Contribution to the design and validation of a 3D finite elements kinematic model of the knee

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Introduction

In the study of the knee-joint kinematics, finite elements modelling offers the major potential of allowing inexpensive parametric studies. However there are few validated 3D kinematic models [2,3,4] including both tibio-femoral and femoro-patellar joint. Moreover, these models allow generally only a partial description of the flexion movement. The purpose of this study was to simulate the flexion of a non-pathologic cadaveric knee-joint using a finite elements model, validating the model through a set of in-vitro experiments. A preliminary use of this model was the quantification of the effects of ligament pretension.

Methods

The finite elements 3D-mesh of a human knee includes the femoral, tibial and patellar bone geometry. This geometry was acquired from a cadaveric human knee, using a magnetic acquisition system (Fastrak ®) in order to obtain a fine mesh as well an accurate positioning of the articular surfaces and ligamentous insertions.

Fig. 1: FE Model

The bone and cartilage were meshed with elastic shell elements. The quadricipital and patellar tendinous system and the ligaments (ACL, PCL, CL, Retinacula) were modelled using non-linear multi-fascicles cables and membrane shells. Due to initially long times of calculation, only the articular surfaces and ligamentous insertions of the tibia were modelled (fig. 1), which were linked using high rigidity beams. The possibility of pre-tensioning or pre-loosening the ligaments was also taken into account. Surface contacts were considered between the various articular surfaces and between the quadricipital tendon and the upper face of the trochlea.

Means of validation were provided by in-vitro experiments simulating the flexion of 18 human cadaveric segments in a fixed-femur/free-tibia with pullback tension experimental protocol (fig. 2 and [1]). The movements of femur, tibia and patella attached referentials were measured using an opto-electronic system (Vicon ®), leading to the determination of the three basic translations and rotations of each segment relative to the initial tibial referential. The following sequence of rotations around mobile axis was used: a flexion around Y, then an axial rotation around Z', finally a varus/valgus rotation around X''.

Those experiments were simulated under the FE software ANSYS 5.6 using the same boundary condition and referential descriptions as in the experiment.

Fig. 2: Experimental device (Dupuis, [1])
Results & Discussion

The calculations yielded a complete simulation of the eighty degrees experimental flexion. After smoothing of the experimental curves, the simulation and experimental results were plotted. Fig. 3 shows an example of the different rotation of the femur and patella relative to the tibia which were obtained.

\[ \text{Simulation} \quad \text{Experiment} \]

\[ \text{Fig. 3 : Femoral axial rotation (around } Z^\prime \text{)} \]

The numerically obtained rotations in function of knee flexion were globally coherent with the experimental curves in terms of evolution and couplings. The simulated translations were of small amplitude and a comparison with experiment was difficult, due to the wide interindividuial disparities between the experimental curves.

The possibility of realizing a complete calculation was found to be very dependant of the choice of the boundary conditions applied to the model, and thus, the choice of an adequate, “constrained” experimental device.

The global behaviour of the model was found to be very dependant of:
- The precise position of the various ligamentous insertions.
- The pretension/preloosening of the different fascicles of the ACL and PCL.
- The lateral stabilization of the patella and the presence of the contact between the quadricipital tendon and the femur.

Particularly, pretensions from –3% to +3% were applied to the anterior and posterior fascicles of the ICL, ACL and PCL.

The calculations showed the necessity of applying initial loosening to the anterior fascicles and initial pretension to the posterior ones in order for the model to converge. The femur and patella backing rotations were found to be directly dependant both from the contact between the femur and the quadricipital tendon, and from the mechanical modelling of the tendon itself.

In conclusion, this model offers a qualitatively realistic behaviour in regard to the literature and the validation experiment it simulates. It yielded a better understanding of the comparative importance between articular geometry on one hand and mechanical properties and insertions of the ligaments on the other. Improvements in the results should be obtained with a finer representation of the cruciate ligaments and the modelling of the meniscus.

This model has already opened the way for possible personalised modelling and studies, which are being currently developped at the LBM, concerning in particular the pathologic and prosthetic knee.
References