Subject-Specific Assessment of Loading Variation In the Knee Ligaments With a View To Preoperative Planning

Andra Chincişan, Hon Fai Choi, Lazhari Assassi, Sean Lynch, Christof Hurschler, Nadia Magnenat-Thalmann

Abstract—The human knee joint is a complex joint of the human body that experiences large loads. The knee stability is mainly ensured by four major ligaments, which all play vital roles to enable a proper joint articulation. As such, the interactions between the mechanical loading in these ligaments needs to be taken into account in order to obtain an adequate assessment of rehabilitation after injury or preoperative planning to restore the function of a damaged ligament. However, the combined effect of knee ligaments during movement has not yet been investigated in detail. In this study, we present a three-dimensional finite element model of a healthy human knee including the four major ligaments. The geometric model of the knee was reconstructed from volumetric data obtained from MR scans. Transversely isotropic Mooney–Rivlin material with fiber orientation was used to represent the mechanical response of the ligaments. For validation, anterior-posterior tibia translations were compared with the results obtained with an in vitro technique performed on cadavers. The purpose of these simulations is to simultaneously evaluate the mechanical behavior of the major ligaments of the knee. The good agreement between the 3D model and the in vitro measurements supports the potential for clinical applications of the model for evaluation of interventions or treatments.

I. INTRODUCTION

The human knee joint is the largest and most complex joint of the human body [1]. The knee joint plays an important role in body movement, involving multiple interactions between bones, cartilages, menisci, ligaments, tendons and muscles. The ligaments have a major role in stabilizing the knee and the maintenance of physiologic knee kinematics. The four major ligaments are: anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL) and lateral collateral ligament (LCL). In general, the MCL is the most commonly injured ligament, while injury of ACL is most frequent in sport-related activities with 100,000-200,000 injury cases per year in the United States [2]. The number of knee ligaments surgeries is increasing every year [3]. Furthermore, Murray et al. [4] reported after a 5 years follow up that 94% of the patients that underwent ligament surgery still had instability in the knee. A good understanding of the mechanical functions of the knee ligaments is of great importance for preventing and treating ligament injuries. More detailed knowledge of ligaments interaction is important because these four ligaments work together to control and stabilize the knee during motion, such that injury in one ligament can lead to progressive damage to the others [5]. This understanding is also required to ensure long-term outcome of surgical treatments, in order to recover physiological loading as much as possible and thus preventing unintended mechanical overloading of the non-treated ligaments.
Several studies were conducted to investigate the mechanical behavior of the knee ligaments. First, ligaments were modeled as one dimensional structures and recently as 3D models [6],[7]. However, most of the studies evaluate the functionality of each ligament separately [6]-[8]. A complete model that incorporates the ACL, PCL, MCL and LCL was presented in [9], but was evaluated only for translation of forces. Lumpaopong et al. [10] investigated the MPFL reconstruction using a validated subject-specific finite element model to demonstrate the potential of the computer modeling techniques to assess surgical outcome. Despite the many studies reported on the knee joint, the combined mechanical behavior of all four ligaments during normal and pathological movements has not been clearly presented with a view to inform surgical intervention.

The objective of this study is to investigate whether a 3D finite element model reconstructed from magnetic resonance (MR) data calibrated with experimental in vitro data provides a suitable tool to simultaneously evaluate the mechanical function in the four major ligaments, providing a means for preoperative planning in order to optimize outcomes of the ligament surgery. Biomechanical investigation of the knee joint kinematics (flexion, internal and external rotation, anterior and posterior translation) is considered, which demonstrates a physiological basis for an instrumental assessment for the preoperative surgery planning.

II. COMPUTATIONAL MODEL

a. 3D Model

A 3D finite element knee model of a healthy volunteer was reconstructed from MR scans. The 3T MR images (Fig. 1) were acquired for a subject in resting supine position [11]. The subject specific model included femur, tibia and fibula bones and the major cruciate and collateral ligaments. The anatomical structures were segmented with a semi-automatic method and validated by a radiologist. The ligaments structures were converted in volumetric meshes with tetrahedral elements using CGAL (INRIA, France) [12]. The bones were converted in triangular polygon meshes.

![Figure 1. MR high resolution knee images](image)

b. Material behavior

Because the focus is on the ligaments, the bones were assumed to be rigid. The ligaments were considered to be transversely isotropic hyperelastic and incorporated the fiber structure. The material response was modeled according to a Mooney-Rivlin behavior [9], with the properties adopted to match the experimental data. The strain energy function, was defined as the combination of the interstitial matrix F1 and the local contribution of the fiber F2 [9], where \( \bar{I}_1, \bar{I}_2 \) are the first and second invariants of the right Cauchy Green deformation tensor \( \bar{C} \). \( \bar{\lambda} \) is the deviatoric part of the fiber stretch.

\[
W = F_1((\bar{I}_1), (\bar{I}_2)) + F_2(\bar{\lambda}) + (K/2)[\ln(J)]^2
\]  

(1)
The ligaments fibers were generated with a method which allows to construct a numerical representation of the fiber orientations as a Laplacian vector field [13].

c. Boundary conditions

The contact surfaces between soft tissues were defined as frictionless. Ligaments insertions to the femur and tibia constrained them to move according to the rigid body to which they were attached. During flexion and internal/external rotation, the tibia was fixed in all 6 degrees of freedom (DOF), while the femur was allowed to move in these directions. For the anterior/posterior translation, the femur was fixed and the tibia was translated. The femur axis origin was determined based on the method proposed by Miranda et al. [14]. The femur condyles were isolated and a cylinder was fitted using the LSGN (Least Square Gauss-Newton) algorithm. The cylinder’s center represents the origin of the femoral anatomical coordinates. The flexion/extension axis or the primary axis was defined as the medial axis of the cylinder. The abduction/adduction axis was defined as the second axis of the cylinder. The third axis was determined by the cross product between the flexion/extension and the abduction/adduction axis.

III. EXPERIMENTAL MEASUREMENTS

Experimental measurements were conducted to determine the material parameters of the FE model by comparing the anterior posterior tibia translations obtained experimentally in vitro from two specimens with the translations predicted by the computational model. The femur was fixed in all the translational and rotational degrees of freedom, whereas the tibia was constrained in rotation and unconstrained in the medial/lateral and superior/inferior translation. Anterior-posterior displacement was applied in the center of the tibia until an anterior- or posterior reaction force of 100N was observed. A sensor guided robot for mechanical testing (KR 15/1, KUKA Robots Augsburg) was used to apply the described boundary conditions to the human cadaver joints for two cycles of anterior/posterior translations. The tibia reaction force in relation to translation in the anterior/posterior direction was compared with computed values. The finite element simulation results closely follow the experimental values as can be seen in Fig. 2. In addition, the obtained results with both methods are similar with reported findings from previous studies [15].

![Figure 2. Anterior/posterior tibial translations in 2 in-vitro cadaver experiments (S1 and S2) and simulated in the 3D FE model (FEM)](image-url)
IV. FINITE ELEMENT ANALYSIS

The numerical simulations were performed using FEBio [16]. Three different cases were investigated in this study: flexion and internal/external rotations. A first FE simulation was performed for (a) flexion from 0 to 45°, (b) the second FE simulation was performed for 0 to 15° internal rotation, (c) the third FE simulation was performed for 0 to 15° external rotation. For all three cases the rotation was applied in the origin of the femur coordinate system. The selected values are in the physiologic range during walking [17].

V. RESULTS

The fiber strain was calculated for all the models. Fig. 3, Fig. 4, Fig. 5 illustrate the fiber strain distributions in the ligaments during (a) passive flexion, (b) internal rotation and (c) external rotation.

a) Flexion

The highest value of the fiber strain during flexion was found for the MCL. The MCL presented a peak value of 0.31 for the fiber strain during the 45° flexion, suggesting that the MCL is the primary ligament to insure stability during flexion.

A small region of fiber buckling was localized in the proximal part of the MCL, close to the femur attachments, but this region increased with the flexion angle. The LCL presented a large region of fiber buckling in the middle proximal part. The highest values were observed close to the femoral attachment area, as this region rotates during flexion.

b) Internal rotation

The fiber strain values were approximately three times lower for internal/external rotation compared with the flexion. The highest fiber strain values (around 0.1) appeared in the collateral ligaments, responsible for stabilizing the sideways movements.
c) **External rotation**

The highest values of fiber strain (around 0.11) for the external rotation was observed in the MCL, but the value was very close to the reported result for the internal rotation. The cruciate ligaments showed to have a higher role in restraining the rotation in this case compared with the internal rotation. The second ligament that supported internal and external movements was found to be the LCL.

![Figure 5. Fiber strain at 15º external rotation](image)

The middle part of the MCL restrained the flexion movement (Fig. 3), while for the internal/external rotation the superior and lower attachments of the MCL to the bones (Fig 4, 5) contributed more to restrain the movements. The fiber strain in the ligaments was also investigated for tibial translations (Fig. 6). The fiber strain values during the anterior movement were highest in the ACL supporting that the ACL plays the main constraining role during the anterior translation (Fig. 6 (a)) while this was the case for the PCL during the posterior movement (Fig. 6 (b)). Of the other ligaments, the MCL contributed the most in controlling the anterior and posterior translations.

![Figure 6. Fiber strain for (a) anterior and (b) posterior translations](image)

We also investigated the variation of the peak fiber strains in the ligaments for various angles (Fig. 7). For lower angles of internal rotation (<10º) the peak values of the fiber strain in the LCL were similar with the peak values from the MCL, while for the external rotation the peak values in the MCL were two times higher compared with the values in the LCL. However, for all the angles of the internal/external rotations the fiber strain in the collateral ligaments was significantly higher compared to the cruciate ligaments. For lower angles of the flexion (<15º) the peak values of the predicted fiber strain for the ACL and PCL were similar. As the flexion angle increased, the ACL had the secondary role in restraining the movement.
VI. DISCUSSION AND CONCLUSIONS

We reconstructed a 3D FE subject-specific model from MR scans in order to evaluate the combined mechanical functions of the major cruciate and collateral ligaments of the knee joint. The four major ligaments, ACL, PCL, MCL and LCL, were modeled as hyperelastic anisotropic material that incorporates a physiologically plausible representation of fiber orientations. The model was validated against experimental in vitro data from two specimens. The model was capable to demonstrate fiber strain distribution in the collateral and cruciate ligaments during various joint movements (flexion, internal/external rotation, anterior/posterior translation). The assessment of the knee joint kinematics gives a better understanding of the ligaments mechanical behavior, while the FE results represent potential preoperative evaluation measurements.

We found that the MCL is most exposed to injury having the peak values for the flexion, internal and external rotations. The highest value of the fiber strain was found for the MCL during flexion. The MCL is the primary ligament that insures stability during internal/external rotation and flexion. The various roles carried out by the MCL during forward, backward and sideways movements expose it to multiple injuries [18]. The fiber strain distribution in the medial collateral ligament (Fig. 3) showed similar distribution with the results reported by Phatak et al. [7] having the peak values of the fiber strain in the anterior part of the MCL and the buckling on the posterior part. The second ligament that supported internal and external movements was found to be the LCL.

The results predicted by the FE model correspond with the literature findings reported for in vitro measurements performed on human specimens [19]. The observed results predicted that the lateral and medial collateral ligaments are controlling the knee during the knee rotations and the cruciate ligaments are restraining the knee joint during the anterior posterior translations. The good agreement between the 3D model and the in vitro anterior-posterior translations used in the model validation supports the potential for clinical applications of the model.

The failure of the ligament reconstruction is a main problem for the knee [20]. Long term follow-up studies show a high incidence number of clinical failure for the patients that have undergone the ACL reconstruction [21]. Another disturbing problem after the ligament reconstruction is the incidence number of the patients that develop osteoarthritis [22]. Accurate subject-specific FE modeling of the ligaments is a promising method for the preoperative planning in order to improve the surgical outcomes.

The potential of computational modeling techniques of the human knee ligaments for subject-specific surgical planning was presented in [10]. The preoperative evaluation based on finite element models and gait analysis can optimize the results of the surgical procedures.
combination of FE modeling calibrated with *in vitro* measurements provides a physiological base for an instrumental assessment for the preoperative surgery planning and for rehabilitation strategies. The results presented in our study demonstrate how a systematic evaluation of joint mobility in a subject-specific model can be used to perform a mechanical analysis of the ligament system, by quantifying the mechanical loading under varying rotational motions. The results also demonstrate the mechanical loading interaction between all major knee ligaments for different ranges of kinematics that has not yet been considered in detail previously. The motions have been varied separately, to allow for a comparison with results in previous studies. For surgical application, combinations of these motions can be simulated to systematically map the mechanical stress, allowing to detect the range of motion that imposes the most risk for further knee destabilization and injury. This information allows the surgeon to refine the diagnosis and to restore the primary function in the ligaments more effectively. In future steps towards clinical application, ligament injuries can be included in the model. The motions can also be varied more systematically in combination to provide a complete map of the mechanical loading, which can be used by the surgeon as an assessment tool to evaluate the functional outcome.

VII. REFERENCES


