DIFFERENCES IN LOWER LIMB JOINT STIFFNESS IN MULTIPLE MOVEMENTS FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

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Altered lower limb joint kinetics are frequently observed following anterior cruciate ligament reconstruction (ACLR), which may lead to an increased risk of re-injury. The aim of this study was to establish the extent to which joint stiffness differs in a unilateral and bilateral drop jump, and a 90° pre-planned cut following ACLR. A cohort of 127 male patients 8–10 months post-ACLR and 45 non-injured controls took part in the study. Both a unilateral and bilateral drop jump, and a 90° pre-planned cut were completed, while ground reaction forces and three-dimensional kinematics were recorded. ACLR patients had lower knee stiffness for the cut (d=0.192, p=0.040) and the bilateral drop jump (d=0.534, p<0.001) compared to non-injured controls. There were no differences in ankle, knee or hip joint stiffness in the unilateral drop jump between groups. To reduce re-injury risk, interventions could focus on quadriceps strengthening to facilitate improvements in stiffness during cuts and bilateral movements, and movement retraining during unilateral movements.

KEYWORDS: ACL, joint stiffness, rehabilitation, return to sport

INTRODUCTION: Non-contact anterior cruciate ligament (ACL) ruptures are one of the most debilitating injuries in multidirectional field sports. These injuries involve sudden decelerations, such as landing from a jump or planting the foot during a cutting manoeuvre (Alentorn-Geli et al., 2009). Even after an extensive course of rehabilitation to restore the function of the knee following ACL reconstruction (ACLR) surgery, alterations in lower limb joint kinetics can still be observed in movements included in return to sport (RTS) assessments, which may contribute to an increase in ACL reinjury risk (Paterno et al., 2010). King et al. (2021) reported reduced whole-body vertical stiffness in athletes who progressed to secondary ACL injury within two years compared to those who did not. However, the differences in ankle, knee and hip stiffness that contribute to whole-body vertical stiffness in these movements are not yet understood. Compared to non-injured controls, ACLR patients had greater ankle range of motion (RoM) throughout the braking phase of a drop landing (Decker et al., 2002) as well as lower average sagittal plane ankle and knee moments, and higher hip moments during a bilateral vertical drop jump (Mueske et al., 2018). A clearer understanding of how ankle, knee and hip joint stiffness differs in post-ACLR athletes across multiple movements may help clinicians identify the readiness of athletes to return to sport (RTS) and potentially help to reduce the risk of reinjury following ACLR. We hypothesised that ACLR patients would demonstrate decreased sagittal plane ankle and knee moments, and increased ankle RoM and hip moments, subsequently displaying lower ankle and knee joint stiffness, and higher hip joint stiffness compared to non-injured controls.

METHODS: A total of 172 male, multidirectional field sport athletes aged 18 - 35 years took part in the study, comprising of 127 ACLR patients (height: 1.81 ± 0.06 m; mass: 82.7 ± 9.3 kg) who had undergone surgery 8-10 months prior to testing and 45 non-injured controls (height: 1.82 ± 0.07 m; mass: 81.4 ± 7.8 kg). All patients in the ACLR group had undergone either a hamstring graft (semitendinosus or gracilis tendons) or a bone patellar tendon bone graft from the ipsilateral side during surgery. The control group were locally recruited from multidirectional field sports teams. Participants visited the laboratory once, completing three movement tasks as part of a clinical testing battery: a bilateral drop jump, a unilateral drop jump and a 90° pre-planned cut. All kinetic and kinematic data were collected using an eight-camera motion analysis system (200 Hz; Vicon Motion Systems Ltd), synchronised with two force platforms (1000 Hz; BP400600, AMTI) recording 24 reflective markers (14-mm diameter) and ground reaction forces (Vicon 2.10.0, Oxford Metrics), respectively. The Plugin-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. The braking phase was defined as the time between initial contact (the frame vertical ground reaction force exceeded 20 N) to the frame preceding the lowest vertical centre of mass (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. Kinematic and kinetic analyses were carried out in MATLAB (R2019b; MathWork, Inc). Standard inverse dynamics procedures were used to calculate joint moments (reported as internal moments) at the ankle, knee and hip joints in the sagittal plane, and the instantaneous body CoM position was estimated based on segment inertial properties. Positive sagittal plane internal joint moments relate to ankle plantarflexion, and knee and hip extension. Joint stiffness was determined as the ratio of change in sagittal plane joint moments (calculated as the magnitude of change from initial contact to lowest CoM) to joint RoM (calculated between the same time points).

Means (M) of all three trials for each participant were computed (± standard deviation; SD). For statistical analysis the Kolmogorov-Smirnov test was used to test for normality for all variables in each condition between groups. A Mann-Whitney test was performed for variables that were found to violate the assumption of normality, and an independent samples t-test was performed otherwise. Cohen's d standardized effect size was calculated and interpreted as small (d = 0.2), medium (d = 0.5), and large (d = 0.8) (Cohen, 2013). Statistical analysis was performed using SPSS Statistics (SPSS 27, IBM). The level of significance was set at $p \leq 0.05$.

RESULTS: For the cut, there was no differences in hip and ankle joint stiffness between the ACLR patients and controls, whilst the ACLR patients had a lower knee joint stiffness (d=0.192, p=0.040) (Figure 1a). There was no difference in hip moment changes between the ACLR patients and controls, however the ACLR patients displayed a respective smaller and greater change in knee and ankle joint moment than the controls (d=-0.848, p<0.001 and d=0.376, p=0.044, respectively) (Table 1). There were no significant differences in ankle, knee and hip RoM between the ACLR patients and controls.

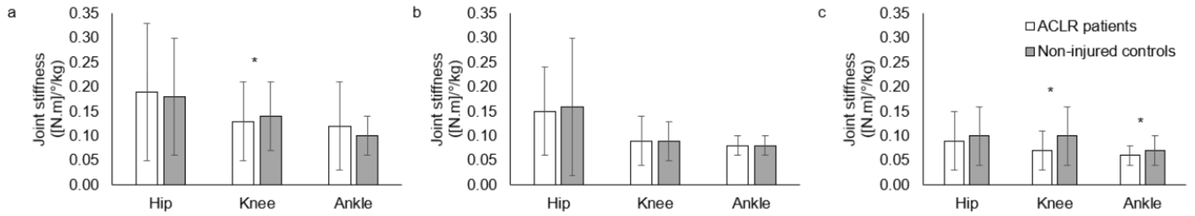

Figure 1. Joint stiffness ±SD at the hip, knee and ankle joints for the (a) 90' pre-planned cut, (b) unilateral drop jump, and (c) bilateral drop jump. White bars represent ACLR patients. Grey bars represent non-injured controls. *$p \leq 0.05$.

For the unilateral drop jump, there was no difference between the ACLR patients and controls in hip, knee and ankle joint stiffness, or any differences in change in hip and ankle internal joint moments and RoM (Figure 1b and Table 1). The ACLR patients had smaller change in knee moments and RoM than the controls (d=-0.634, p<0.001 and d=0.437, p=0.013, respectively) (Table 1).

For the bilateral drop jump, compared to the controls, the ACLR patients had lower knee and ankle joint stiffness (d=0.534, p<0.001 and d=0.457, p=0.003, respectively) and moments (d=-0.906, p<0.001 and d=-0.480, p=0.006, respectively) (Figure 1c and Table 1). There were no differences between the ACLR patients and controls in hip joint stiffness, change in hip moments, or change in hip, knee and ankle RoM.

Table 1. Mean (SD) data for internal joint moments and angular displacement for ACLR patients and non-injured controls at the hip, knee and ankle joints for the cut, unilateral drop jump and bilateral drop jump.

Variables	Group	90° pre-planned cut			Unilateral drop jump			Bilateral drop jump		
		M (SD)	*p-value*	Cohen's *d*	M (SD)	*p-value*	Cohen's *d*	M (SD)	*p-value*	Cohen's *d*
Δ hip flexion moment ([N.m]/kg)	ACLR patients	-1.18 (0.76)	0.134	-0.16	1.36 (0.74)	0.652	0.10	1.39 (0.65)	0.383	0.15
	Non-injured controls	-1.29 (0.62)			1.29 (0.74)			1.30 (0.53)		
Δ knee flexion moment ([N.m]/kg)	ACLR patients	-3.07 (0.78)	**<0.001**	-0.85	2.67 (0.84)	**<0.001**	-0.63	2.61 (0.72)	**<0.001**	-0.91
	Non-injured controls	-3.72 (0.71)			3.20 (0.82)			3.24 (0.65)		
Δ ankle moment ([N.m]/kg)	ACLR patients	-2.01 (0.47)	**0.044**	0.38	3.08 (0.75)	0.192	-0.23	2.36 (0.79)	**0.006**	-0.48
	Non-injured controls	-1.83 (0.51)			3.25 (0.73)			2.76 (0.88)		
Hip RoM (°)	ACLR patients	8.30 (6.01)	0.075	0.16	11.31 (7.22)	0.874	0.04	19.85 (11.81)	0.273	-0.12
	Non-injured controls	9.16 (5.04)			11.59 (7.67)			18.38 (12.37)		
Knee RoM (°)	ACLR patients	26.88 (7.91)	0.159	0.25	33.77 (9.40)	**0.013**	0.44	43.31 (14.34)	0.411	-0.19
	Non-injured controls	28.81 (7.79)			37.79 (8.65)			40.71 (13.59)		
Ankle RoM (°)	ACLR patients	23.16 (10.77)	0.206	-0.22	41.43 (6.23)	0.062	0.33	45.01 (7.48)	0.210	-0.22
	Non-injured controls	20.91 (8.53)			43.40 (5.39)			43.42 (6.55)		

Note: p-values and effect sizes are reported. Bold indicates p≤0.05. RoM; range of motion. Δ; change in.

DISCUSSION:

Our hypothesis was partially supported as ACLR patients produced lower knee joint stiffness and moments during the cut and the bilateral drop jump compared to controls. In the unilateral drop jump, there were no differences in ankle, knee, or hip joint stiffness, though the ACLR patients displayed smaller changes in knee joint internal moments and smaller RoM compared to controls.

Due to smaller changes in sagittal plane internal knee moment, a decreased knee stiffness was found for ACLR patients during the bilateral drop jump and cut compared to controls. An ACLR limb has been found to have a lower knee extension moment through stance compared to the contralateral healthy limb in jump testing (Lewek et al., 2002; Schmitt et al., 2012) and planned/ unplanned 90° cutting tasks (King et al., 2018), which has been linked with ongoing quadriceps strength deficits. Due to the quadricep muscles being responsible for generating the knee extensor moment during the braking phase, an isolated decrease in quadriceps force would produce a smaller knee extensor moment (Gardinier et al., 2012). Persistent quadriceps weakness and subsequent diminished ability to absorb load on the ACLR limb may increase the risk of re-injury to the knee joint for ACLR patients returning to sport (Rice & McNair, 2010). As it is possible to improve quadriceps strength through rehabilitation, it would be advantageous for clinicians to resolve these persistent strength deficits prior to RTS.

Unlike the bilateral drop jump and the cut, in the unilateral drop jump there were no differences in knee joint stiffness between groups. However, whilst during the bilateral drop jump and the cut ACLR patients had smaller changes in knee moments without differences in knee RoM compared to controls, during the unilateral drop jump ACLR patients had a smaller change in knee moment as well as reduced knee RoM compared to controls. Lower knee RoM during unilateral rebounds are often referred to as *stiffer* landings (Johnston et al., 2018), but our findings show joint level stiffness to be unaffected. However, lower knee RoM has been associated with greater ACL and knee joint loads (Blackburn & Padua, 2008; Tsai et al., 2017). This may potentially increase the risk of sustaining a second ACL injury, but knee RoM can be increased using movement retraining and is recommended following ACLR (Tsai et al., 2017).

CONCLUSION: This study found reduced knee stiffness in ACLR patients that may be associated with ACL re-injury risk. Knee joint stiffness should therefore be monitored in ACLR patients in RTS assessments and targeted though interventions if required. To reduce re-injury risk, interventions could focus on quadriceps strengthening to facilitate improvements in stiffness during cuts and bilateral movements, and movement retraining during unilateral movements.

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ACKNOWLEDGEMENTS: The authors would like to acknowledge the Biomechanics team at Sports Surgery Clinic for assistance with data collection and processing.