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Does the anterolateral ligament protect the anterior cruciate ligament in the most common injury mechanisms? A human knee model study

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1. Introduction

An anterior cruciate ligament (ACL) rupture is a frequent injury in athletes and may lead to reduced activity level and subsequent joint lesions due to a non-compensable instability [1]. In most cases, ACL reconstruction can restore anterior-posterior and rotational stability and enables return to competitive sports [2,3]. However, in some cases, rotational instability with positive pivot phenomenon persists and raises questions about additional secondary stabilizers which support the ACL in preventing rotational instability [2,4–6]. The anterolateral ligament (ALL) is the current figurehead of such structures and several surgeons add the ALL reconstruction to the surgical treatment of patients with ACL injuries. Currently accepted indications for an additional ALL reconstruction include chronic ACL injuries, revision ACL reconstructions, hyperlaxity with high-grade pivot phenomenon and ACL reconstruction in athletes [4,6–12]. The ALL predominantly attaches posterior and proximal to the lateral femoral epicondyle, and the origin of the lateral collateral ligament (LCL) runs superficial to the LCL and attaches on the tibia midway between the anterior border of the fibular head and the proximal border of Gerdy's Tubercle, between 4.0 and 7.0 mm below the tibia plateau, and is known for preventing the internal rotation of the tibia [13,14]. In this context a contradiction is revealed: common injury mechanisms of an ACL rupture consist of (besides valgus stressing) not only internal rotation (external femoral rotation) of the tibia but also external rotation of the tibia (internal rotation of the femur) [15–17]. Thus, there is still uncertainty which rotational component favors an ACL rupture, and it is also unclear which secondary structure protects the ACL comprehensively. It must be doubted that the ALL protects the ACL in other injury mechanisms [18].

Therefore, the presented human knee finite element (FE) model study evaluates which extra-articular structure optimally supports the ACL in excessive tibial internal and external rotation. We hypothesize that other extra-articular structures than the ALL contribute more to the protection of the ACL in injury mechanisms including tibial external rotation.

2. Methods

2.1. Human knee model

The Global Human Body Model Consortium (GHBMC) full human body model represents a 50th percentile male in an upright standing posture. The model has been developed by GHBMC [19] and is commonly used for traffic accident simulations involving human beings as occupants and pedestrians in combination with the explicit FE solver LS-DYNA (Livermore Software Technology Corporation, LSTC) [20]. The knee angle was adjusted to 25° in order to acquire a more critical reference configuration for ACL ruptures. In this configuration, the reference lengths of the ligaments are shown in Table 1. All material properties and contact definitions in the model components were kept constant and were not modified.

The same material model with distinct properties for tension and compression (*MAT_PLASTICITY_COMPRESSION_TENSION) already used for the existing knee ligaments was assigned to the additional extra-articular structures. The material model used for the ligaments follows an approach by Untaroiu et al. [14]. Because ligaments are much stiffer in tension than in compression, an isotropic elastic-plastic material model with different properties in compression and tension was used. Material parameters are shown in Table 2. Because identical material parameters are applied to all ligaments (including ALL), the numerical simulation can quickly reveal a relative load distribution. The predominantly loaded ligaments can be identified easily using this approach, as long as the applied moment is not excessively high and the stress level in the ligaments is not near failure. The average tensile stress-strain curve reported by Quapp et al. [21] and a less stiff curve were assigned to the material model in tension and compression, respectively [22]. The isolated FE model (knee joint) was cut approximately 170 mm above and 140 mm below the tibia plateau. The exact cutting edges were along the given spatial discretization. The model consists of roughly 50,000 elements and 37,000 nodes. All physical components (bones, muscles, ligaments, soft tissue) are organized by a total of 32 components. The isolated knee model encompasses a volume of 3.7 l and has a mass of 4.2 kg. The nodes on both cutting surfaces, on the femoral side and on the tibial side, are kinematically constrained such that no relative movement of the nodes is possible. While the rigid section of the tibia was fixed, the rigid section of the femur was loaded instantaneously by a constant moment of 20 Nm in order to establish both scenarios, femoral external and femoral internal rotation. The duration of the simulation was 100 ms. Because the final nodal positions were almost constant after approximately 60 ms, the final rotation angle and the normal forces within the internal ligaments and the extra-articular structures were averaged from this point of time to the end of the simulation.

Table 1
Reference lengths of the ligaments in adjusted knee flexion angle of 25°.

	ACL	PCL	LCL	MCL	ALL	POL	PLT	AML
Length (mm)	21.6	34.5	50.5	73.6	45.6	52.6	56.0	56.8

ACL, anterior cruciate ligament; ALL, anterolateral ligament; LCL, lateral collateral ligament; MCL, medial collateral ligament; PCL, posterior cruciate ligament; PLT, popliteal tendon; POL, posterior oblique ligament.

Table 2
Material parameters for all ligaments [14].

Parameter	Unit	Value
Physical density	g/cm ³	1.000
Young's modulus	GPa	0.180
Poisson ratio	–	0.480
Failure strain	–	0.500
Yield stress (compression)	GPa	–0.003
Yield stress (tension)	GPa	0.003

2.2. Measurement

The left knee of the GHBMCM50 full human body FE model with anatomical ACL, posterior cruciate ligament (PCL), lateral collateral ligament (LCL), medial collateral ligament (MCL) and an intact medial and lateral meniscus was isolated (Figure 1). Three additional anatomic structures (anterolateral ligament, ALL), popliteal tendon (PLT) and posterior oblique ligament (POL), were added to the human knee model separately and then all together (Figure 2). The femoral and tibial ALL fixation was performed isometrically, 4 mm posterior and 8 mm proximal to the lateral epicondyle and at a point equidistant between the Gerdy tubercle and the fibular head 10 mm below the lateral joint line [18]. The length of the ALL prior to the rotation was 45.6 mm (Figure 3). For the sake of simplicity, any pre-stresses in the ligaments were neglected. The reference configuration of the model was assumed to be completely stress-free and undeformed.

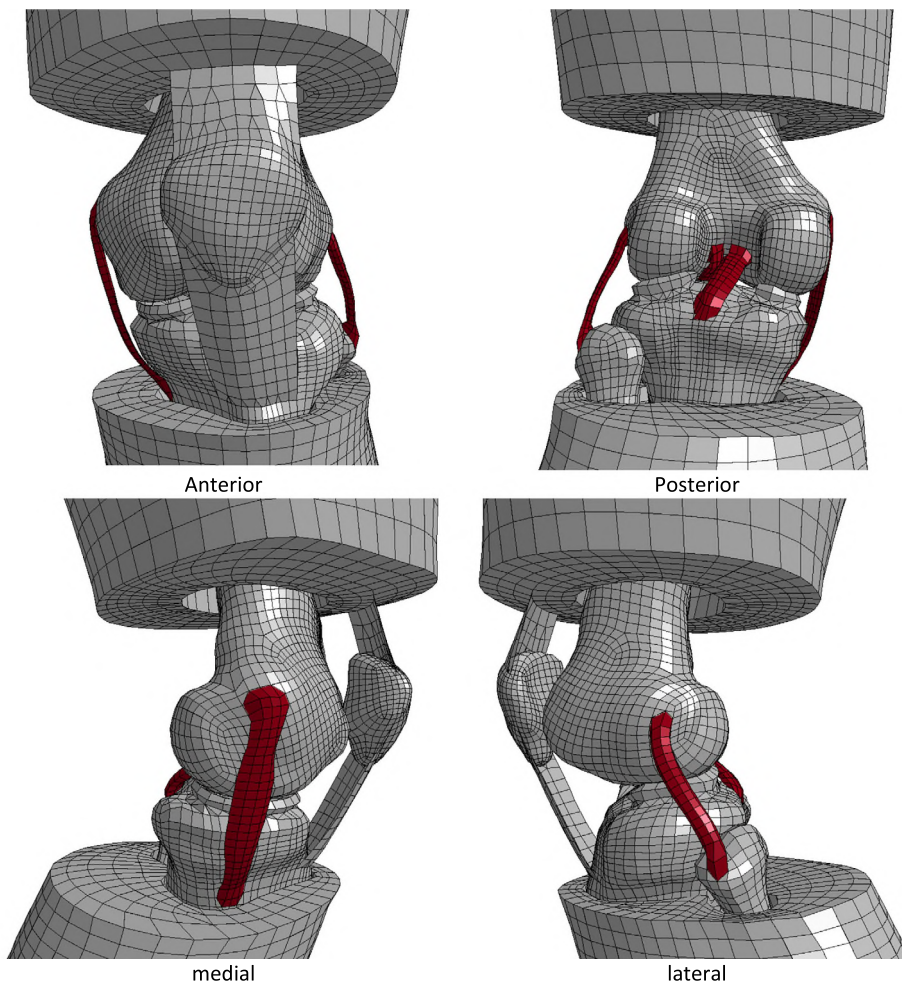


Figure 1. Reference model in undeformed configuration at an inclination angle of 25°. The cruciate ligaments and the lateral ligaments are marked in red. For improved visualization, the soft tissue in the central region is hidden.

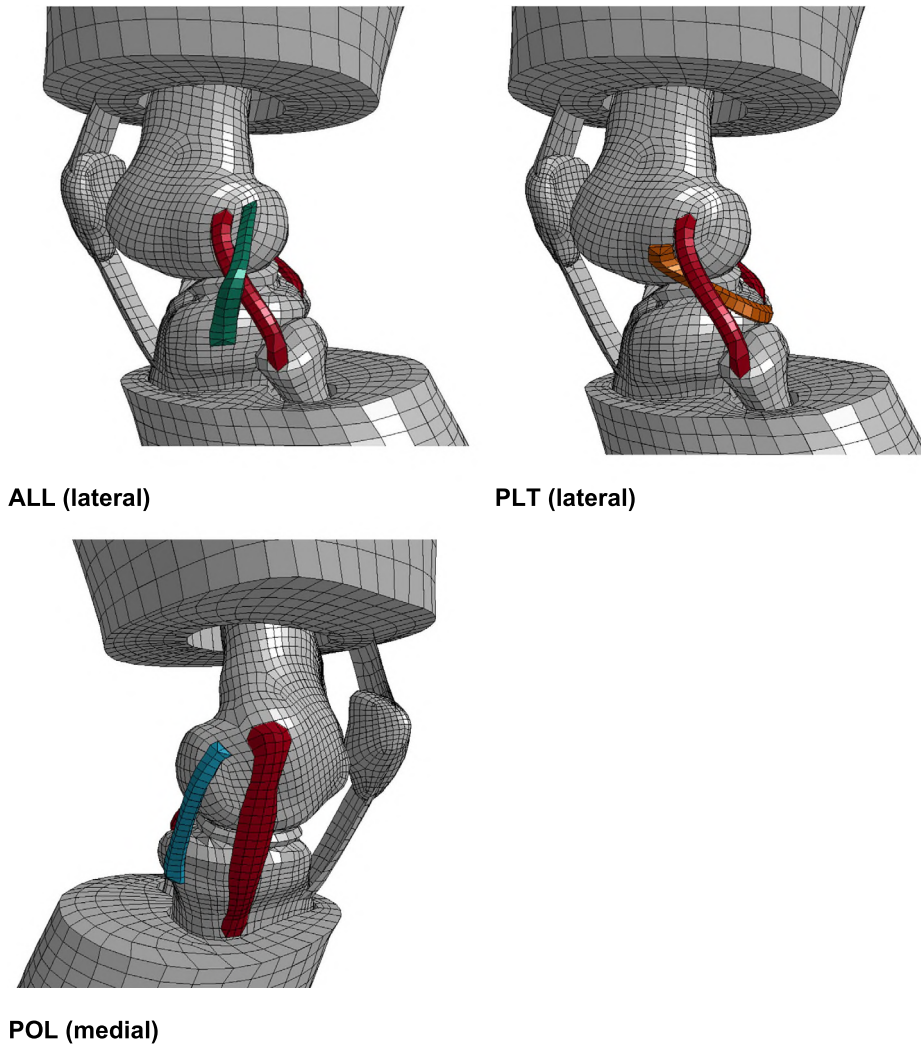


Figure 2. Model variants with different extra-articular ligaments in undeformed configuration at an inclination angle of 25°. For improved visualization, the soft tissue in the central region is hidden. ALL, anterolateral ligament; PLT, popliteal tendon; POL, posterior oblique ligament.

An external–internal torque was applied to the femur section which is defined rigid (highlighted in green in [Figure 4](#)) with and without the three additional anatomic structures by an external load.

The torque was applied about the longitudinal axis of the femur. The longitudinal femoral axis was defined by the centre points of the femur at the femur section and the centre point on the tibial plateau. The translational movement of the femur section along the transversal direction was restricted. The translational movement along the longitudinal axis was left free, also the remaining rotational degrees of freedom. The tibia section was defined rigid and completely fixed in space, all translational and rotational degrees of freedom were restricted. All other parts of the model were deformable.

The intensity of the applied torque was selected by trial and error in order to establish a loading scenario where the ligaments were subjected to an intermediate stress level. The intensity should be strong enough to reveal the relative load distribution in all ligaments of interest, but still far below the failure limit to avoid unphysical results. The maximum forces carried by the ligaments were in the range of 200–400 N and seemed to be realistic. According to Kennedy et al. [23] the tensile strength of a medial collateral ligament is in the range of 467 ± 33 N.

measured and the final rotational displacements of the rotated body part were determined for each case. Along the half-length of all ligaments in the model, cross-sections were defined for tracing the forces carried by the ligaments along their longitudinal directions. The location and the orientation of the cross-sections were updated each cycle according to the current nodal positions.

Data collection and descriptive statistical analysis was performed with Statistical Package for the Social Science (SPSS) after measurements. Data were presented as mean $\pm$ standard deviation (SD).

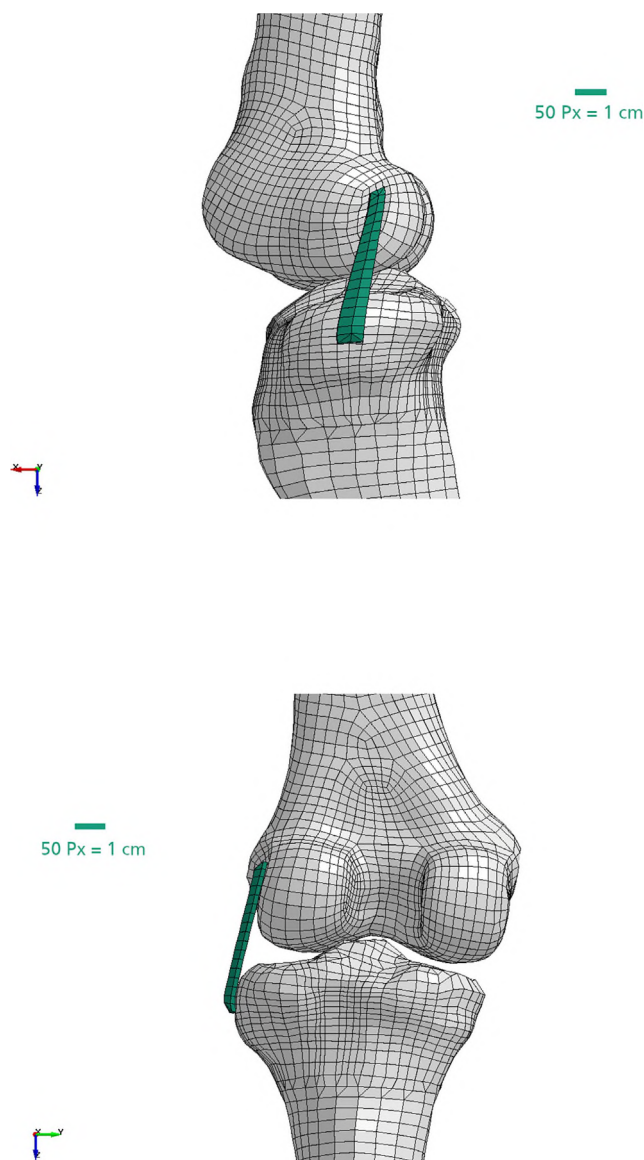


Figure 3. Origin and length of the anterolateral ligament prior to the rotation.

2.3. Ethical approval

All procedures performed in this study were in accordance with ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

2.4. Informed consent

Informed consent was obtained from all patients included in the study.

3. Results

In the human knee model, the ACL was the most loaded ligament both in tibial internal and external rotation during slight flexion (25°) and no valgus/varus load. The least loaded ligament was the LCL in tibial internal rotation and the PCL in tibial external rotation (Table 3). The ALL was the main stabilizer of the tibial internal rotation (46%) and prevented the tibial external rotation only by 3%. The ALL reduced the load on the ACL in tibial internal rotation by 21%, in tibial external rotation only by 2% (Figure 4, Table 4). There was no load reduction on other ligaments (PCL, LCL, MCL) by the ALL (Figure 3). The POL

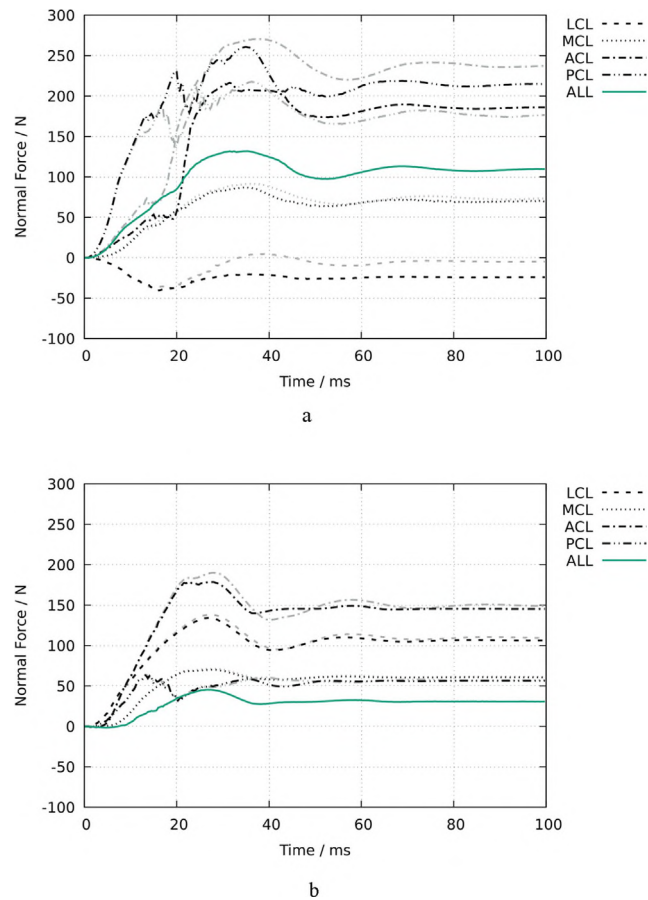


Figure 4. Force history of all knee ligaments under an external and an internal tibial rotation in 25° flexion when an anterolateral ligament is attached. Grey lines denote the force signal for the reference model without the anterolateral ligament. ACL, anterior cruciate ligament; ALL, anterolateral ligament; LCL, lateral collateral ligament; MCL, medial collateral ligament; PCL, posterior cruciate ligament.

Table 3
Numerical results for reference model at final equilibrium position.

Component	Quantity	Unit	Internal rotation	External rotation
Tibia	Angle	Degrees	−24.6 (±0.0)	11.9 (±0.0)
LCL	Force	N	−5.0 (±0.1)	109.6 (±0.1)
MCL	Force	N	73.3 (±0.2)	61.4 (±0.0)
ACL	Force	N	236.7 (±0.4)	149.5 (±0.2)
PCL	Force	N	177.0 (±0.3)	56.9 (±0.1)

Listed are average quantities and standard deviations after 60 ms.

Table 4
Influence of various extra-articular ligaments on the anterior cruciate ligament section force.

Variant	Unit	Internal rotation	External rotation
No extra ligaments	N	236.7	149.5
ALL only	N	(−21%) 186.0	(−2%) 145.5
PLT only	N	(−6%) 220.8	(+1%) 152.4
POL only	N	(−8%) 215.7	(−1%) 146.7
All extra ligaments	N	(−42%) 136.0	(−14%) 128.5

ALL, anterolateral ligament; PLT, popliteal tendon; POL, posterior oblique ligament.

and PLT did not reduce the load on the ACL in tibial external rotation by more than 1%, in tibial internal rotation the POL reduced the load on the ACL by 8%, the PLT by 6%. In the combined measurements with all additional structures (ALL, PLT, POL) the load on the ACL was nearly halved in tibial internal rotation. In tibial external rotation the load on the ACL

was reduced by 14% (Table 4). However, 55% of the total load reduction of the ACL in tibial internal rotation was due to the ALL.

4. Discussion

The presented data show that the ACL is a structure at risk, both in tibial internal and external rotation. However, the tibial external rotation, which can be crucial part of common injury mechanisms in ACL ruptures, is not considerably prevented by the ALL.

Due to our results the ACL restricts both the internal and external tibial rotation and gets loaded in these positions. Therefore, an ACL rupture appears to happen in motion patterns which consist of one of the above-mentioned joint positions at the time of trauma. Several previous studies have evaluated the mechanisms of an ACL rupture in athletes [17,24–26]. It is currently believed that internal rotation of the tibia (external rotation of the femur) is the most crucial and common rotational mechanism of an ACL rupture [27,28]. However, due to the difficult evaluation of various injury mechanisms, external rotation of the tibia cannot be excluded in many injuries and the exact mechanism of an ACL rupture therefore remains often unclear [17,25,29]. Nonetheless, it is generally accepted that especially landing manoeuvres after jumps with sudden valgus collapsing and additional rotational forces are obligatory [25,26,29]. Both, tibial internal or external rotation can play a major role in the most common injury mechanisms in ACL ruptures [15–17,25,26,29]. If tibial external rotation was part of the injury mechanism, pathologically increased external rotation of the tibia (internal rotation of the femur) must exist in patients after ACL rupture. Therefore, a structure that should have the potential to support the ACL in restoring rotational stability or to protect the ACL from damage in these common injury mechanisms must decrease tibial external rotation. In the present study the ALL, the POL and the PLT did not restrict the tibial external rotation considerably. However, the LCL or lateral meniscocapsular structures might be important structures in preventing the ACL in trauma mechanisms with tibial external rotation because high forces were observed in the LCL in this rotational position in the present study. This would make sense, because the LCL and the posterolateral corner are already known as secondary stabilizers of the ACL and an additional reconstruction of these structures seems useful in certain cases [3,30].

In contrast, the reconstruction of the ALL is probably only useful if the injury mechanisms consisted of a distinct tibial internal rotation (femoral external rotation) with subsequent instability in these directions. In these cases, the reconstruction of the ALL seems rational and can protect the ACL transplant in such injury mechanisms in the future. However, it should be mentioned that a patient after ALL reconstruction has only an improved stability in tibial internal rotation and the ACL is not more supported or protected in a trauma with valgus stressing and external rotation of the tibia by the ALL transplant. Moreover, the precise role of the ALL in eliminating the pivot shift remains controversial and many reported results of an additional anterolateral procedure in patients with ACL reconstruction with almost always negative pivot phenomenon may be linked to a misinterpretation of the pivot shift test itself [31–34]. Even if some authors support the assumption that the ALL plays an important role in high-grade pivot shift, other authors postulated that the pivot shift test reflects primarily an ACL insufficiency [35–39]. They even specified that a concomitant lesion of the meniscus, especially the lateral meniscus, can rather lead to a high-grade test result [28,35]. The influence of a lesion to the anterolateral complex (ALC) on the pivot shift test were classified as low [35,38,39]. In an ACL-insufficient knee, the lateral and medial femur condyle dislocate dorsally and shift internally [28]. While performing the pivot shift test, the femur gets repositioned by increasing the flexion regardless of a damaged or intact ALC [35]. Therefore, the pivot shift test seems not to be an optimal tool to evaluate a benefit of an additional ALL reconstruction in patients after ACL reconstruction and the negative test results might be rather linked to the quality of the ACL reconstruction or concomitant meniscal lesions.

In summary, depending on the injury mechanism, concomitant lesions of the knee joint need to be evaluated in patients with ACL rupture. In this context several medial- and lateral sided structures must be considered, especially in patients with ACL re-ruptures, high-grade pivot phenomenon or persisting pivot phenomenon after ACL injury or failed ACL reconstruction. Moreover, the MCL should get more attention in patients with ACL injury. Valgus stressing or collapsing is part of almost all injury mechanisms regardless of the rotation, and the MCL is already known as second stabilizer of the ACL [24,25,29,40]. The tight connection between the MCL and the medial meniscus and the oblique course of the MCL are predisposing factors in stabilizing the knee joint in complex movements and a lesion of this structure is a common concomitant finding in many patients with ACL rupture [21,40–44]. These lesions often may not be adequately treated, which leads to higher forces on the ACL transplant after singular ACL reconstruction [40]. Therefore, future studies are needed to identify secondary structures which stabilize specifically the tibial external rotation and protect the ACL in such injury mechanisms. To our knowledge, this is the first FE study which evaluates the behaviour of the ALL in different rotational positions. It has to be noted that the present knee model is not based on computed tomography scans but isolated out of a full human body model. Moreover, the material model is isotropic and plastic and might be inferior to anisotropic and hyperplastic models [45,46]. However, both facts do not affect the fundamental study results. In comparison with other FE studies, the knee model of present study is similar and therefore the methodology is valid [45–47].

The present study has some limitations. Firstly, the human knee model is merely an image of the natural knee and may contain geometric, biomechanical, and material deficiencies such that only biomechanical tendencies may be displayed. Moreover, in the present study the same material model was used for all tested ligaments. This may have accentuated the results in a quantitative manner. Second the human knee model includes an intact capsule and an intact medial and

lateral meniscus. Therefore, a possible influence of these structures to the load of the ACL or the knee stability in external and internal rotation is not considered. Third, the mechanism of an ACL rupture is mostly a combination of rotational forces and valgus/varus stressing as well as tibial translation. In the present study, only the femoral internal and external rotation were evaluated in 25° flexion. Therefore, structures such as the MCL or LCL and the influence of structures in other flexion angles might be underestimated in their function as a protector of the ACL. Moreover, the iliotibial band (ITB) with its potentially complex influence on knee stability was not considered in present study.

5. Conclusion

The ALL protects the ACL in injury mechanisms with tibial internal rotation but not in mechanisms with tibial external rotation. In injury mechanisms with tibial external rotation other structures that support the ACL need to be considered.

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Author contributions

All six authors made substantial contributions to the conception, design, acquisition, analysis and interpretation of data for the work. Moreover, all authors took part in drafting the work and revising it critically for important intellectual content. All authors participated in the final approval of the version to be published and are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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