FEMALE ELEMENT ANALYSIS OF EFFECTS OF GENDER-DEPENDENT 3D KNEE GEOMETRY AND JOINT LAXITY ON ACL IMPINGEMENT AGAINST THE INTERCONDYLAR NOTCH

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INTRODUCTION

Females demonstrated 2-9 times higher ACL injury rate, narrow notch width and higher joint laxity in multi-planar directions [1,2]. One of potential ACL injury mechanisms is ACL impingement against the lateral wall of the femoral intercondylar notch [3], expressed as elongated and deformed ACL geometry [3] and contact area and contact pressure between the ACL and the intercondylar notch [4]. However, it has remained unclear about the contribution of gender-dependent joint laxity and 3D knee geometry on the susceptibility of ACL impingement against the femoral intercondylar notch. The goal of this study was to investigate the effects of gender-dependent joint laxity and 3D geometry of the knee on ACL impingement against the femoral intercondylar notch using a validated knee finite element model [4].

METHODS

Two knee FEMs (one female cadaver knee and one male knee from a live subject) including gender-dependent tibial external rotation laxity as kinematic boundary conditions were investigated. The finite element model was previously developed and validated using a cadaver specimen [4] with the following procedures. The three dimensional (3D) femur, tibia, and ACL images were segmented using commercial software, Mimics 14.01 image analysis software (Materialise N.V., Leuven, Belgium). Then, the reconstructed geometries of the femur, tibia, and ACL were meshed using HyperMeshTM (11.0, Altair Engineering, Inc, Michigan). The femur and tibia were meshed as rigid elements (R3D3). The femur and tibia were meshed as rigid elements (R3D3). ACL was modeled as fiber-reinforced matrix models including hexahedral elements (C3D8RH) representing an isotropic hyper-elastic ground substance matrix and non-linear spring elements (SpringA) representing neo-Hookean materials to behave the ACL as transversely isotropic materials following the below constitutional equations (1) for the ground substance matrix , (2), and (3) for non-linear spring, similar to the previous study [4]. The connections between the ACL and femur, and the ACL and tibia were carefully meshed using HyperMorph function in HyperMeshTM to obtain anatomically realistic connections between ACL and femur, and between ACL and tibia.

φm = C1(I1 − 3) 
σ = \begin{cases} 
C2(e^{C3(\lambda−1)} − 1) & \text{if } \lambda < 1 \\
C4\lambda + C5 \text{ if } 1 \leq \lambda < \lambda^* \\
C5 = C2(e^{C3(\lambda^*−1)} − 1) − C4\lambda^* 
\end{cases} 

where φm denotes the strain energy; I1 the first invariant of the right Cauchy-Green strain; and C1 a material constant. The spring elements are characterized by the nonlinear force-stretch relationship in Eqs (2) and (3) [4] and experimentally obtained ACL material properties. The fiber-reinforced FEM was analyzed using Abaqus (6.9, Dassault Systèmes). Knee flexion/extension, abduction/adduction, and the internal/external rotation angle were defined in the joint coordinate system [5]. The femur and tibia represented as rigid bodies. Kinematic boundary conditions experimentally obtained from previous studies representing gender-dependent mean+1STD tibial external rotation laxity as 23.0° from 10 healthy males and as 31.7° from 10 healthy females [1] and a common knee abduction as 10.0° at a given knee flexion angle [4]. The notch width index (NWI) was compared between the female knee and the male knee and the femur geometries were normalized to the knee width.
RESULTS AND DISCUSSION

The NWI of the female knee was 0.25 and the male knee was 0.31. Overall, narrower 3D intercondylar notch shape in the normalized female knee was observed in comparison to the normalized male knee (Fig. 1).

In the female knee model, ACL impingement against the intercondylar notch wall was seen during the kinematic sequence of knee abduction from 0° to 10.0° and tibial external rotation from 0° to 31.7°. Furthermore, higher tibial external rotation laxity led to higher maximum contact pressure and larger contact area (Fig. 2) as the ACL impinged against the intercondylar notch wall. Specifically, at the intermediate step corresponding to lower laxity of 21.1° tibial external rotation and 6.7° valgus, the maximum contact pressure was 3.55 MPa and the contact area was 4.11 mm², while at the higher laxity of 31.7° tibial external rotation and 10.0° valgus, the maximum contact pressure was 6.16 MPa and the contact area was 15.53 mm². Based on the known contact area and mean cell size of ACL as 90 μm, number of contacted ACL cells was estimated as 4.57*10⁴ at the lower laxity and 1.73*10⁵ at the higher laxity. The relationships between the laxity and contact area were not linear, which might be due to the non-linear biomechanical behaviors of the ACL.

CONCLUSIONS

In the female knee model, higher maximum contact pressure and larger contact area due to higher laxity and narrower notch were observed, while the male knee model did not show any impingement. The result may help us understand the causes for higher ACL injury rate in females. Stronger impingement with larger contact area between the ACL and the intercondylar notch wall indicated potential chronic sub-failure damage and cell death of ACL, such episodes may occur repeatedly, accumulate and lead to potential ACL rupture [4,6]. Although the models were generated from a female cadaver and a live male subject, the findings are justified because femur and tibia were rigid bodies with the ACL geometry obtained from “fresh-frozen” specimen. Further studies are needed over a larger sample to investigate clinical applications of the findings.

REFERENCES