

Anterior cruciate ligament deficiency: rotational instability in the transverse plane. A preliminary laboratory *in vivo* study

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SUMMARY

Background. Rotational instability is a major feature of anterior cruciate ligament (ACL) deficiency. Few biomechanical studies have focused on the transverse plane when assessing the function of the ACL. **Objective.** To analyse the biomechanics of ACL deficient knees in the transverse plane under torsional conditions to detect rotational instability. **Methods.** Seven subjects (eight ACL deficiency) (ACLd group) and nine recreational athletes (controls) were recruited. Each performed two tasks: crossover and pivoting-jump. Biomechanical data were collected in a movement analysis laboratory. Comparisons were made for torque, rotation and torque curves in transverse plane between ACLd, contralateral knees and controls. **Results.** Torque curves showed an initial avoidance pattern followed by increased values in crossover task, and lesser values for ACLd group compared to controls in pivoting-jump task. Internal rotation in crossover was 19.8°, 13.7° and 19.1° for ACLd, contralateral and controls respectively ($p = 0.176$). In pivoting-jump these values were 18.6°, 13.8° and 18.1° ($p = 0.297$). Crossover peak torque were 257, 178.4 and 184.8 Nmm for ACLd, contralateral and controls ($p = 0.5$), while pivoting-jump values were 238.4, 152.2 and 218 Nmm for ACLd, contralateral and controls ($p = 0.288$). **Conclusion.** Torque curve analysis identified a distinctive pattern differentiating ACLd and control group. However, no statistically significant differences were found in peak transverse plane parameters between groups.

KEY WORDS

anterior cruciate ligament injury; kinematics; kinetics; rotational instability

BACKGROUND

Anterior cruciate ligament (ACL) tears are common sports-related non-contact injuries (1). ACL deficiency can lead to knee instability and secondary joint damage (2). The management of ACL deficiency aims to restore knee function, and

subjective and functional outcomes of surgical treatment have been reported as good and excellent in up to 80% of patients, with sport return rates near to 50% in amateur patients (3,4). Therefore, a high percentage of patients may experience suboptimal outcomes after treatment.

Osteoarthritis may develop after ACL injury or reconstruction in up to 13% of patients with isolated ACL injuries, and in up to 48% of patients with combined lesions at 10 years of follow up (5,6).

Persistent rotational instability is associated with poor outcomes, and surgical reconstruction techniques have moved from classical transtibial towards more anatomic reconstructions (7,8), with an increasing interest in reconstruction of the anterolateral structures (9). Restoration of the local anatomy is a cornerstone to optimise clinical and biomechanical outcomes (10). Nevertheless, ACL reconstruction does not necessarily restore normal biomechanics (11,12). This probably reflects the fact that the function of the ACL is complex, as it contributes to both anterior translational and anterolateral rotational stability.

Static translational anterior stability can be assessed clinically and instrumentally with the Lachman test and arthrometry, but rotational stability has been difficult to evaluate objectively (13). The pivot-shift test has the highest specificity, but only moderate sensitivity and reliability, and is highly examiner dependent (14). The pivot shift test involves motion in more than one plane, but evaluations of rotational stability should be performed under weight bearing conditions, thus reflecting real life instability (15-17). Previous biomechanical studies focused on the kinematics and kinetics in the sagittal and coronal planes, but less on transverse plane kinetics (12).

Therefore, the present study analysed both kinetic and kinematic parameters on the transverse plane in ACL deficient knees, assuming that rotational instability of the knee can be assessed under torsional weight-bearing conditions. In this way, we wished to ascertain whether a distinctive pattern in the transverse plane torque in ACL deficient knees under dynamic torsional conditions can be identified.

METHODS

Ethics

The University Ethics Committee approved all the procedures described in the present study. Each subject received a detailed information sheet and signed a consent form before participating. This study meets the ethical standards of Muscles, Ligaments and Tendons Journal (18).

Subjects

A total of 16 subjects were recruited. Seven had a total of eight ACL deficient knees, and constituted the experimental group (ACLd group), with a mean age of 33 years (range 20-41). Five subjects had primary ACL injuries, one subject

had a chronic re-injury after a full functional recovery, and one subject had a bilateral injury. There were six non-contact injuries related to football practice, and one contact injury in hockey. All subjects met the following five inclusion criteria: a confirmed ACL injury at magnetic resonance, a minimum of 6 months since the injury, an absence of relevant chondral or meniscal lesion, a completed rehabilitation program, and a positive pivot shift. All ACLd subjects were involved in recreational non-pivoting sports at the moment of testing. The mean IKDC score was 69 (range 56-81).

Nine healthy recreational athletes with a mean age of 26 years (range 23-41) and without history of knee pathology were recruited as a control group.

The demographics details of both groups are reported in **table I**.

Procedures

All subjects performed two manoeuvres: a crossover task (19) and a pivoting-jump task (15). All tests were performed at the Human Performance Laboratory of our University.

The crossover task consisted of four strides walking fast towards the force plate, and then turning 90° over the force plate towards the side of the planted foot, crossing over the swing limb. The planted foot had to remain pointing forward avoiding slipping over the force plate (**figure 1**). The subjects were instructed to reach the centre of the force plate with the tested foot without changes in speed or stride length.

In the pivoting-jump task, the subject started standing over the force plate with the limb to be tested, following by a knee flexion of 90° or more, while twisting the trunk forward and towards the same leg. In such way, the oppo-

Table I - Demographics and functional features of ACLd and control group.

	ACLd group (n = 7)	Control group (n = 9)	p value
age (years)	33.2 (20-41)	26.7 (23-41)	0.098
gender	m = 5; f = 2	m = 6; f = 2	0.554
weight (kg)	79.7 (63-107)	73.1 (68-93)	0.331
height (cm)	175 (168-180)	176 (159-185)	0.870
dominance	r = 7; l = 1	r = 6; l = 2	0.554
time since injury (years)	7 (0.5-20)	na	
IKDC score	69 (56-81)	97 (92-100)	< 0.001 ¹

Age, weight, height, time since injury and IKDC score are given in mean (range).

Na, not applicable; m, male; f, female; r, right; l, left.

¹Significant difference.

site shoulder should go over the plane of the planted lower limb. From this twisted position, the subjects were asked to jump vertically as high and fast as possible (**figure 1**).

Both tasks force the knee into internal rotation.

Before the definitive data collection, each subject performed at least 10 training attempts to familiarise themselves with the required tasks, which were performed without pain or discomfort. Before the experimental procedures, all subjects were examined by a fellowship trained sports trauma surgeon to verify the diagnosis of ACL deficiency.

Data collection

Kinematics data were collected using the Codamotion® 3D optoelectronic system (Charnwood Dynamics Ltd., Leicestershire, UK) at the Human Performance Laboratory, Centre for Sports and Exercise Medicine, Queen Mary University of London. Four Coda cx1® cameras aligned in a global coordinate system captured infrared signals at a sampling frequency of 200 Hz. Active markers were placed bilaterally on 13 anatomically defined points: the anterior and posterior iliac spines, the lateral and medial femoral epicondyles, the anterior tibial tuberosity, Gerdy tubercle, medial tibial plateau and lateral malleolus, the lateral aspect of the heel, and the head of the fifth metatarsal. Additional clusters of four markers were placed on the lateral aspect of the thigh and leg, and three additional markers were placed onto the patella (one at the inferior pole and two at the superior pole).

Kinetic data were collected using a ground level force plate (Kistler®, Winterthur, Switzerland) at a sampling frequency of 500 Hz. A set of three data collection bouts was made for each subject in each task with both legs, and five subjects of each group were tested in two consecutive weeks for reliability purposes.

Data analysis

Data extraction and analysis were made using inverse dynamics in Matlab® software (MathWorks®, Natick, Massachusetts, USA), version r2009a, using custom routines. The kinematic and kinetic data calculated were knee rotation and torque in the transverse plane. For these purposes, the actual knee transverse plane was extrapolated, thus torque was referred to that plane regardless of the degree of motion in the other planes. The average of the three trials for each task was calculated. In the control group, the average of both sides was also calculated, as no significant differences were found between dominant and non-dominant limbs. For torque curve comparisons, an average of curves in the ACLd and control group was obtained, and the whole stance period was divided into 40 equal time intervals.

Statistics

Descriptive and inferential statistics were performed using the IBM® SPSS® Statistics software, version 20. Demographic and anthropometric characteristics between groups were compared with the independent samples t-test for numerical variables, and with the Fisher's exact test for categorical data. Dependant variables were tested for distribution in each group with the Kolmogorov-Smirnov and Shapiro-Wilk tests ($p > 0.2$ and $p > 0.5$, respectively). One-way ANOVA test was used to assess differences between groups (ACLd, contralateral and Control groups). Tukey *post hoc* test was applied for multiple comparisons. Torque curves comparing the ACLd and control groups were analysed normalising stance time in 40 equal time intervals. A t test was applied for each interval, and the values obtained were checked with t tables.



Figure 1 – Left, right-hand side crossover task; right, right-hand side pivoting-jump task.

Significant difference was set at p value < 0.05. Reliability for the dependent variables was tested with the Intraclass Correlation Coefficients (ICC).

RESULTS

Reliability

The reliability of tibial internal rotation was good in the pivoting jump task (ICC 0.870), and reasonable in the crossover (ICC 0.703). Regarding the internal rotation moment, reliability was good for both the pivoting-jump (ICC 0.757) and the crossover task (ICC 0.808).

Function

As mentioned above, the mean IKDC subjective score was 69 (range 56-81) in the ACLd group, and 97.2 (range 92-100) in the control group. All ACLd subjects exhibited a positive pivot shift test. Five were classified as (++) and two as (+). No subject in the control group exhibited a positive pivot shift test.

Tibial internal rotation

Crossover task

Maximum tibial internal rotation values were not significantly different between ACLd, contralateral and control groups ($19.8^\circ \pm 7.3^\circ$, $13.7^\circ \pm 5.7^\circ$ and $19.1^\circ \pm 4.4^\circ$, respectively; p = 0.176).

Pivoting-jump task

No significant differences were found in tibial internal rotation between ACLd, contralateral and control groups ($18.6^\circ \pm 9.2^\circ$, $13.8^\circ \pm 6.3^\circ$ and $18.1^\circ \pm 4.3^\circ$, respectively; p = 0.297).

Torque

Crossover task

No significant differences were found in the peak internal rotation torque between ACLd, contralateral and control

groups (257 ± 152.4 , 178.4 ± 129.7 and 184.8 ± 83.4 Nmm, respectively; p = 0.5).

Pivoting-jump task

Peak internal rotation torque values were not significantly different between ACLd, contralateral and control groups (238.4 ± 104.4 , 152.2 ± 91.8 and 218 ± 73.6 Nmm, respectively; p = 0.288).

A summary of biomechanical data is given in **table II**.

Torque curves

Crossover

The knee internal rotation torque during stance was significantly different between ACLd and the control group at three time intervals (5 to 8, 22 to 29, and 33 to 39), showing the last interval higher values in the ACLd group (**figure 2**).

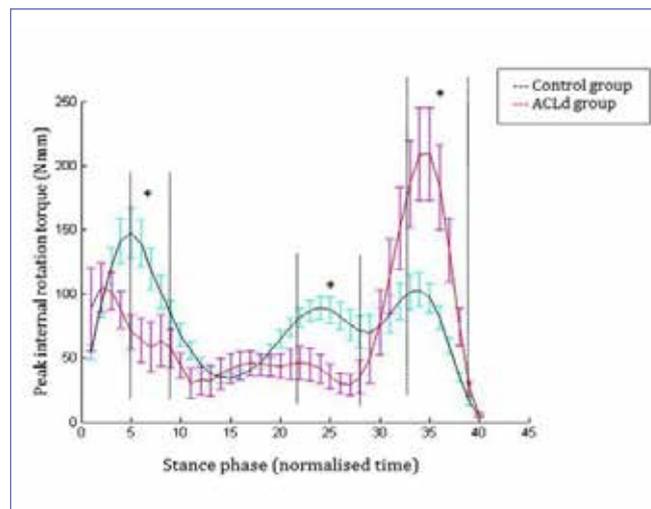


Figure 2 - Internal rotation torque (mean \pm standard deviation) in the ACLd and control group during the stance phase of the crossover task. Black vertical dashed lines with the asterisks show the periods in which the differences were significant.

Table II - Maximum tibial internal rotation and internal rotation torque for each group.

	Task	ACLd	Contralateral	Control	p value
Internal rotation	crossover	19.8 ± 7.3	13.7 ± 5.7	19.1 ± 4.4	0.176
	pivoting	18.6 ± 9.2	13.8 ± 6.3	18.1 ± 4.3	0.297
Torque	crossover	257 ± 152.4	178.4 ± 129.7	184.8 ± 83.4	0.5
	pivoting	238.4 ± 104.4	152.2 ± 91.8	218 ± 73.6	0.288

Values for internal rotation are in degrees (means \pm SD). Values for torque are in Nmm (means \pm SD). No significant differences were found.

Pivoting-jump

Torque values were lower in the ACLd group across the whole stance period, with significant differences from 13 to 18 time interval (figure 3).

DISCUSSION

Torque curves showed significant differences for internal rotation torque between ACLd and the control group at some stance intervals in both tasks, especially in the crossover task.

During the crossover task, the ACLd group showed lower internal rotation torques compared to the control group in the first two thirds of stance, but higher torques toward the end of the manoeuvre. These values can be interpreted as a dual behaviour, in which an initial avoidance pattern (i.e. lower protective values) at heel strike and mid stance is followed by a period of higher load. At this point, maximal torsional stress is transmitted to the knee if the supporting foot stands still until the swing limb completes the 90° turn. Perhaps it is not possible for ACLd subjects to maintain control or compensate as the crossover approaches to the end.

Remarkably, this increased internal rotation torque was not associated with an increase in internal rotation of the tibia. Therefore, regardless of the increase in the rotating torque acting at the knee, and regardless of the presence of clinical instability, actual dynamic instability was not detected with this manoeuvre.

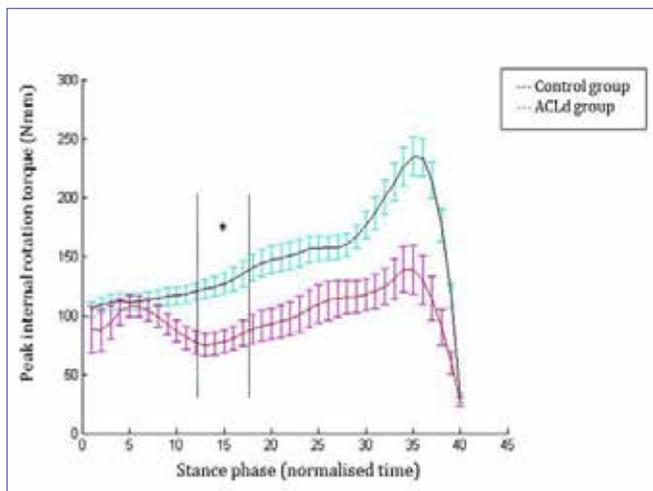


Figure 3 - Internal rotation torque (mean \pm standard deviation) in ACLd and control group during the stance phase of the pivoting task. Black vertical dashed lines with the asterisks show the period in which the differences were significant.

These results are different from other studies which have reported transverse plane parameters in crossover-like tasks. In particular, Houck et al. (16) did not find differences in the transverse plane parameters and curves between ACLd deficient and control groups. However, they showed that compensation occurs at hip level. On the other hand, Tsarouhas et al. (17) reported, using a step-cut manoeuvre task, lower values of internal rotation moment in ACLd knees compared to the contralateral knee and the control group. Our study did evidence higher values of internal rotation moment, thus highlighting a non-avoidance pattern.

The fact that no differences were found in maximum tibial internal rotation could be explained in several ways. First, compensatory mechanisms can be acting to avoid knee rotation, regardless of the amount of rotation torque calculated by inverse dynamics. These compensations may include complex neuromuscular adaptations, which lead to multilevel protective strategies (20,21). Secondly, it is possible that the method used to collect and calculate knee rotation was not sensitive enough. This protocol was used for the first time with marker placement that led to a different segmentation strategy. The use of skin markers can interfere with precise movement measuring. However, the values obtained are quite standard and in line with other studies in this field. Moreover, similar and simpler protocols have shown good sensitivity and reliability to detect tibial rotation (22). Finally, the task itself could be insufficient to produce a detectable increment in internal rotation of the tibia. It is possible that greater internal rotation moments, alone or combined with other force components, are necessary to reproduce rotational instability.

On the other hand, pivoting-jump task, beyond the interval of significant difference, showed a tendency to an avoidance pattern during the whole stance phase. This finding is similar to that reported by Sanchis-Alfonso et al. (15), who found an avoidance pattern in pivoting-jump tasks performed in external and internal rotation. These authors collected only kinetic data, and values of torque were calculated on the force plate surface itself, with the assumption that the knee lies over the point of application of the force, fact that was not proved. Their study concluded that an external rotation-pivoting task was useful to detect such avoidance pattern. This was not the case for the internal rotation task, which was the testing modality used in the present study. However, the authors did not comment on some features of the internal rotation task that were significantly different, such as the impulse, which can be an important variable, as it reflects the time in which the torque is acting. Additionally, as they collected only kinetic data, kinematics (i.e. internal rotation) were not reported.

The present study could be improved in several aspects. First, the experimental group was not homogenous. Two re-injured subjects were included, but, as they exhibited isolated chronic ACL instability without concomitant injuries, they were considered suitable to assess ACL related rotational instability. Additionally, tasks could be made more standardised to avoid performance bias. The factors that could be controlled are, for instance, speed or actual cutting angle in the crossover task, and knee flexion or trunk torsion in the pivoting jump. Also, the lack of normalization of torque data, more than a weakness itself, is an issue to be considered. In fact, the lesser values of torque were obtained in the heaviest subject, who performed the pivoting-jump task in such way that the ground reaction force passed very close to the centre of the knee. This example reinforces on the one hand the idea of performance standardization, and on the other the fact that the need of normalisation should be evaluated.

Therefore, this study should be considered preliminary, and must inform further investigation involving a greater number of subjects, or perhaps adding different tasks and measurements, so as to identify possible associations between torque applied to the knee and internal rotation of the tibia that could be obtained.

Torque curves can be easily obtained compared with kinematic data collection in a dedicated motion laboratory. Thus, finding a correlation between internal rotation and those curves, we could develop a valid, reliable and time saving method to assess biomechanically in vivo rotational behaviour of ACL deficient or reconstructed knees, as a fine-tuning evaluation of ACL reconstruction.

CONCLUSION

Given the small size of our cohort, the current study did not identify differences in biomechanical parameters in the transverse plane in the crossover and the pivoting-jump tasks between ACLd, contralateral knee and control groups. Torque curve analysis identified a distinctive pattern in the ACLd group compared to the control group. First, in the crossover task, lower values of internal rotation torque were found at the beginning and mid stance time intervals, followed by higher values toward the end of the stance phase. Secondly, pivoting-jump task showed a tendency towards avoidance pattern. These findings were not associated with increased internal rotation of the tibia. Further work is warranted to improve the quality of the results and stronger conclusions.

Conflict of Interest

The authors declare that they have no conflict of interest.

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