A STUDY ON THE EFFECT OF LIGAMENTS' MATERIAL MODEL ON JOINT KINEMATICS IN FINITE ELEMENT MODELS OF THE KNEE

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INTRODUCTION

Finite Element (FE) modelling is an efficient tool to broaden our knowledge about the knee joint biomechanics. It allows to capture the individual soft tissue contribution under complex loading conditions during joint motion. However, the reliability of the model is highly dependent upon factors such as proper geometrical representation of the tissues and their assigned material properties. Knee supporting ligaments are dense connective tissues consisting of aligned collagen fibres that are embedded in a compliant solid matrix of proteoglycans, which results in their anisotropic and nonlinear behaviour [1]. Considering the significant role of the ligaments in maintaining the knee stability during motion, their 3D representation in the FE model and the constitutive equations used to describe their behaviour seems to have a noticeable effect on the model results. Hence, some studies have addressed the effect of 1D and 3D ligament modelling techniques on joint kinematics [2]. The objective of the present study is to investigate the effect of using the transversely isotropic hyper-elastic material model and the neo-Hookean material model for the 3D ligaments on the extracted joint kinematics.

METHODS

Computerized tomography (CT) and magnetic resonance imagining (MRI) scans of an adult female volunteer suffering from Genu varum were used to extract tissue geometries. The segmentation process was performed manually to extract the 3D geometry of the relevant bones from the CT images, and the soft tissues including the articular cartilage, menisci, cruciate and collateral ligaments, patellar and quadriceps tendons (PT and QT) from MRI.

The model geometries were imported to Abaqus FE package to be meshed and assembled into the FE model (Fig. 1). All the soft tissues were meshed using solid eight-node hexahedral elements. Bony structures (femur, tibia, fibula, and patella) were considered to be rigid bodies and thus their surfaces were meshed using four-node shell elements. Cartilage and menisci were modelled as a single-phase linear elastic and isotropic material. The PT and QT material models were assumed to be nearly incompressible neo-Hookean. All the major ligaments including the anterior cruciate ligament (ACL), the posterior cruciate ligament (PCL), the medial collateral ligament (MCL), and the lateral collateral ligament (LCL) were modelled as nearly incompressible transversely isotropic hyper-elastic structures [3]. The direction of fibres at each point was calculated and attributed to the corresponding elements via a Python code along the length of each ligament. The material model for the major ligaments were changed to be isotropic neo-Hookean hyper-elastic in a second model.

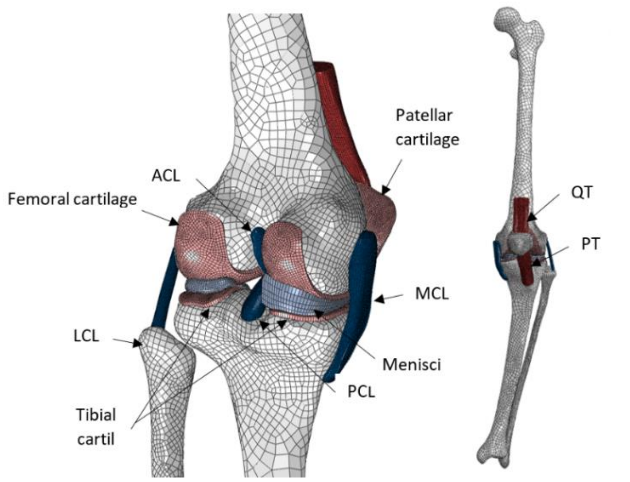

Fig 1: Computational FE model of the left knee of an adult female

The contact interaction between the structures has been considered by defining a general contact between all the surfaces. Penalty method has been used as a governing contact algorithm in the normal direction while the tangential behavior has been considered to be frictionless. In addition, the attachment of the cartilages and ligaments to the bony surfaces were modelled using tie constraints.

All the translational and rotational degrees of freedom of the femoral bone were set to be fixed during the simulation. Meanwhile, tibial and patellar bones were left totally unconstrained throughout the simulation. The minimum necessary load to create a quasi-static flexion of the knee was applied to the tibial pilon toward the centre of the femoral head. Additionally, a 10N quadriceps load was applied to the model during knee flexion. The joint kinematics was captured by defining the anatomic coordinate systems based on the literature [4]. The three components of translation as well as the internal/external rotation and abduction/adduction of the joint were plotted as opposed to the degree of flexion angle to monitor the joint kinematics and compare the results with experimental corridors.

RESULTS AND DISCUSSION

The kinematic results of the knee FE model to investigate the effect of changing the ligaments' material model from transversely isotropic hyper-elastic to neo-Hookean material is presented in Figure 2. The flexion range of the model starts at 22˚ that is the flexion degree of the joint while taking the MRI. The joint continues to adduct with increasing flexion angle, although the adduction takes place with a higher slope in the model using transversely isotropic hyper-elastic constitutive low. The knee is 1.31˚ adducted at 22˚ of flexion and it reaches a maximum adduction of 7.03˚ at the end of flexion for the transversely isotropic model. The adduction amount for the neo-Hookean model is 2.10˚ and 6.15˚ respectively at 22˚ and 64˚ of flexion.

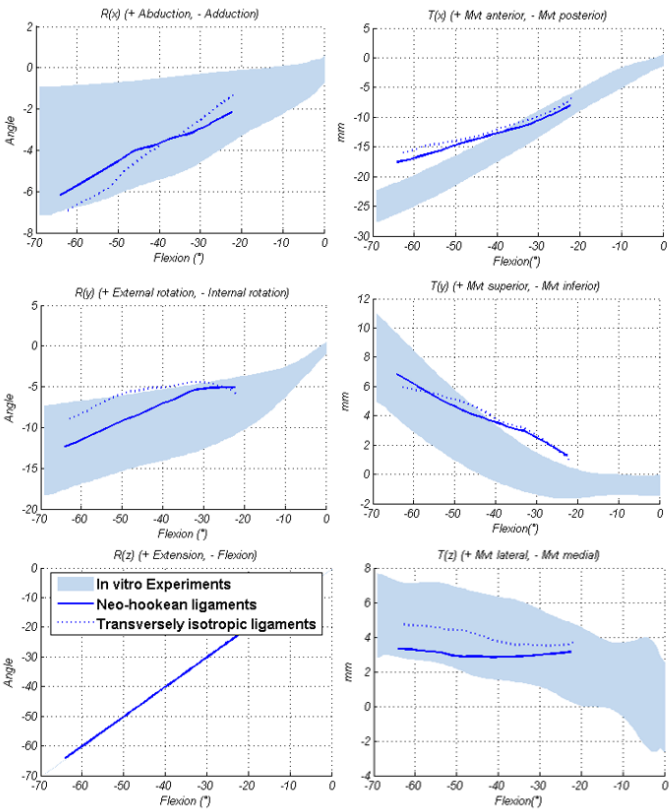

Fig 1: The double forward somersault with two twists high bar mount is rarely seen in elite competitions.

The tibia tends to move more internally in the neo-Hookean model having a maximum of 12.32˚ at the end of flexion compared with the transversely isotropic model which presents a maximum of 8.87˚. The centre of tibia keeps moving posteriorly and superiorly in both cases. The neo-Hookean assigned model undergoes 17.47mm of posterior translation and 6.86mm superior translation at 64˚ of flexion. The model with transversely isotropic hyper-elastic ligaments undergoes 15.91mm of posterior translation and 5.96mm superior translation at the end of knee flexion. The tibial mediolateral movement shows a minimal alteration during knee range of motion for both models. However, the model with neo-Hookean material has a lower lateral translation (maximum 3.34mm at 64˚ flexion) compared with the transversely isotropic hyper-elastic model (maximum 4.74mm at 63˚ flexion).

The results have been compared against a native knee experimental corridor derived from the literature [5]. The comparison shows that a deviation from the experimental corridors is present at higher degrees of flexion for the anteroposterior movement and at lower angles of flexion in terms of the superior movement for both material models. This can be explained by the fact that knee model is generated from a patient suffering from joint deformity and not a normal knee. Thus it is not beyond expectation that the joint movement path does not match entirely to the corridors of the normal knee kinematics. However, changing the material model has not caused a remarkable alteration in the deviation from the experimental corridors in any of the degrees of freedom.

CONCLUSIONS

In conclusion, the results of the present study have demonstrated that changing the material model of the ligaments from neo-Hookean to anisotropic hyper-elastic while keeping the other factors unchanged affects the extracted kinematics of the joint in all degrees of freedom during a quasi-static knee flexion. However, the amount of alteration occurred in the knee kinematics due to changing the material model did not noticeably alter the deviation of the movement path from the native knee experimental corridors.

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