. (2019). Optimising the late-stage rehabilitation and return-to-sport training and testing process after ACL reconstruction. *Sports Medicine (Auckland, NZ)*, *49*(7), 1043–1058. https://doi.org/10.1007/s40279-019-01102-z

Buckthorpe, M., & Della Villa, F. (2020). Optimising the 'Mid-Stage' training and testing process after ACL reconstruction. *Sports Medicine*, *50*(4), 657–678. https://doi.org/10.1007/s40279-019-01222-6

Burland, J. P., Lepley, A. S., Frechette, L., & Lepley, L. K. (2020). Protracted alterations in muscle activation strategies and knee mechanics in patients after anterior cruciate ligament Reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, *28*(12), 3766–3772. https://doi.org/10.1007/s00167-019-05833-4

Butler, R. J., Crowell, H. P., & Davis, I. M. (2003). Lower extremity stiffness: Implications for performance and injury. *Clinical Biomechanics*, *18*(6), 511–517. https://doi.org/10.1016/S0268-0033(03)00071-8

Croisier, J. L., Ganteaume, S., Binet, J., Genty, M., & Ferret, J.-M. (2008). Strength imbalances and prevention of hamstring injury in professional soccer players: A prospective study. *The American Journal of Sports Medicine*, *36*(8), 1469–1475. https://doi.org/10.1177/0363546508316764

Davis, R. B., & DeLuca, P. A. (1996). Gait characterization via dynamic joint stiffness. *Gait & Posture*, *4*(3), 224–132. https://doi.org/10.1016/0966-6362(95)01045-9

Decker, M. J., Torry, M. R., Noonan, T. J., Riviere, A., & Sterett, W. I. (2002). Landing adaptations after ACL reconstruction. *Medicine and Science in Sports and Exercise*, *34*(9), 1408–1413. https://doi.org/10.1097/00005768-200209000-00002

Dempster, W. T. (1955). Space requirements of the seated operator: Geometrical, kinematic, and mechanical aspects of the body with special reference to the limbs. *WADC Technical Report*, *5*, 5–159. https://deepblue.lib.umich.edu/handle/2027.42/4540.

Dixon, S. J., Hinman, R. S., Creaby, M. W., Kemp, G., & Crossley, K. M. (2010). Knee joint stiffness during walking in knee osteoarthritis. *Arthritis Care & Research*, *62*(1), 38–44. https://doi.org/10.1002/acr.20012

Farley, C., Houdijk, H. H. P., Van Strien, C., & Louie, M. (1998). Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses. *Journal of Applied Physiology*, *85*(3), 1044–1055. https://doi.org/10.1152/jappl.1998.85.3.1044

Friemert, B., Franke, S., Gollhofer, A., Claes, L., & Faist, M. (2010). Group I afferent pathway contributes to functional knee stability. *Journal of Neurophysiology*, *103*(2), 616–622. https://doi.org/10.1152/jn.00172.2009

Gokeler, A., Hof, A. L., Arnold, M. P., Dijkstra, P. U., Postema, K., & Otten, E. (2010). Abnormal landing strategies after ACL reconstruction. *Scandinavian Journal of Medicine & Science in Sports*, *20*(1), 12–19. https://doi.org/10.1111/j.1600-0838.2008.00873.x

Gokeler, A., Neuhaus, D., Benjaminse, A., Grooms, D. R., & Baumeister, J. (2019). Principles of motor learning to support neuroplasticity after ACL injury: Implications for optimizing performance and reducing risk of second ACL injury. *Sports Medicine*, *49*(6), 853–865. https://doi.org/10.1007/s40279-019-01058-0

Johnston, P., McClelland, J., & Webster, K. (2018). Lower limb biomechanics during single-leg landings following anterior cruciate ligament reconstruction: A systematic review and meta-analysis. *Sports Medicine*, *48*(9), 2103–2126. https://doi.org/10.1007/s40279-018-0942-0

Jones, H., Moore, I. S., King, E., Stiles, V. H., Laudani, L., McCarthy-Ryan, M., McFadden, C., & Daniels, K. A. J. (2022). Movement strategy correspondence across jumping and cutting tasks after anterior cruciate ligament reconstruction. *Scandinavian Journal of Medicine & Science in Sports*, *32*(3), 612–621. https://doi.org/10.1111/sms.14104

King, E., Richter, C., Daniels, K. A. J., Franklyn-Miller, A., Falvey, E., Myer, G. D., Jackson, M., Moran, R., & Strike, S. (2021). Can biomechanical testing after anterior cruciate ligament reconstruction identify athletes at risk for subsequent ACL injury to the contralateral uninjured limb? *The American Journal of Sports Medicine*, *49*(3), 609–619. https://doi.org/10.1177/0363546520985283

King, E., Richter, C., Franklyn-Miller, A., Daniels, K., Wadey, R., Moran, R., & Strike, S. (2018A). Whole-body biomechanical differences between limbs exist 9 months after ACL reconstruction across jump/landing tasks. *Scandinavian Journal of Medicine & Science in Sports*, *28*(12), 2567–2578. https://doi.org/10.1111/sms.13259

King, E., Richter, C., Franklyn-Miller, A., Daniels, K., Wadey, R., Jackson, M., Moran, R., & Strike, S. (2018b). Biomechanical but not timed performance asymmetries persist between limbs 9 months after ACL reconstruction during planned and unplanned change of direction. *Journal of Biomechanics*, *81*, 93–103. https://doi.org/10.1016/j.jbiomech.2018.09.021

King, E., Richter, C., Franklyn-Miller, A., Wadey, R., Moran, R., & Strike, S. (2019). Back to normal symmetry? Biomechanical variables remain more asymmetrical than normal during jump and change-of-direction testing 9 months after anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine*, *47*(5), 1175–1185. https://doi.org/10.1177/0363546519830656

Kline, P. W., Morgan, K. D., Johnson, D. L., Ireland, M. L., & Noehren, B. (2015). Impaired quadriceps rate of torque development and knee mechanics after anterior cruciate ligament reconstruction with patellar tendon autograft. *The American Journal of Sports Medicine*, *43*(10), 2553–2558. https://doi.org/10.1177/0363546515595834

Kosaka, T., Sasajima, S., Yasuda, A., Mino, S., & Kubo, K. (2023). Determinants of joint stiffness and jumping height during drop jump. *Physiological Reports*, *11*(11), e15678. https://doi.org/10.14814/phy2.15678

Kristianslund, E., Krosshaug, T., & Van Den Bogert, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. *Journal of Biomechanics*, *45*(4), 666–671. https://doi.org/10.1016/j.jbiomech.2011.12.011

Lewek, M., Rudolph, K., Axe, M., & Snyder-Mackler, L. (2002). The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. *Clinical Biomechanics*, *17*(1), 56–63. https://doi.org/10.1016/S0268-0033(01)00097-3

Maestroni, L., Papadopoulos, K., Turner, A., Korakakis, V., & Read, P. (2021). Relationships between physical capacities and biomechanical variables during movement tasks in athletic populations following anterior cruciate ligament reconstruction. *Physical Therapy in Sport*, *48*, 209–218. https://doi.org/10.1016/j.ptsp.2021.01.006

Marshall, B. M., Franklyn-Miller, A. D., King, E. A., Moran, K. A., Strike, S. C., & Falvey, É. C. (2014). Biomechanical factors associated with time to complete a change of direction cutting maneuver. *The Journal of Strength & Conditioning Research*, *28*(10), 2845–2851. https://doi.org/10.1519/JSC.0000000000000463

Mueske, N. M., VandenBerg, C. D., Pace, J. L., Katzel, M. J., Zaslow, T. L., Padilla, R. A., & Wren, T. A. L. (2018). Comparison of drop jump landing biomechanics and asymmetry among adolescents with hamstring, patellar and quadriceps tendon autografts for anterior cruciate ligament reconstruction. *The Knee*, *25*(6), 1065–1073. https://doi.org/10.1016/j.knee.2018.09.005

Oh, J., & Lee, H.-D. (2022). Influence of eccentric strength of knee extensor muscles on biomechanical factors of a vertical drop jump. *Journal of Electromyography and Kinesiology*, *64*, 102648. https://doi.org/10.1016/j.jelekin.2022.102648

Padua, D. A., Carcia, C. R., Arnold, B. L., & Granata, K. P. (2005). Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. *Journal of Motor Behavior*, *37*(2), 111–126. https://doi.org/10.3200/JMBR.37.2.111-126

Pamukoff, D. N., Pietrosimone, B. G., Ryan, E. D., Lee, D. R., & Blackburn, J. T. (2017). Quadriceps function and hamstrings Co-activation after anterior cruciate ligament reconstruction. *Journal of Athletic Training*, *52*(5), 422–428. https://doi.org/10.4085/1062-6050-52.3.05

Pappas, E., Hagins, M., Sheikhzadeh, A., Nordin, M., & Rose, D. (2007). Biomechanical differences between unilateral and bilateral landings from a jump: Gender differences. *Clinical Journal of Sport Medicine*, *17*(4), 263–268. https://doi.org/10.1097/JSM.0b013e31811f415b

Paterno, M., Ford, K. R., Myer, G. D., Heyl, R., & Hewett, T. E. (2007). Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. *Clinical Journal of Sport Medicine*, *17*(4), 258–262. https://doi.org/10.1097/JSM.0b013e31804c77ea

Paterno, M., Rauh, M. J., Schmitt, L. C., Ford, K. R., & Hewett, T. E. (2012). Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clinical Journal of Sport Medicine*, *22*(2), 116–121. https://doi.org/10.1097/JSM.0b013e318246ef9e

Paterno, M., Schmitt, L. C., Ford, K. R., Rauh, M. J., Myer, G. D., & Hewett, T. E. (2011). Effects of sex on compensatory landing strategies upon return to sport after anterior cruciate ligament reconstruction. *Journal of Orthopaedic & Sports Physical Therapy*, *41*(8), 553–559. https://doi.org/10.2519/jospt.2011.3591

Rice, D., & McNair, P. (2010). Quadriceps arthrogenic muscle inhibition: Neural mechanisms and treatment perspectives. *Seminars in Arthritis and Rheumatism*, *40*(3), 250–266. https://doi.org/10.1016/j.semarthrit.2009.10.001

Rudolph, K. Michael J. Axe, Thomas S. Buchanan, John P. Scholz & Lynn Snyder-Mackler. (2001). Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surgery, Sports Traumatology, Arthroscopy*, *9*(2), 62–71. doi:10.1007/s001670000166.

Schmitt, L., Paterno, M. V., Ford, K. R., Myer, G. D., & Hewett, T. E. (2015). Strength asymmetry and landing mechanics at return to sport after anterior cruciate ligament reconstruction. *Medicine and Science in Sports and Exercise*, *47*(7), 1426–1434. https://doi.org/10.1249/MSS.0000000000000560

Schöllhorn, W. I., Hegen, P., & Davids, K. (2012). The nonlinear nature of learning - a differential learning approach. *The Open Sports Sciences Journal*, *5*(1), 100–112. https://doi.org/10.2174/1875399X01205010100

Serpell, B. G., Ball, N. B., Scarvell, J. M., & Smith, P. N. (2012). A review of models of vertical, leg, and knee stiffness in adults for running, jumping or hopping tasks. *Journal of Sports Sciences*, *30*(13), 1347–1363. https://doi.org/10.1080/02640414.2012.710755

Serpell, B. G., Scarvell, J. M., Pickering, M. R., Ball, N. B., Perriman, D., Warmenhoven, J., & Smith, P. N. (2016). Vertical stiffness is not related to anterior cruciate ligament elongation in professional rugby union players. *BMJ Open Sport and Exercise Medicine*, *2*(1), e000150. https://doi.org/10.1136/bmjsem-2016-000150

Shelbourne, K. D., Benner, R., Gray, T., & Bauman, S. (2022). Range of motion, strength, and function after ACL reconstruction using a contralateral patellar tendon graft. *Orthopaedic Journal of Sports Medicine*, *10*(11). https://doi.org/10.1177/23259671221138103

Shi, H., Huang, H., Ren, S., Yu, Y., Liang, Z., Wang, Q., Hu, X., & Ao, Y. (2019). The relationship between quadriceps strength asymmetry and knee biomechanics asymmetry during walking in individuals with anterior cruciate ligament reconstruction. *Gait & Posture*, *73*, 74–79. https://doi.org/10.1016/j.gaitpost.2019.07.151

Shimokochi, Y., Yong Lee, S., Shultz, S. J., & Schmitz, R. J. (2009). The relationships among sagittal-plane lower extremity moments: Implications for landing strategy in anterior cruciate ligament injury prevention. *Journal of Athletic Training*, *44*(1), 33–38. https://doi.org/10.4085/1062-6050-44.1.33

Smeets, A., Verheul, J., Vanrenterghem, J., Staes, F., Vandenneucker, H., Claes, S., & Verschueren, S. (2020). Single-joint and whole-body movement changes in anterior cruciate ligament athletes returning to sport. *Medicine and Science in Sports and Exercise*, *52*(8), 1658–1667. https://doi.org/10.1249/MSS.0000000000002308

Smith, H. C., Johnson, R. J., Shultz, S. J., Tourville, T., Holterman, L. A., Slauterbeck, J., Vacek, P. M., & Beynnon, B. D. (2012). A prospective evaluation of the landing error scoring system (LESS) as a screening tool for anterior cruciate ligament injury risk. *The American Journal of Sports Medicine*, *40*(3), 521–526. https://doi.org/10.1177/0363546511429776

Verheul, J., Clansey, A. C., & Lake, M. J. (2017). Adjustments with running speed reveal neuromuscular adaptations during landing associated with high mileage running training. *Journal of Applied Physiology*, *122*(3), 653–665. https://doi.org/10.1152/japplphysiol.00801.2016

Williams, D. S., Davis, I. M., Scholz, J. P., Hamill, J., & Buchanan, T. S. (2004). High-arched runners exhibit increased leg stiffness compared to low-arched runners. *Gait & Posture*, *19*(3), 263–269. https://doi.org/10.1016/S0966-6362(03)00087-0

Williams, D. S., McClay, I. S., & Hamill, J. (2001). Arch structure and injury patterns in runners. *Clinical Biomechanics*, *16*(4), 341–347. https://doi.org/10.1016/S0268-0033(01)00005-5

Wojtys, E. M., Huston, L. J., Schock, H. J., Boylan, J. P., & ASHTON-MILLER, J. A. (2003). Gender differences in muscular protection of the knee in torsion in size-matched athletes. *The Journal of Bone and Joint Surgery-American Volume*, *85*(5), 782–789. https://doi.org/10.2106/00004623-200305000-00002