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HUMAN KNEE JOINT FINITE ELEMENT MODEL USING A TWO BUNDLE ANTERIOR CRUCIATE LIGAMENT: VALIDATION AND GAIT ANALYSIS

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INTRODUCTION

Anterior cruciate ligament (ACL) deficient individuals are at a much higher risk of developing osteoarthritis (OA) compared to those with intact ACLs, likely due to altered biomechanical loading [1]. Research indicates the ACL is comprised of two “bundles”, the anteromedial (AM) and posterolateral (PL) bundles [2]. Although the function of both bundles is to restrain anterior tibial translation (ATT), each bundle has their own distinct range of knee flexion where they are most effective [3].

Articular cartilage contact stress measurements are difficult to measure in vivo. An alternative approach is to use knee joint finite element models (FEMs) to predict soft tissue stresses and strains throughout the knee. Initial and boundary conditions for these FEMs may be determined from knee joint kinematics estimated from motion analysis experiments. However, there is a lack of knee joint FEMs which include both AM and PL bundles to predict changes to articular cartilage contact pressures resulting from ACL injuries. The purpose of this study is to develop and validate a knee joint FEM using both AM and PL bundles and subsequently perform a gait analysis of varying ACL injuries.

METHODS

FEM Development. An FEM of a right knee joint was built from sagittal plane magnetic resonance images (MRIs) (GE Medical Systems, Ideal GRE, TR=7.428ms, TE=4.16ms, slice spacing=1.5mm, flip angle=45°, pixel spacing=.3156) of a healthy, 33 year old male with no prior history of injuries. FEM tissue structures modeled included: femur and tibia bone; medial and lateral menisci; femoral and tibial articular cartilage; ACL, posterior cruciate (PCL), medial collateral (MCL) and lateral collateral (LCL) ligaments.

The 3-D solids of the knee structures were created from the MR images using Mimics (Materialise NV, Leuven, Belgium) and were smoothed to remove any imperfections, before importing into SolidWorks (Dassault Systemes, Velizy-Villacoublay, France) to remove any residual overlap between structures. The ACL was divided into AM and PL bundles in SolidWorks based on their reported femoral and tibial attachment sites [4]. Soft tissue structures were meshed in TrueGrid (XYZ Scientific Applications, Inc., Livermore, California, USA) using linear, hexahedral elements. Bones were modeled as rigid bodies with 2-D shell elements. Each mesh was imported into Abaqus (Dassault Systemes, Velizy-Villacoublay, France) for FEM analyses (Figure 1).

The articular cartilage and ligaments were attached to bone using tie constraints. The distal portion of the LCL had three sets of spring elements attached, acting in the longitudinal and transverse directions to mimic tension in this ligament [5,6]. The menisci were constrained to the tibia using four sets of spring elements [7]. Articular cartilage (E=15MPa, ν=0.475 [8]) and menisci (E=59MPa, ν=0.49 [9]) were modeled as a linear elastic, homogenous, isotropic materials. Ligaments were modeled as linear elastic, transversely isotropic, homogeneous materials (Table1) [10,11,12].

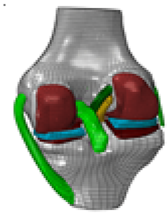

Figure 1: Right knee FEM

Table 1: Ligament material properties.

	E_L (MPa)	E_T (MPa)	ν_{12}, ν_{13}	ν_{23}	G_{12}, G_{13} (MPa)	G_{23} (MPa)
PCL,LCL,MCL	153.7	5.1	1.4	.3	1.72	1.9
AM	212.23	7.07	1.4	.3	1.72	1.9
PL	115.55	3.85	1.4	.3	1.72	1.9

FEM Validation. To validate the FEM, three experiments were simulated and FEM predictions of articular cartilage contact pressure, ATT and/or ACL strains were compared to experimental results: 1)

Axial compressive load (1000 N) applied to the tibia of intact ACL cadaver knees [13]; 2) Anterior tibial load (134 N) applied to an intact ACL and AM deficient cadaver knees [14]; 3) Posterior femoral load (130 N) applied to intact ACL cadaver knees [15]. Only cases with a flexion angle of 0° were used with appropriate boundary and loading conditions applied to the tibia and femur to replicate the three different experimental protocols. The FEM was considered validated if the predicted results were within one standard deviation of reported mean values.

Gait Analysis. A parameter study was performed on gait to predict the effects of ACL injury during gait: 1) intact ACL; 2) AM deficient ACL; 3) PL deficient ACL; 4) complete ACL rupture. The FEM simulated the 15% and 52% phases of gait by fixing the tibia and rotating the femur to the proper flexion angles and releasing all other degrees of freedom. Three individuals' gait analysis data [16] were imported into OpenSim's Joint Reaction Analysis to obtain the necessary kinematic and kinetic data to determine joint forces and moments applied at the joint center.

RESULTS

FEM Validation.

Tibial cartilage contact pressures (Figure 2A) and the ATT of an intact ACL knee (Figure 2B) deviated from the reported experimental means by less than one standard deviation. The predicted ATT of an AM deficient knee was greater than one standard deviation less than the experimental value (Figure 2B), but the predicted proportional increase in ATT from intact ACL to AM deficient (32.8%) matched very well with that observed (32.5%) [14]. FEM predicted AM strain matched the experimental results well (Figure 2C).

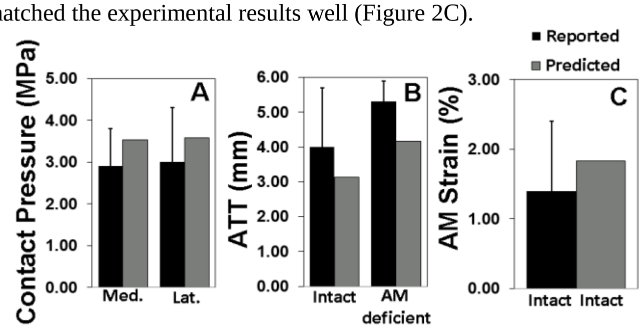

Figure 2: FEM predicted values vs reported.

Gait Analysis.

Maximum lateral pressure increased at 15% and decreased at 52% for increasing levels of ACL injury (Tables 2 and 3). ATT decreased at 15% and increased at 52% for increasing levels of ACL injury. PL deficient knees had a larger change in ATT and maximum lateral pressure at 15% gait, compared to AM deficient knees. AM deficient knees had a larger change in ATT and maximum lateral pressure at 52% gait, compared to PL deficient knees. There was a noticeable posterior shift in medial contact pressure from intact ACL knees to ACL ruptured (Figure 3)

Table 2: FEM predicted values at 15% of gait.

	Maximum medial pressure (MPa)	Maximum lateral pressure (MPa)	ATT (mm)
Intact	8.41	5.31	3.59
AM Deficient	8.45	5.39	3.41
PL Deficient	8.39	5.43	2.83
Complete Rupture	8.40	5.48	2.44

Table 3: FEM predicted values at 52% of gait.

	Maximum medial pressure (MPa)	Maximum lateral pressure (MPa)	ATT (mm)
Intact	5.78	3.94	7.17
AM Deficient	5.67	3.55	8.24
PL Deficient	5.76	3.68	7.68
Complete Rupture	5.96	3.41	8.26

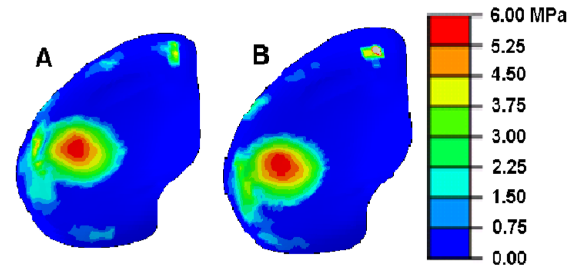

Figure 3: Predicted medial contact pressure at 52% gait: A) intact; B) ACL rupture.

DISCUSSION

FEM Validation. The FEM was considered to be validated based on the three experiments simulated. Almost all predicted values were similar to experimental results, with the exception being the predicted ATT in an AM deficient knee. Still, the predicted proportional increase in ATT from intact to AM deficient (32.8%) matched the reported proportional ATT increase (32.5%). It should be noted that the FEM has not yet been validated under combined loading. Validation for this study was performed at 0° because much of gait remains at low angles (< 20°). Reported ATT were higher than predicted values likely because experimental results were from older knees (ages 53-71) [14], consistent with findings indicating that older ligaments have demonstrated a Young's modulus reduction of 41% [6].

Gait Analysis. The 15% and 52% gait phases were chosen for their associated peak in compressive and anterior tibial joint force, respectively. Even though both phases of gait analyzed were at small knee flexion angles (<30°), predicted results suggest that combined loading has a more prominent role on bundle activation than knee flexion angle. Predicted results show that when the adduction moment and compressive load dominate (15% gait) the PL bundle supports more load than the AM bundle. FEM results also show that when the internal tibial torque, knee extension moment and anterior tibial load are more prominent (52% gait) the AM bundle supports more of the load. The decrease in ATT at 15% gait was expected due to the applied posterior direction of the tibial contact load.

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