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ACL deficiency influences medio-lateral tibial alignment and knee varus–-valgus during in -vivo activities

Abstract

Purpose: The role of the anterior cruciate ligament (ACL) in knee biomechanics in vivo and under weight-bearing is still unclear. The purpose of this study was to compare the tibiofemoral kinematics of ACL--deficient knees to healthy contralateral ones during the execution of weight-bearing activities.

Methods: Eight patients with isolated ACL injury and healthy contralateral knees were included in the study. Patients were asked to perform a single step forward and a single leg squat first with the injured knee and then with the contralateral one. Knee motion was determined using a validated model-based tracking process that matched subject-specific MRI bone models to dynamic biplane radiographic images, under the principles of Roentgen stereophotogrammetric analysis (RSA). Data processing was performed in a specific software developed in Matlab.

Results: Statistically significant differences ($p<0.05$) were found for single leg squat along the frontal plane: ACL-deficient knees showed a more varus angle, especially at the highest knee flexion angles (40-50° on average), compared to the contralateral knees. Furthermore, ACL-deficient knees showed tibial medialization along the entire task, while contralateral knees were always laterally aligned. This difference became statistically relevant ($p<0.05$) for knee flexion angles included between 0° and about 30°.

Conclusion: ACL-–deficient knees showed an abnormal tibial medialization and increased varus angle during single leg squat when compared to the contralateral knees. These biomechanical anomalies could cause a different force distribution on tibial plateau, explaining the higher risk of early osteoarthritis in ACL deficiency. The clinical relevance of this study is that also safe activities used in ACL rehabilitation protocols are significantly altered in ACL deficiency.

Level of evidence: Level III

Keywords: Anterior cruciate ligament, Knee kinematics, In vivo, Single leg squat, Biplane radiography

Introduction

The role of anterior cruciate ligament (ACL) in knee kinematics has been largely investigated. ACL function as a primary restrain of the anterior tibial displacement in static conditions is widely accepted, like its probable role in acting like a secondary restraint of internal tibial rotation [1, 5, 8–11, 17–19, 24, 31]. The relevance of biomechanical studies and the importance of their constant technological improvement derive~~s~~ from the necessity of a better comprehension of mechanisms that lead to an improved risk of osteoarthritis in patients affected by ACL deficiency [1, 2, 5, 6, 9, 10, 14, 18, 23, 33].

In particular, the comprehension of how the lack of ACL modifies knee biomechanics not only in vivo and dynamically, but also under weight-bearing conditions, is crucial to gain information as close as possible to what happens in daily life motion.

Motion capture tools such as video- analysis and radiostereometry are valuable tools to understand better the biomechanics of the knee during common movements of daily and sport activities [1, 5, 8–10, 15, 18, 26, 33]. The main limits of these methods are related to their accuracy, because reconstruction of joint kinematics is based on skin~~s~~ sensors, which are affected by relevant artifacts. Double fluoroscopy overcomes the previous problem, because it allows studying directly bone movements through radiographs' exposition of patients executing motor tasks [3, 4, 6, 14, 29, 33]. In this scenario, joint~~s~~ biomechanical anomalies following distinct pathologies could be investigated in a more accurate way, thanks to dynamic

Roentgen stereophotogrammetric analysis (RSA) [3, 4]. Biomechanical differences between the anterior cruciate ligament-~~–~~deficient (ACLD) knees and contralateral of the same subjects could be identified using a biplane radiographic system. In the present study, gait and single leg squat were analyzed, since the first one is a basic activity of daily living and the second one is a more demanding motor task, but safe and easy to perform for the patients [17, 31].

The aim of the present study was to identify knee biomechanical anomalies following ACL rupture, during the execution of in vivo under weight-bearing activities, to investigate mechanisms that lead to improved risk of osteoarthritis in ACL deficiency.

It was hypothesized that knee tibiofemoral kinematics is altered after ACL tear and that the alteration probably does not involve only anterior posterior laxity or internal–-external rotation, but also flexion–-extension and medio-lateral tibial alignment, as previously reported by other investigators [1, 5, 9, 15, 18, 19].

The clinical relevance of this work is that proving a significant impairment and altered patterns in gait kinematics could support a wider recourse to surgery, because walking is a basilar activity and its constant alteration could influence knee degeneration more than sport activities, which most of the people do occasionally. Moreover, an altered knee kinematics in single leg squat could confirm the necessity of surgery for athletes.

Materials and methods

All the patients involved in this research study signed informed consent forms. This study obtained the approval from the Institutional Review Board (IRB) of Rizzoli Orthopaedic Institute (ID: 40/CE/US/ml—Clinical Trial Gov ID: NCT02323386). This study represents the secondary analysis of data collected from a prospective study, aimed to evaluate the outcome of ACL reconstruction. Based on the original study protocol, 62 patients were included and assessed preoperatively with 1.5 T MRI analysis and dynamic RSA of injured and contralateral knee. The inclusion criteria for the original study were:

- Age 16–50 years.
- Complete, traumatic and unilateral ACL injury.
- No previous knee ligament reconstruction or repair.

- No concomitant posterior cruciate ligament, postero-lateral corner, lateral collateral ligament or medial collateral ligament lesion.
- Absence of mild or advanced knee osteoarthritis (Kellgren–Lawrence III–IV).

For the purpose of the present study, the inclusion criteria were:

- Isolated ACL tear.
- No injury of contralateral knee.

Exclusion criteria were:

- Concomitant other ligamentous or meniscal injuries.
- Incomplete kinematic data.
- Unwillingness to take part in the study.

From the 62 patients of the initial cohort, 10 patients underwent dynamic RSA of the contralateral knee. Two more patients were then excluded because of incomplete kinematic data. Overall, eight patients (5 men, 3 women, 30 ± 12 years old) matched the inclusion criteria and were included in the study.

Motor tasks

The patients were asked to perform two motor tasks: a single step and a single leg squat. The tasks were performed with the ACLD limb and subsequently with the contralateral one. Patients were asked to perform the tasks according to their possibilities. The investigators carefully checked the initial position of the foot to limit the bias caused by internal–-external alignment: the foot had to be aligned with the ideal antero-posterior axis of the knee, thus pointing forward. The acquisition was performed in a specialized radiographic room. The tasks were performed three times per limb, the first two to gain comfort with the experimental set-up (no X-ray exposure) and the third one for data acquisition (X-ray exposure).

Data acquisition

The data were collected using a radiographic set-up for dynamic RSA. The device used (BI-STAND DRX 2) was developed in our institute, in collaboration with ASSING (ASSING Group, Rome, Italy). The specifics of the RSA radiographic set-up were –analogous to the ones already published in previous articles from the same study group [3, 4] (Figure 1A).

Bone models of tibia and femur were obtained from a 1.5T MRI of either the affected or the contralateral knee. When

MRI images of the contralateral knees were not available, the models were derived from a process of mirroring of the ones of the affected knee and of their correspondent reference systems. The radiographic images were processed in a dedicated software in Matlab® (R2016a, MathWorks Inc., Natik, MA, USA) developed at our institute, applying algorithms related to the Model-Based Dynamic RSA. A 3D virtual environment was used for semi-automatic segmentation of bone contours on radiographic images and, subsequently, to place the bone models according to the contours (Figure 1B).

The dynamic RSA was validated before to start the clinical study. The validation protocol was based on radiograph computer simulations of the radiological setup and images, with different quality and noise level. The accuracy of the radiological scene reconstruction and of the model position was assessed according to the ISO-5725 regulation [34]. The global accuracy of model positioning and orientation, evaluated in terms of “trueness ± precision”, resulted to be sub-millimetric, respectively, 0.22 ± 0.46 mm and 0.26 ± 0.2 °. Kinematics data are presented as mean ± standard error over the percentage of the task. Figure 2 shows the reference systems of the tibial and femoral models in the RSA software. The kinematical quantitative data for each patient, in 6 degrees-of-freedom, were calculated using the Grood and Suntay decomposition [13].

Since it was impossible to standardize the time elapsed to perform the motor task by each patient, we normalized the data on the percentage of the task (% task), based on specific moments to determine the beginning, the middle and the end

(Table 1). Regarding the gait, only the stance phase was taken into account.

Statistical analysis

The kinematic data were processed using Matlab. The paired *t*- test was used to compare the data of the ACLD an contralateral knees along each frame of the entire motor task for all the parameters. Differences were considered statistically significant for p<0.05.

An a- priori power analysis was conducted, based on previous studies using fluoroscopic technique to evaluate knee kinematics in ACLD conditions [6, 29, 30]. Considering a medio-lateral translation of 2.51 ± 1.30 mm for ACLD knee and of 0.89 ± 1.47 mm for contralateral knee, to achieve a power of 0.8 and an alpha level of 0.05, the minimum number of patients required was set to seven.

Results

Frontal plane

Regarding the joint angles and translations on the frontal plane, there were statistically significant differences between ACLD and contralateral knee ($p<0.05$) (Table 2). In particular, varus–valgus rotations were statistically different from the 50% to the 80% of the squat (Figure 3B): ACLD knee showed, on average, a more varus rotation compared to the contralateral knee. Furthermore, medio-lateral translations showed a more medial tibial alignment for ACLD knees with respect to the frontal plane. This trend was present both in the squat and in the step (Figs. 3A, 4): in the squat, the difference was statistically significant from 0% to 35% and from 65% to 100% of the task; no statistical differences were found in the step.

Sagittal and transverse plane

Regarding sagittal and transverse plane joint angles and translation, no statistical differences were found between ACLD and contralateral knee kinematics along the entire percentage of both motor tasks (n.s.).

Discussion

The main findings of the present study were:

- Statistically significant differences were found in medio-lateral translations between ACL-deficient and contralateral knees during single leg squat from 0% to

35% and from 75% to 100% of the motor task (that correspond to an average flexion value from 0° to 30°);

- During single leg squat, significant differences were found in varus–valgus angle from 50% to 80% of motor task;
- No differences were observed between afflicted and contralateral knee during the stance phase of the gait.

The influence of ACL deficiency on knee kinematics is a hot topic in recent orthopedic researches, due to the correlation altered biomechanics is supposed to have with increased risk of early osteoarthritis [1, 2, 5, 6, 9, 10, 14, 18, 23, 33]. To the best of our knowledge, this is one of the first studies aimed to analyze, with an advanced and highly accurate technology, the translations and rotations of ACLD and contralateral knee joint in vivo and under weight-bearing conditions. On purpose, two tasks that differed in terms of closed (squat) and open (step) kinetic chain were analyzed. Onthe one hand, gait is one of the commonest daily activities, easily performed by ACLD patients too. On the other hand, the squat was chosen since it is more demanding but, at the same time-safe to perform [17, 31].

Other investigators have already observed the concept of tibial medialization (Figure 5) after ACL injury, inferring this is due to the oblique orientation of ACL. Li et al. [18], analyz~~s~~ed single leg weight-bearing lunge through double fluoroscopy and found a significant lateral shift of tibio-femoral cartilage contact points, both in the medial (between 0° and 60° of flexion) and the lateral compartment of the tibia (between 15° and 30° of flexion). This finding was reproduced also in a cadaveric study [19], where the application of different loading conditions in specimens with ACLD knee led to a significant tibial medialization between 15° and 30° of flexion. Furthermore, DeFrate et al. [5] found a greater tibia medialization in ACLD knees from 0° to 90° of flexion during the execution of a quasi-static lunge. These results are in accordance with the findings of the present study, since a significant tibial medialization was observed in correspondence to a knee range of flexion between 0° and 30°. This abnormal position could explain the high incidence of osteoarthritis on the medial femoral condyle and anterior tibial spine in chronic ACL deficiency [7, 23]: medial shift of the tibia could reduce the distance between these two knee structures, leading to an altered force distribution on their surfaces [18].

The contribution of ACL in varus–valgus laxity is also a controversial topic [12, 22, 29, 32]. In the present study, ACLD knees were found significantly more varus than the contralateral ones in the first degrees of the re-extension phase of the squat, after they reach the maximum flexion. A crucial role of ACL in frontal plane knee rotations can therefore be supposed. Previous literature studies drew the same conclusion. Yamazaky et al. [32] demonstrated ACL injured limbs had a more knee varus than uninjured of about 5° at the maximum flexion angle of a single leg squat, using an electromagnetic device. In another study [29], performed with fluoroscopy, knees after ACL reconstruction were shown to be more varus than contralateral during downhill running. This aspect could endorse the surgical techniques’ inability to restore physiologic knee varus–valgus after

ACL tear. Lastly, there is the recent concept of valgus collapse as a frequent mechanism involved in ACL non-contact injury [25], which could bring to suppose knee valgus as a position of discomfort for patients simulating the ligament rupture biomechanics. ACL-injured patients could probably maintain an easier balance keeping a more varus position [32].

Differently than expected, no differences were found ~~n~~either in tibial anterior–~~-~~posterior translation ~~n~~or in knee internal–~~-~~external rotation. Closed kinetic chain exercises like squat are considered safer than open kinetic chain ones in ACL injury rehabilitation programs, especially when patients need to increase muscle activity, because they are supposed to cause less ligament strain [20]. For this reason, squat exercises have a role in ACL deficiency rehabilitation: the high muscular co-activation of quadriceps and hamstrings provides a greater anterior–posterior tibial stability [17, 31]. This consideration could justify the absence of differences in tibial position in anterior–posterior knee laxity and in internal–external rotation in our data. Moreover, some previous studies described a higher tibial internal rotation in ACLD knees, but for motor task different from the squat [5, 10].

In step, we did not found any statistical difference between ACLD knee kinematics and contralateral one. These results are partially in contrast with literature: several studies [9, 15] identified anomalies in knee flexion–extension during walking, but showed neither significantly more anterior tibial translation nor an increased antero-posterior laxity range. Gao et al. [9] described an increased tendency of the

ACLD knees to remain in flexion at the end of the stance phase of the gait, while Hurd and Snyder-Mackler [15] described a “joint stiffness strategy” as a combination of reduced peak knee flexion and lack of extension during the mid-stance. The main thesis for this altered knee flexion pattern relies on abnormal muscle activation in patients with ACL tear, aimed to better control knee anterior–-posterior laxity. Indeed, many studies based on electromyography highlighted differences in activation of quadriceps and hamstrings after ACL injury, even if there is no consensus regarding the adaptation mechanism [15, 26, 27].

In the present study, no flexion–-extension anomalies were identified. The step was executed at a low speed and usually with small step length. Previous investigators demonstrated that small spatiotemporal parameters influence knee flexion during stance, thus resulting in a stiff knee strategy [21, 28] and an almost full extension, similar to our results. In brief, the findings of the present study could indicate ~~on top of~~ the role of ACL in knee biomechanics: in vivo and under weight-bearing conditions, the ACL could decisively contribute to medio-lateral tibial alignment and knee varus–~~-~~valgus. So far, the ACL reconstruction techniques have focused on the restoration of anterior–~~-~~posterior and internal–~~-~~external rotation knee stability, without considering the anomalies on frontal plane. Actually, previous studies reported that ACL reconstruction does not restore these parameters [6, 29]. According to the present study, surgeons should observe ACL injury from a wider perspective, thus considering also ACLD knee motion anomalies in the frontal plane, to develop reconstruction techniques aimed to reproduce physiological knee stability.

The present study has several limitations. First, due to the controlled nature of the tasks (especially the step), the small sample size could have affected the statistical analysis and probably failed to reveal other differences between the two groups. However, it was possible to demonstrate some consistent trends. A second, intrinsic limitation linked to the sample size relied upon the high intra-subject knee motion variability. The choice to acquire, under radiograph exposure, only one repetition per task, was made due to ethical reasons. This issue was minimized through a direct comparison of healthy and unhealthy limbs of the same patients.

The other two considerations include the selection of patients based on time from injury and the choice of contralateral limbs as gold standard. When debating on ACL-deficient knee biomechanics, the time from injury is crucial, because patients may progressively develop muscular asymmetries to stabilize the joint [33]. Nevertheless, the present study was mainly focused on how the injury affected the biomechanics and not on how rehabilitation could restore knee stability. The contralateral knees might not reproduce a normal knee kinematics [16]. Anyhow, obtaining a pool of healthy controls would have been highly unethical due to radiograph exposure; furthermore, the evaluation of contralateral knees as controls is typical of nearly all the fluoroscopic studies.

Lastly, the choice of the tasks was related to the actual radiographic set-up: due to the limited spaces and the obstacles represented by the medical devices around, it would have been unsafe and impossible to analyz~~e~~ high-dynamics tasks, such as jumps or cut ~~-~~maneuver~~s~~. These last tasks could have stressed the knee joint more, and maybe underlined further differences from the contralateral. A future set-up development will permit ~~-~~acquire more complex and stressing tasks.

Conclusion

ACL-~~—~~deficient knees showed an abnormal tibial medialization and increased varus angle compared to the contralateral knees. These biomechanical anomalies may lead to different force~~s~~ distributions on the tibial plateau, explaining the higher risk of early osteoarthritis in ACL deficiency. Clinicians should take into account the influence of ACL tear on frontal plane knee kinematics in movement commonly used in ACL rehabilitation protocols.

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Figures Legend

Figure 1 Radiological set-up of the RSA device, where patients performed motor tasks. The orthogonal arrangement of flat panels and X-ray tubes allows a 3D reconstruction of bone~~s~~ movements (A); v~~V~~irtual reconstruction of a motor task in the RSA software, where mathematical data describing tibio-femoral kinematics were extrapolated (B).

Figure 2 Anatomical reference systems of tibia and femur in the RSA software. X-axis: flexion angle and the medio-lateral translation; Y-axis: varus–-valgus rotation and anterior–-posterior translations; Z-axis: internal–-external rotations and proximal–-distal translation.

Figure 3 Medio-lateral translations (mean ± SEM) of the tibia with respect to the femur during single leg squat; notice that significant differences were found from 0% to 35% and from 75% to 100% of the motor task (that correspond to an average flexion value from 0° to 30°) (A). Varus–-valgus rotations (mean ± SEM) of the tibia with respect to the femur during single leg squat; notice that significant differences were found from 50% to 80% of the motor task (B).

Figure 4 Medio-lateral translations (mean ± SEM) of the tibia with respect to the femur during the stance phase of the gait; notice that, despite no significant differences being~~were~~ found, the tibias of ACLD knees were on average shifted to a more medial position than the ones of the contralateral knees.

Figure 5 Difference in medio-lateral tibial position between the normal knee (A) and the ACL-~~-~~deficient knee (B).

Tables

Motor task normalization		
Time percentage	**Phase of the step**	**Phase of the squat**
0%	Heel-strike	Initial extension
50%	Midstance	Maximum flexion
100%	Heel-off	Terminal extension

Table 1 - List and value of the specific moments used to normalize the data for the execution of the motor tasks.

Significant differences				
	% of the task	**Injured**	**Contralateral**	**p value**
Squat medio-lateral translations (mm)	0 - 35 %	1.4 ± 0.4	-1.2 ± 0.7	< 0.05
	65 - 100 %	1.5 ± 0.6	-1.9 ± 0.9	< 0.001

Squat varus–valgus angles (°)	50 - 80 %	-0.9 ± 1.3	-5.3 ± 2.2	< 0.05

Table 2: A~~a~~verage ± standard error values of the significant differences between ACL-~~-~~deficient and contralateral knee

List of abbreviations

ACL Anterior cruciate ligament

ACLD Anterior cruciate ligament deficient

RSA Roentgen stereophotogrammetric analysis