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Intact and ACL-Deficient Knee MODEL Evaluation

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Abstract**—**The human knee joint has a three dimensional geometry with multiple body articulations that produce complex mechanical responses under loads that occur in everyday life and sports activities. To produce the necessary joint compliance and stability for optimal daily function various menisci and ligaments are present while muscle forces are used to this effect. Therefore, knowledge of the complex mechanical interactions of these load bearing structures is necessary when treatment of relevant diseases is evaluated and assisting devices are designed.

Numerical tools such as finite element analysis are suitable for modeling such joints in order to understand their physics. They have been used in the current study to develop an accurate human knee joint and model its mechanical behavior. To evaluate the efficacy of this articulated model, static load cases were used for comparison purposes with previous experimentally verified modeling works drawn from literature.

Keywords**—**biomechanics, finite element modeling, knee joint

I. Introduction

THE human knee joint is a three dimensional geometrical structure with multiple body articulations which produce complex mechanical responses. This complex joint faces mechanical loads that occur in daily as well as sports activities. The necessary knee joint compliance and stability to function optimally every single day, every single minute are provided passively by various menisci, ligaments as well as actively by muscle forces. Therefore, knowledge of the complex mechanical interactions of these load bearing structures is helpful in evaluating treatment of relevant diseases and designing assisting devices.

The ligaments control the passive movement of the knee joint while the dynamic stability of the joint is actively provided by muscular movements. Injuries or damage to any of these load bearing structures lead to degradation or loss of the joint function. In the knee joint the anterior cruciate ligament (ACL) plays an important role in maintaining normal knee function [1], and injuries to it are commonly treated with surgical reconstruction as damage to it results in joint instability in the anterioposterial direction.

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To understand the mechanical behavior of this ligament, experiments have been performed by various researchers [2], [3], [4]. These studies usefulness is limited by the fact that the ligament mechanical properties have different values and behavior when in vivo compared to in cadaveric form. These studies can therefore only provide quantitative information for the stresses and strains developed in the knee joint. On the other hand, various biomechanics researchers have long demonstrated that realistic mathematical modeling is an appropriate tool for the simulation and analysis of complex biological and physical structures such as the human knee joint in spite the limited ability for validation [5]. This is due to material properties which show a wide range of values, compared to man made materials (e.g. metal alloys), and the complex geometry of the systems modeled. During the past two decades, a number of analytical model studies with different degrees of sophistication and accuracy, have been presented in literature [6], [7], [8], [9], [10], 11]. An alternative to in vivo measurement of body structural behavior is the calculation of ligament forces using numerical modeling. In particular, previous attempts to model the ACL mechanics have employed a computer model where different approaches have been attempted, either were ligaments behave as a multiple fiber bundle with a non-isometric behavior [12], or not [13].

In this work the efficacy of a geometrically accurate three dimensional model of the knee structure, developed by the authors (fig. 1), is being evaluated. Static load cases were used for comparison purposes with previous experimentally verified modeling works drawn from literature.

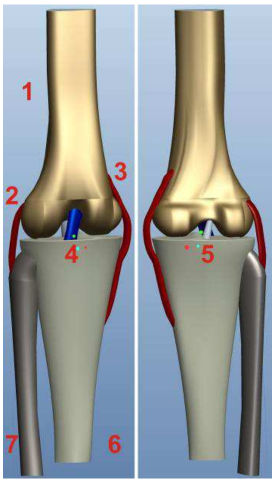


Fig. 1 The developed three dimensional geometric knee model : (1) Femur, (2) Lateral collateral ligament (LCL), (3) Medial collateral ligament (MCL) (4). Anterior cruciate ligament (ACL), (5) Posterior cruciate ligament (PCL), (6) Tibia, (7) Fibula

II. METHODS

To construct a realistic and physically accurate three-dimensional geometric model of the knee joint, three-dimensional scanned data from a replica of the knee were used. The assembled three-dimensional knee joint geometric model was input to the finite element analysis module of the commercial software Pro Mechanica. The model was discretized using 5,812 three dimensional solid elements. Material properties of the individual parts of the assembly were assumed to be linear elastic, and applied constrains, which define the degrees of freedom each knee joint element has, were drawn from literature and assigned to geometric entities. The development of the knee joint three-dimensional geometric model and the finite element model are described in detail in a previous work by the authors [14]. The response of the finite element model under simplified real life static loads, which are in accordance to loads previously used in literature to validate similar models, is studied and evaluated [14]. The developed finite element model of the whole assembly of the knee joint, for both calculated stresses and strains, showed a linear response when increased loads were applied to produce increased stresses and strains, for each type of load. This response is the expected for such a model, as linear material properties were used in this study.

The current work aims to verify further the developed model, by exploiting static load cases presented in previous experimentally verified modeling works [1], [15].

In the first of the published works [1] a three dimensional finite element model of the human knee cartilage, menisci and ligaments was presented, which was analyzed using custom developed numerical analysis software. Both, the intact knee and the joint with the ACL severed, were studied under static passive loading at different flexion angles. Bony structures were ignored in the model and the subsequent analysis, due to their high rigidity relative to other structures of the joint. Non linear material data were used for different ligaments, while the meniscus was assumed to be a non homogeneous isotropic composite part. Articulations between cartilage and meniscus were simulated to have frictionless contact. It was found that the tibiofemoral joint became significantly more flexible with an absent ACL and produced much larger femoral translations than the intact knee, for all loads and flexion angles. The posterior cruciate ligament (PCL) was active in load sharing for high flexion angles in all cases, with its load sharing effect being pronounced in the intact knee model. The relatively important mechanical role of the meniscus was shown when the stresses developed in the cartilage were calculated, emphasizing the need for ACL reconstruction whenever needed.

In the second work [15], a three dimensional model of the healthy human knee joint, based on geometric data derived from MRI and CT scans of live volunteers, was constructed for study using the commercial numerical analysis package ABAQUS. In a similar fashion as in the previous paper, bones were considered as rigid bodies and not involved in the solution, and frictionless contact was also assumed. Ligaments were assumed to behave as hyperelastic solids and menisci as composed of linear elastic material. As the loading time of the analyses was small no time-dependent effects, like viscous behavior, were necessary to be considered. The model incorporated initial strains prior to applying various loads, which were applied to the hyperelastic soft tissues as a result of growth and damage mechanism that occurs during the life of the tissues. The numerical model was validated from other literature sources for combined compressive and external horizontal loading, a combined compressive load with a torque and a third load case where all three individual loads were applied, with all load cases applied to a no flexion knee joint. The load distribution between ACL and the medial collateral ligament, as well as the menisci was estimated. As expected, calculated values were dependent on material properties such as Young's modulus and Poisson ratio.

In the current study, the same load cases used in the abovementioned papers were applied in the model and the calculated results were compared for verification purposes.

In order to verify the current finite element model with [1] the load cases applied to the intact and the ACL-deficient knee joint model were applied. The femur was subjected to a posterior horizontal force, and ten different load cases were studied for different forces, as in the work of Moglo and Shinazi [1], ranging from 10 N to 100 N with a 10 N step size. Comparative force-displacement graphs were produced for assessment purposes. In the graphs the displacement is calculated in two different directions, in the posterior-anterior (post/ant) direction and in the medial-lateral (med/lat) direction.

In order to verify the current finite element model with [15] two of the three load cases studied were applied in the current model. A combined load of 1150 N in compression and 134 N with an anterior–posterior direction was applied to the femur in the first case. In the second case, the same compression load of 1150 N was applied together with a valgus torque of 10 Nm. The maximum calculated stress values in different ligaments of the knee joint were compared. In addition, the load distribution in the knee joint was qualitatively compared between the two papers.

III. RESULTS AND DISCUSSION

Fig. 2 shows the comparison between the current study intact knee model and that of Moglo - Shinazi intact knee model for displacement for the different force load cases. The developed model showed similar response to the experimentally verified model of Moglo – Shinazi, with the calculated values being very close. In the posterior/anterior direction, the current model calculated displacement values were lower than the Moglo – Shinazi model values, while in the medial/lateral direction, the calculated values were higher. The average difference for displacement was about 21%.

Fig. 3 shows the comparison between the current study ACL-deficient knee model and that of Moglo - Shinazi ACL-deficient knee model for displacement for the different force load cases. The developed model showed similar response to the experimentally verified model of Moglo – Shinazi, with the calculated values being very close. In the posterior/anterior direction, the current model calculated displacement values were higher than the Moglo – Shinazi model values for lower and higher loads and they were lower for medium load magnitudes. This is probably because of the non-linear materials used in the Moglo – Shinazi model. In the medial/lateral direction, the calculated values were higher. The average difference for displacement was about 8.5%. As expected, the calculated displacement values were significantly higher than the values calculated for the intact knee model, with a difference of about an order of magnitude, showing the importance of this type of injuries in the knee joint stability.

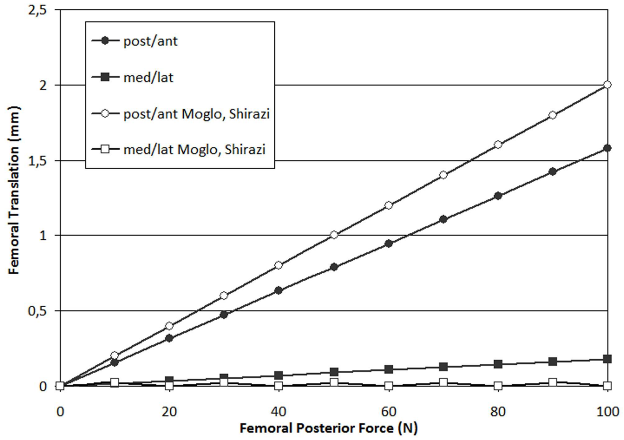


Fig. 2 Comparison between the current intact knee model and the equivalent Moglo - Shinazi model for calculated displacement for the different force load cases studied

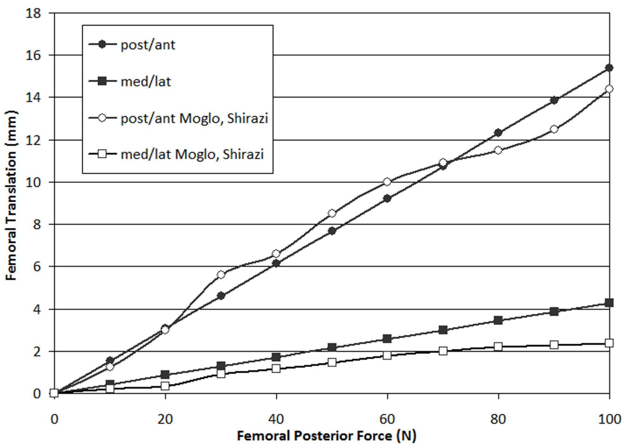


Fig. 3 Comparison between the current ACL-deficient knee model and the equivalent Moglo - Shinazi model for calculated displacement for the different force load cases studied

In the case of the verification of the current model with that of Pena et al. [15], where a combined load of 1150 N in compression and 134 N in the anterior–posterior direction was applied to the femur, the calculated maximum stresses were similar (Table 1), but with the current model calculating significantly lower stresses. As load distribution and the areas where high stresses appear are similar between the two models, this deviation in the maximum stress can be attributed to the complexity of the knee joint geometry. No two geometries are exactly the same, in a similar fashion to nature, and therefore different results are produced, but with both analyses showing quantitative agreement with the same stress distribution being calculated.

In the second case [15] used to verify the current model a compression load of 1150 N was applied together with a valgus torque of 10 Nm, and the maximum stresses are shown in Table 2. The response of the current model is similar to literature [15]. For this load case the maximum stresses are very close, and the average difference between them is about 15%. Similarly to the previous verification case, the load distribution and the areas of high stresses, are similar between the two models.

TABLE I
MAXIMUM STRESS FOR THE FIRST LOAD CASE

Compressive Force 1150 N and Anterior Force 134 N	Max Stress [Mpa]	
	Pena et al [15].	Current Model
PCL	3	1,2
ACL	15	3,2
LCL	3,4	0,5
MCL	3,5	1,7

TABLE II
MAXIMUM STRESS FOR THE SECOND LOAD CASE

Compressive Force 1150N and Valgus Torque 10 Nm	Max Stress [Mpa]	
	Pena et al. [15]	Current Model
PCL	-	2,32
ACL	2,65	2,16
LCL	5,3	5,95
MCL	-	1,76

Fig. 4 shows the stress distribution in the knee joint ligaments for the second load case for the current model compared to the Pena et al. [15] model.

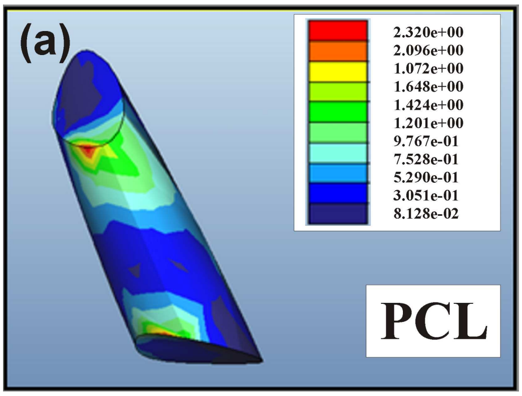
The calculations for the load cases studied demonstrate that the developed finite element knee joint model is reliable, as the results obtained are consistent with models available in literature, which in turn have been verified experimentally.

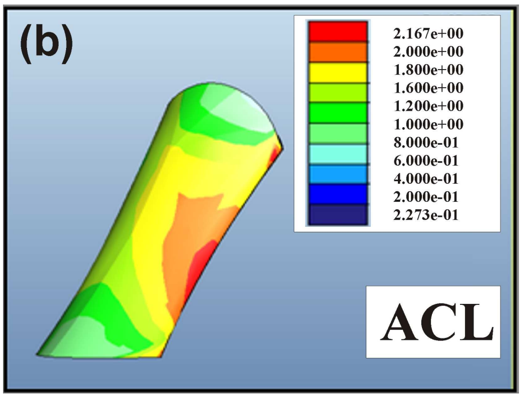
All the load cases studied are based on loads that affect the knee joint in real life. In every case higher stresses appear in the ligaments close to the area where they are connected with bones as well as in the middle of their length.

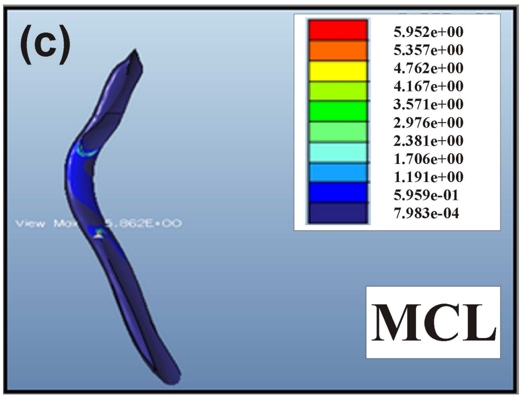
IV. CONCLUSIONS

A realistic three dimensional finite element model of the knee joint which incorporates bone structures as well as ligaments and menisci was developed and a number of analyses for static loads for an intact and an ACL-deficient knee were performed and the following conclusions were drawn:

- the model developed has calculated stresses and displacements that were within the material elastic range, which is the expected response the load magnitudes involved
- the stress distribution calculated in the knee ligaments is reasonable, with no high stresses developing at the connection points to the bone structures of the knee. If these were present would be confusing and they would be numerical artifacts
- the material properties used were linear elastic, and produced comparable results for stress and displacement with other validated models which used hyper-elastic material properties. This agreement can be attributed to the fact that stresses produced were small in magnitude in the elastic region, while not high enough for the enhanced material properties to affect significantly the calculated values
- the model developed was validated against the results produced by other numerical model, which in turn had been validated with experimental data.







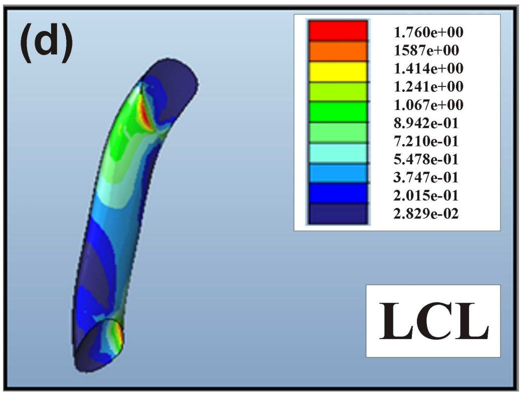


Fig. 4 Stress distribution knee joint ligaments for the second load case of the model verification with the Pena et al. [15] model

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