IN VITRO VALIDATION OF A DYNAMIC FINITE ELEMENT TKR MODEL

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INTRODUCTION

The objective of this study was to develop and validate a 3D dynamic finite element (FE) model of a total knee replacement (TKR) that could be used to simulate implant mechanics under functional loading conditions.

To date, dynamic FE TKR models have mainly been used to simulate implant testing environments (Godest *et al*, 2002). The ability to simulate the loading conditions and movement constraints experienced by a TKR in vivo would greatly enhance understanding of knee implant mechanics. Recently, dynamic FE models that simulate the implanted environment have begun to appear (Halloran *et al*, 2005; Barink *et al*, 2005). The model presented here is unique by virtue of 1) representing the full degrees of freedom (DOF) of all components (femur, tibia and patella) simultaneously under the control of a quadriceps load and 2) validation by direct comparison with in vitro kinematic and force data. The model is capable of reproducing experimental data as well as predicting responses to perturbations.

METHODS

A knee specimen was prepared by resecting all tissue surrounding the joint, leaving the joint capsule and quadriceps muscle. A posterior-cruciate-retaining TKR (PFC Sigma, Size 4, DePuy, Warsaw, IN), including patellar resurfacing, was implanted by an experienced orthopaedic surgeon using standard procedures. The specimen was mounted in a modified Oxford rig (Zavatsky, 1997) and a 6 DOF force transducer (MC3A-250, AMTI, Watertown, MA) was placed at the distal tibia in line with the bone. Kinematic tracking arrays (Optotrak 3020, NDI, Waterloo, ON) were fixed to the femur, tibia and patella and a probe was used to register the implant components and bones to corresponding computer models.

Kinematic and force data were collected as the knee joint was extended via a cable fixed to a clamp on the quadriceps muscle. The cable was wound by a motor attached to the proximal femur (cable velocity 16 mm/s). Trials were performed at Q-angles of 10° and 15°. Afterwards, the specimen was dissected and insertion locations of the major ligaments were recorded with the probe.

The Oxford rig was simulated with the non-linear dynamic explicit FE code LS-DYNA (LSTC, Livermore, CA) using built-in penalty-based mechanical joints to simulate the various connections in the rig. Rigid masses were used to connect the various joints together and to model the inertial properties of the rig. Hexahedral FE meshes with element edge lengths of 1.0 mm were constructed for the TKR components based on CAD representations of the implants. The femoral component was modelled as rigid, while the UHMWPE tibial insert and patellar button were represented using a non-linear elastic-plastic material model. The bones were considered rigid and the tibial insert was fixed to the tibia. A coefficient of friction of 0.09 was used.

Six ligament bundles were modelled (LCL, superficial MCL, deep MCL, PMC, anterior PCL and posterior PCL) along with the patellar ligament and the quadriceps muscle. For each bundle, nine non-linear cable elements were used. Stiffness and reference strain values were obtained from the literature and insertion locations relative to the femoral and tibial components were generated from the experimental data. Registration data from the experimental trials were used to set initial poses. Simulations were performed for both Q-angles.

RESULTS AND DISCUSSION

The 3D joint kinematics for the tibiofemoral joint (TFJ) and patellofemoral joint (PFJ), along with ankle joint reaction forces and moments, were extracted from the simulations and compared to data from the experimental trials. Trends for individual trials were evaluated along with the changes due to the Q-angle increase.

The simulated TFJ kinematics produced trends of motion that were consistent with the experimental data. The simulations had a TFJ varus angle offset along with an internal rotation relative to the experimental data, possibly due to a lack of posterior-lateral soft tissues in the model. The simulated PFJ kinematics produced correct trends but were offset from the experimental data with an increased medial tilt and medial spin. The reaction force and moment data were reproduced accurately by the simulation with only minor offsets.

The increase in Q-angle produced a valgus and lateral shift in the experimental TFJ kinematics which were not reproduced well in the simulation. However, the increased medial tilt and lateral spin observed for the PFJ were accurately simulated. The Q-angle change produced a lateral force shift and varus moment shift that were both captured by the simulations (Figure 1).

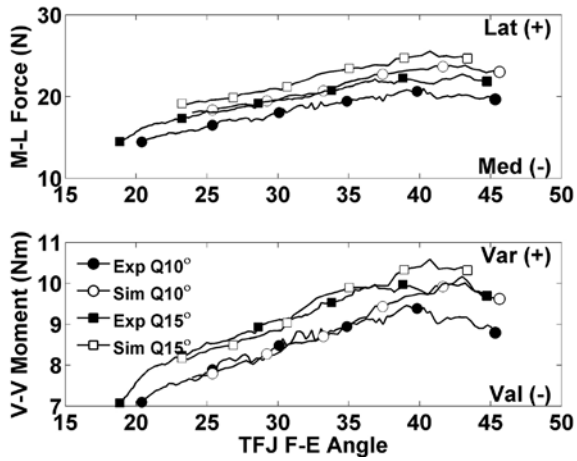

Figure 1: Comparison of experimental (Exp) and simulated (Sim) medial-lateral (M-L) forces and varus-valgus (V-V) moments for both Q-angles (Q10° & Q15°) as a function of TFJ flexion (F-E) angle.

SUMMARY/CONCLUSIONS

A unique 3D dynamic TKR model has been presented that simulates full TFJ and PFJ function during a weight bearing extension motion controlled by quadriceps loading. The model was validated by direct comparison to an in vitro experiment and was able to reproduce measured kinematic and reaction force data. Changes in PFJ kinematics and reaction force data due to an increase in Q-angle were accurately predicted by the model.

REFERENCES

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