INTRODUCTION

A large number of finite element models have been developed to study the behaviour of the knee joint under different loading conditions. They have been used to study knee ligament function, knee prosthesis design and ligament reconstruction procedures.

The terms pretension or prestrain of a knee ligament refer to the strain in the ligament when the joint is at full extension and little is known about its influence on the kinematics of the joint. In knee models, the ligament reference strains are usually merely estimated [1] and sometimes adapted by means of trial and error in order to get better agreement with experimental data [2]. As a consequence, very different values can be found in the literature. The purpose of this study was to analyze how ligament prestrains can affect the kinematics of the knee predicted with a FE model.

METHODS

A finite element model of the tibiofemoral joint has been developed. The model includes the bone structures (femur and tibia), menisci, articular cartilage and the four main ligaments of the knee (anterior cruciate ligament, ACL, posterior cruciate ligament, PCL, medial collateral ligament, MCL and lateral collateral ligament, LCL) (Fig. 1).

Fig. 1. Finite element model of the tibiofemoral joint

The femur and the tibia were reconstructed from CT-scan images of a left human knee joint at full extension. Due to the much greater stiffness of bone compared to the joint soft tissues, they were modelled as rigid bodies. The articular cartilage and the menisci were modelled as linear elastic isotropic materials (E_c = 12 MPa, v_c = 0.45, E_m = 80 MPa, v_m = 0.3). Each ligament was modelled by a number of non-linear elastic spring elements. These elements were assumed to carry load only when in tension and the magnitude of the force in each element was expressed as:

\[
F = \begin{cases} 
0 & \text{where } \varepsilon \leq 0 \\
K_1(L - L_o)^2 & \text{where } 0 \leq \varepsilon \leq 2\varepsilon_i \\
K_2(L - (1 + \varepsilon_i)L_o) & \text{where } \varepsilon \geq 2\varepsilon_i
\end{cases}
\]

Where \( \varepsilon_i \) is the nonlinear strain level parameter assumed to be 0.03, \( K_1 \) and \( K_2 \) are the stiffness coefficients and \( L \) and \( L_o \) are the current and slack lengths of the ligament, respectively. At full extension, the initial strain of each element is given by the parameter \( \varepsilon_i \), which, together with the length of the element at full extension \( L_o \), determines the slack length of the element:

\[
\varepsilon_i = \frac{L_o - L}{L_o} \quad L_o = \frac{L}{\varepsilon_i + 1}
\]

The values of the stiffness coefficients and the reference strains of the spring elements were taken from the literature [3] (Table 1) and the response of the model was calculated when varying the initial strain in each of the ligaments by \( \pm 5\% \) and \( \pm 5\% \).

While fixing the femur, the tibia was subjected to anterior/posterior loads of 100 N, internal/external torques of 10 Nm or varus/valgus torques of 15 Nm. The motions of the tibia with respect to the femur were obtained for each load case.

RESULTS

The predicted motions of the knee under the different loading conditions were in the range of those reported in experimental studies. As expected, the predicted kinematics of the tibiofemoral joint were significantly influenced by the initial strains in the ligaments. The anterior placement of the tibia under 100 N anterior tibial load was highly influenced by the prestrains in the anterior cruciate ligament and posterior tibial load was significantly affected by the prestrains in both cruciate ligaments. The medial collateral ligament pretension significantly influenced the amount of external and valgus rotations, while the internal and varus rotations were mostly affected by the lateral collateral ligament.

DISCUSSION AND CONCLUSION

Our findings demonstrate that the predicted kinematics of the tibiofemoral joint are sensitive to the ligament initial strains. Variations in ligament prestrains of \( \pm 5\% \) caused changes in the range of motions of around 30 %. This has significant relevance in finite element modelling of knee ligamentous structures and in ligament reconstruction procedures, since pretension of the ligamentous graft may determine the kinematics of the treated knee.

Further study will include refinements of the model to add the patella and the anisotropic behaviour of the menisci and analysis of the model under different loading conditions.

REFERENCES


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