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Abstract

Purpose To quantify the influence of ALL lesions on staticand dynamic laxity in ACL-deficient knee.

Methods The study was performed in 10 fresh-frozen knees. The joints were analysed in the following condi- tions: intact, ACL resection and ACL ALL resection. Testing parameters were defined as: anterior displacement at 30° and 90° of flexion (AP30, AP90) applying a manual-maximum load; internal rotation at 30° and 90° of flexion (INT30, INT90) applying a 5 N m torque and internal rotation and acceleration during manual pivot-shift (PS) test. Kinematics was acquired by a navigation system; a testing rig and a torquemeter were used to control the limb posi- tion and the applied torque. Paired Student's t test was con- ducted to assess statistical difference, and significance was set at $P < 0.05$.

Results The ALL resection determined a significant increase in terms of internal rotation (INT30 P 0.02, INT90 P 0.03), while AP30 (P n.s) and AP90 (P n.s) were not affected. ALL resection produced a significant increase in terms of acceleration during PS test ($P < 0.01$), but no significant change in PS internal rotation was observed.

Conclusion The ALL plays a significant role in controlling static internal rotation and acceleration during PS test. On the other hand, ALL resection did not produce any significant change in terms of anterior displacement. A trend was seen for the internal rotation during the pivot-shift test to increase after ALL resection was higher when comparedto the intact and isolated ACL lesion states; however, the differences were not significant. The results highlight the clinical relevance of this structure that should be assessed before an ACL reconstruction in order to avoid residual laxity.

Keywords Anterolateral · Laxity · Navigation system ·Combined lesions

Introduction

According to the current literature, the importance of the secondary restraint of the knee as a key factor in the ACL reconstruction failure has been emphasized [12, 17, 19]. The function of the majority of the stabilizing soft tissues of the knee joint has been widely investigated. However, the anatomy and function of the anterolateral structures of the knee have been poorly understood. In the 1879, Ségond [25] first described a "pearly, resistant, fibrous band" asso- ciated with the avulsion fracture now named as the "Ségond fracture". Other previous studies have used different ter- minology to allude to this structure of the knee: "Anterior oblique band", "Capsulo-osseous layer of iliotibial tract", "Lateral capsular ligament" and "Mid-third lateral capsular ligament" [5, 10, 13, 15, 24].

Due to the complex relationships among the structures of the anterolateral aspect of the knee, there are few dis- crepancies in the anatomical description of this structure in the anterolateral aspect of the knee now termed anterolat- eral ligament (ALL). Claes et al. [3] described a ligamen- tous structure connecting the femur with the tibia with con- nections to the lateral meniscus. They identified the femoral attachment over the epicondyle slightly anterior to the attachment of the lateral collateral ligament (LCL). Dodds et al. [6] identified an extracapsular structure without any connection with the lateral meniscus and with a femoral attachment described as being proximal and posterior to the epicondyle. However, it has been clearly defined that the ALL is a distinct ligamentous structure with an incidence ranging from 83 % [6] to 100 % [24]. Given the recent improvements in understanding the anatomy and incidence of the ALL, the kinematic role of this ligament and its clinical relevance have yet to be fully determined. It has been suggested that the ALL acts as sec-ondary restrain to control rotational laxity [6, 13, 27, 28]. Further, it has been hypothesized to be associated with the "Segond fracture" that is

considered to be pathognomonic for ACL injury. However, in the current literature, there is a paucity of biomechanical data focused on the effect of an ALL tear in an ACL-deficient knee.

Therefore, the aim of this study is to investigate in vitro the effect of an ALL tear on the static and dynamic laxity parameters of an ACL-deficient knee. Moreover, in order to perform an evaluation reproducible in vivo, a navigation system was used to assess the laxity parameters.

The hypothesis was that a lesion of the ALL in ACL- deficient knee would produce significant alterations in the kinematic of the knee joint. In particular, it has been hypothesized an increase in both dynamic and static laxity levels with particular attention to the rotational contribution.

Materials and methods

Ten (5 matched pairs) fresh-frozen cadaveric specimens were used in the study (mean age 79 5 years old). Only joints without evidence of prior knee injury, surgery±arthri-tis or anatomical abnormality were included in the present work. Cadaveric specimens were stored at 20 °C and thawed at least 36 h before use.

Skin and subcutaneous fat were removed 15 cm from the joint line on tibia as well as on femur. The ligamentous and the tendinous structures were left intact. The iliotibial band was incised along its fibres in order to identify the ALL. After separating the fibres of the iliotibial tract, a manual internal torque was applied and tense fibres were identified. Those fibres were running obliquely over the lateral collat-eral ligament (LCL) until their fanlike insertion on the tibia proximally and posterior to the Gerdy's tubercle. Those fibres were isolated from the capsule and were identified
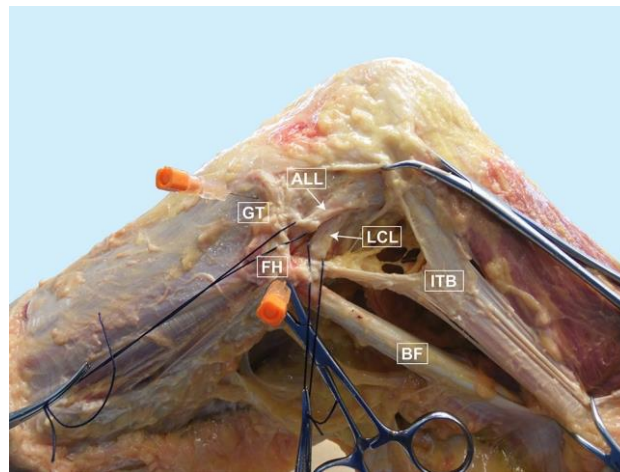
Fig. 1 Anterolateral ligament (ALL): The figure shows a well- defined structure. Also, iliotibial band (ITB), biceps femoris (BF) and lateral collateral ligament (LCL) have been highlighted. The two nee-dles correspond to Gerdy's tubercle (GT) and fibular head (FH)

as the ALL (Fig. 1). A medial parapatellar arthrotomy was performed to assess the status of knee joint to access the ACL.

After the preparation of the limb, a 3-mm bicortical pin was inserted into the diaphyseal area of both femur and tibia. Then, a tracker-holding device was attached to the pins in order to set-up the navigation system (Polaris, NDI, Waterloo, Ontario, Canada) embedded with a custom-made software (MATLAB, The MathWorks Inc., Natick, Mas- sachusetts, USA). An anatomical femoral and tibial coor- dinate system was defined for each joint using a tracked probe to select palpable anatomical landmarks. In particu- lar, the femoral system of reference needs the acquisition of the medial and lateral epicondyles and the definition through a pivoting motion of hip joint centre. For the tibial anatomical reference system are required the medial and lateral malleolus and the most medial as well as the most lateral point of the tibial plateau. The foot was fastened to a testing rig in order to maintain the correct limb position during the kinematic testing.

Biomechanical testing

A single surgeon, experienced with navigation system, performed the ligament sectioning and the entire kinemat- ics evaluation. The specimens were tested in the following conditions: (1) intact knee, (2) resection of the ACL (ACL) and (3) resection of the ALL (ACL ALL).

All the testing conditions were subjected to a manual- maximum anterior tibial load at 30° and 90° of knee flex- ion, and

+

5 N m internal rotation torque was applied at 30° and 90° of flexion. The selected flexion angles were based on the commonly performed clinical test (i.e. Lachman and Drawer test) as well as on the available scientific manu- scripts [2, 7, 8, 29]. Anterior–posterior test at 30° and 90° of knee joint flexion (AP30, AP90), internal rotation test at 30° and 90° of flexion (INT30, INT90) and pivot-shift (PS) test were performed. In order to quantify static laxity level, the tibial displacement has been evaluated, with respect to femoral system of reference, in anterior–posterior direction during AP30 and AP90. Moreover, the internal rotation of the tibial system of reference versus the femoral one during INT30 and INT90 test was assessed.

Pivot-shift test was executed following the procedure reported by Galway and MacIntosh [9] and Jakob [14]. The laxity parameters evaluated during PS test were the accel- eration displacement of the lateral tibial compartment as well as the internal rotation. Lateral compartment has been reported being the one mainly affected by the PS phenom- enon [1]. The motion in the described anatomical coordi- nate systems was evaluated according to the Grood and Suntay algorithm [11]. Between the testing of each knee state, the joint was maintained damp applying saline. All the kinematics data were elaborated offline with a MAT- LAB (The MathWorks Inc, Natick, Massachusetts, USA) interface specifically developed. The 3D root-mean-square (RMS) volumetric accuracy of the navigation system in the localization of a single passive marker declared by manu- facturer is equal to 0.35 mm [32]. According to this, all the results were rounded to the first decimal digit. Reliability of the performed tests has been determined in a previous in vivo study where the joints were tested at manual-max- imum force. For AP30/AP90, it has been found an intra- tester repeatability of about 1 mm, while for rotational test, it was 1° [30]. Also, the repeatability of the pivot-shift test manually performed has been deeply analysed in a previ- ous in vivo navigated study [20] underling encouraging value. To control the 5 N m torque load applied for the exe-cution of rotational test, an analogical torquemeter (Stryker Howmedica Dall Miles Instruments, Limbach-Oberfrohna, Germany; full scale 20 N m/180 lb-In) arranged to the test-ing rig was used.

All the biomechanical tests have been performed at Lab- oratoire d'Anatomie, Universitè Françoise-Rabelais. IRB approval was not required.

Statistical analysis

Based on an alpha level of 0.05, ten specimens were found to be sufficient to detect a significant difference among the tested conditions with 80 % of power.

Normality of the acquired data has been evaluated by Kolmogorov–Smirnov test. Paired Student's t tests were used to analyse differences in laxity between intact, ACL-deficient and ACL + ALL-deficient states after each

Results

Kolmogorov–Smirnov test confirmed the normal distribu- tion of the data for all the acquired data.

Anterior–posterior displacement at 30° and 90° of knee flexion (AP30, AP90)

While tested under manual-maximum load, the ACL-defi- cient condition had significantly higher ($P < 0.01$) anterior–posterior displacement at 30° of knee flexion compared to the intact state. When even the ALL was resected and the two states ACL-deficient knee and *ACL* ALL-deficient knee were compared, no further significant increase in lax- ity was found (n.s).

Analogously, at 90° of knee flexion, both the ACL and ACL + ALL-deficient knee state had significantly increased average anterior–posterior translation when com-pared with the intact condition (P 0.03 and $P < 0.01$, respectively). There were no significant differences (n.s) between ACL and ACL + ALL-deficient knee state (Fig. 2a, b).

Considering the absolute value of anterior–posterior displacement, the highest mean value was still found at 30° of flexion after ACL ALL resection. Anyway, dif- ference between absolute value of AP30 and AP90 for the ACL ALL-deficient knee condition was not statistically significant (n.s).

Internal rotation at 30° and 90° of knee flexion (IE30, IE90)

The ACL ALL state had significantly (P 0.02) more internal–external rotation when compared with the iso- lated ACL-sectioned state under a 5 N m internal rotation torque. Analogously, at 90° of flexion, the ACL + ALL- deficient knee condition displayed significant increase in internal rotation when compared to the ACL-deficient state (P 0.03). No other significant differences were found for other comparisons with the cutting conditions (Fig. 3a, b).

Considering the absolute value of internal rotation, the highest mean value was obtained at 90° of flexion after ACL + ALL

resection. INT90 for the ACL ALL-defi- cient knee condition was significantly higher than INT30 for the same state ($P = 0.04$).
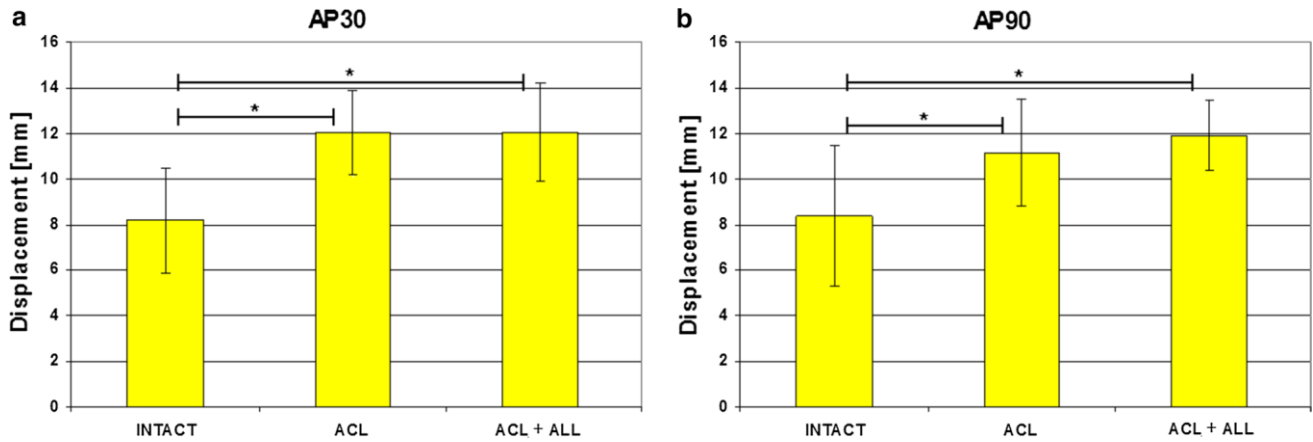
Fig. 2 Mean (SD) values of anterior tibial translation (mm) at 30° (**a**) and 90° (**b**) of flexion for INTACT, ACL deficient and ACL ALL- deficient joints status. Tests have been manually performed at the manual-maximum force. Statistically significant ($P < 0.05$) differ-ences have been underlined by *asterisks* sign
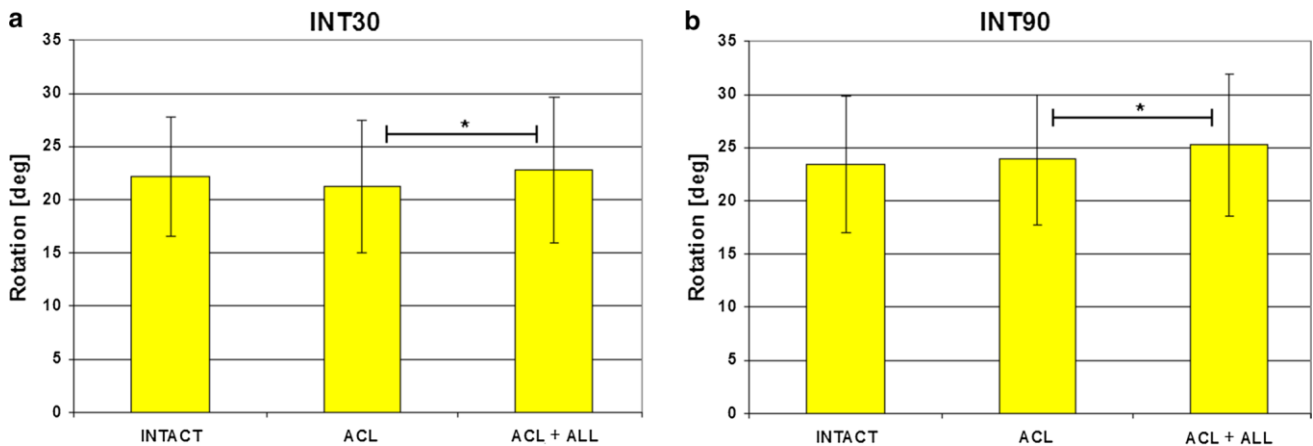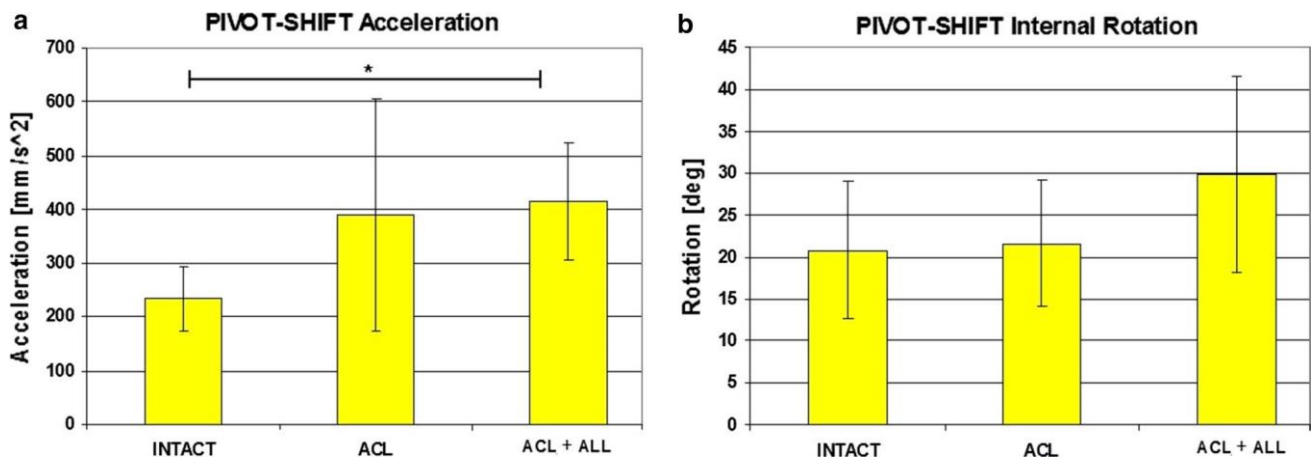

Fig. 3 Mean (SD) values of tibial internal rotation (°) at 30° (**a**) and 90° (**b**) of flexion for INTACT, ACL deficient and ACL ALL- deficient knees status. Tests have been manually performed apply-ing a 5 N m torque load controlled by a analogical torquemeter (Stryker Howmedica Dall Miles Instruments, Limbach-Oberfrohna, Germany). Statistically significant ($P < 0.05$) differences have been underlined by *asterisks* sign

Pivot-shift test: acceleration and internal rotation

The cutting of the ACL showed no significant differ- ences in acceleration compared with the intact state. The ACL ALL-deficient knee condition had significantly more acceleration ($P < 0.01$) than the intact state during pivot-shift state. Considering the internal rotation dur- ing pivot-shift test, no significant differences have been found when comparing the intact, ACL-deficient and ACL + ALL-deficient knee (Fig. 4a, b).

Discussion

The most important finding of the current study was that ALL has a specific biomechanical role as it significantly restrains static internal rotation in an ACL-deficient knee.On the other hand, ALL resection did not produce any sig-nificant change in terms of anterior displacement. Further,an ALL tear produced a significant increase in terms ofacceleration during PS test. A trend was seen for the inter-nal rotation during the pivot-shift test to increase after ALLresection as this laxity parameter is increased of almost 10°(Fig. 4b). This increase was higher than the one producedduring the static internal rotation, but it was not significant.In the 70s, Hughston et al. [13], in a dissection bio- mechanical study of the lateral compartment of the knee,identified the ''midthird capsular ligament'' as key restrainagainst the occurrence of anterolateral rotatory instability.In a recent paper [6], the ALL was described as an isomet-ric structure from 0° to 60° of knee flexion. They observedan increase in the ligament length with an internal tibial

Fig. 4 Mean (SD) values of acceleration (mm/s^2) (**a**) and internal rotation (°) (**b**) during pivot-shift test for INTACT, ACL deficientand ACL + ALL-deficient knees status. Tests have been manually performed. Statistically significant ($P < 0.05$) differences have beenunderlined by *asterisks* sign

rotation from 30° to 90° of flexion. Claes et al. [3] observedthis structure to be tensioned by coupled flexion and inter- nal rotation; however, they did not quantify the kinematic function of the ALL.

In an in vitro set-up similar to the current study, Monacoet al. [21] performed a cutting study of the two bundles of the ACL and the anterolateral aspect of the knee. The resec-tion of the anterolateral aspect of the knee produced a sig- nificant increase in the internal rotation at 30° of flexion. These authors noticed that the anterior tibial displacement was significantly increased by the anterolateral resection.In the current paper, this laxity parameter was not affected by the ALL status. A reason for this difference might be in the cutting procedure as they did not isolate the ALL from the capsule, but they performed a wide resection 2 cm longthrough all the structures of the third layer of the anterolat- eral aspect of the knee [13]. Further, they reported high cor-relation among the anterolateral resection and the pivot-shiftphenomenon, which was clinically evaluated. In the currentpaper, a significant difference was observed concerning theacceleration during the pivot shift, which as been demon- strated to be a parameter that correlate with clinical grade of pivot shift [18]. Interestingly, the isolated lesion of the ACL did not significantly affect the acceleration; this find- ing might suggest that when a significant pivot shift is noted in clinical practice, a possible unrecognized lesion to the anterolateral aspect of the knee might occur.

Recently, Spencer et al. [26] assessed the biomechanical function of the ALL from lesion to reconstruction. In their cutting study, the ALL resulted to be effective in control- ling internal rotation in the setting of a combined complete ACL tear during the early phase of simulated pivot shift.In the current paper, the influence of the ALL on the inter- nal rotation during pivot shift was not significant; however, a trend was seen for this laxity parameter to increase after ALL resection. The authors believe that this lack of sig- nificance might be due to the size of the series and dueto the complexity of the pivot-shift phenomenon whichis affected from anatomical features and other stabiliz-ing structures [22]. Consistently to the current paper, they observed that sectioning the ALL did not produced any sig-nificant increase in terms of anterior translation compared to an isolated ACL tear. In another biomechanical study [23], the ACL, the ALL and the lateral collateral ligament (LCL) were randomly sectioned achieving

similar findings.Concerning anterior translation, they reported significant changes produced by the ACL but not by the ALL. During internal rotation, both ligaments resulted to be significant restrains. Interestingly, they noticed that the ALL contribution increased with the knee flexion, while the ACL con- tribution followed an opposite trend. In the current paper, absolute value of internal rotation with both ligaments resected was higher at deeper angle of flexion. However, these findings are difficult to compare as avoiding rand- omization precludes the possibility to evaluate the func- tion of each ligament at different angles of flexion. On the other hand, a recent paper reported the superficial and deeplayers of the iliotibial tract to be the primary restraint to tibial internal rotation between 30° and 90° of flexion and 30°–45° during a simulated pivot shift, while the ALL was just a minor restraint [16]. These results were criticized by an international group of experts [4] postulating that deep layer of the iliotibial tract and the ALL of the knee are basi-cally the same structure but isolated with different proce- dures. The authors of the current paper agree with this last point of view as no distinct structure other than the ALL was identified during the dissection between the capsule and the iliotibial tract.

The authors noted some limitations. First, the cohortsize was limited, and the age of the cadavers was not simi- lar to a normal ACL injury population. Second, the cutting sequence was not randomized; however, varying the order of ligament sectioning would not have been consistent with the aim to investigate the effect of an ALL tear on an ACL-deficient knee. Third, the kinematic evaluation was performed by means of a navigation system in place of a robot testing system. The robot is capable of higher kin- ematic measurement [31]; however, the navigation system allowed for an experimental set-up is closer to the in vivo one. Therefore, the authors believe that the result of the current paper can be more directly applied to the everyday clinical practice.

Conclusion

In conclusion, this study shows that ALL plays a significant role in controlling static internal rotation and pivot shift in the setting of an ACL-deficient knee. These findings high- light the importance of ALL as secondary restraint of the knee. The authors recommend evaluation of the anterolat- eral aspect of the knee when facing an ACL reconstruction in everyday clinical practice in the attempt to prevent resid-ual rotational laxity.

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