Finite Element Model of the Knee for Investigation of High Rate Injury Mechanisms: Development and Validation

INTRODUCTION:

Finite element (FE) methods have provided considerable insight into knee joint biomechanics, including ligament function, ligament reconstruction technique, and implant design. Most current knee FE models are often only validated using static and quasi-static data. Due to the dynamic nature of knee injury, validated FE models to predict high-rate behavior of the knee are needed. The purpose of this study was to develop and perform validation of a finite element model of the knee to simulate both quasi-static and high-rate activities over a wide range of loading conditions. A variety of knee injury mechanisms can be investigated using this model with special emphasis on ACL injury.

METHODS:

CT and MRI scans from the knee of a healthy young female athlete were taken in neutral position following IRB approval (0.5 mm slice thickness). Mimics software (Materialise, Plymouth, MI, USA) was used to digitize bony structures and soft tissue from CT and MRI scans, respectively. Bone and soft tissue geometry was hexagonally meshed (thickness). Mimics software (Materialise, Plymouth, MI, USA) was used to anisotropic hyper-elastic material formulation. Thus, the ligaments did not transmit any compression. The material properties of model components were adapted from the literature [1–4]. For model validation, nineteen fresh frozen cadaveric lower extremity specimens (45 ± 7 years, 10 female and 9 male) were tested under quasi-static and dynamic loadings. In each set of the experiments, the quadriceps and hamstrings tendons were used to simulate muscle loads. ACL strain was calculated using DVRT (Microstrain, Williston, VT, USA) mounted on the ACL (anterior-medial bundle). MCL strain was calculated using three DVRTs placed across the joint line (superior-inferior orientation). Rigid body motion of the femur, patella and tibia were tracked by an Engineering Center for Orthopaedic Research Excellence, University of Toledo, Toledo, OH, for 50 Nm adduction to 50 Nm abduction moment combined with 268 N experimental data corresponding to 1200 N quadriceps and 800 N of hamstrings loads was used.

RESULTS:

In vitro data and FE prediction of internal-external rotation from 0 to 90° of flexion for three different quasi-static loading conditions are plotted in Figure 2. Loading 1 included only simulated muscle forces (quadriceps: 400 N and hamstrings: 200 N), while Loading 2 and Loading 3 simulated 15 Nm internal or external rotation load plus Loading 1 conditions. Figure 3 shows tibial motion in the coronal plane for 50 Nm adduction to 50 Nm abduction moment combined with 268 N anterior shear and simulated muscle forces (quadriceps: 400N and hamstrings: 200N) at a 25° flexion angle. ACL and MCL strain are calculated from DVRT (Microstrain, Williston, VT, USA) mounted on the ACL (anterior-medial bundle). MCL strain was calculated using three DVRTs placed across the joint line (superior-inferior orientation). Rigid body motion of the femur, patella and tibia were tracked by an Engineering Center for Orthopaedic Research Excellence, University of Toledo, Toledo, OH, for 50 Nm adduction to 50 Nm abduction moment combined with 268 N experimental data corresponding to 1200 N quadriceps and 800 N of hamstrings loads was used.

DISCUSSION:

To the authors’ knowledge, this model is among the first finite element models of the knee joint validated against both quasi-static and dynamic experiments under a wide range of motion and loading conditions. Based on the Pearson’s correlation coefficient, a strong correlation was observed (r>0.95, all comparisons) between model predictions and cadaveric data. Also, differences between model predictions and cadaveric data were less than one standard deviation of the average experimental data. Such a validated computational model will aide in understanding the biomechanical response of the knee under more complex and physiologically relevant loading conditions that may not be experimentally feasible. Considering the prevalence of ACL injury and knee osteoarthritis, especially for high rate, weight bearing activities, a validated FE model becomes a powerful tool in the understanding and prevention of these pathologies.

SIGNIFICANCE:

Validated FE models may be used to predict biomechanical parameters under complex, clinically relevant loading conditions that cannot be readily measured experimentally (in vitro).

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REFERENCES: