Poplitues Tendon and Popliteofibular Ligament Are Indispensable for More Reliable Computational Knee Joint Models

Tserenchimed Purevsuren, MS, Kyungsoo Kim, PhD, Yoon Hyuk Kim, PhD.
Kyung Hee University, Yongin-si, Korea, Republic of.

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Introduction: Huge number of computational models of human knee joint had been developed to estimate the kinematic and kinetic behaviours of human knee joint and the corresponding forces, pressures on bones and soft tissues [1-3]. Basically, four dominant ligaments including anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL), and lateral collateral ligament (LCL) were conventionally included in the models. Clinically, it is well established that the posterolateral corner (PLC) structures, including the LCL, popliteus tendon (PLT), and popliteofibular ligament (PFL) play critical roles in maintain knee stability (especially in posterior translation, and varus and external rotation) and interact with PCL to reduce posterior translation and external rotation [4]. Although cadaveric studies investigated contribution of PFL to posterolateral stability and functional role of the PLC structures in providing knee joint stability [5], the PFL and PLT have been usually excluded from previous knee joint models due to the underestimated importance of PLC structures. In this study, a three-dimensional (3D) multi-body knee joint model which included the PLC structures (PLT and PFL) was developed and the model was validated with previous experimental studies. The contribution of PLC structures to the knee joint translational and rotational stabilities was then evaluated by comparing the outcome between two different models (with PLC and without PLC structures). The posterior drawer test, the dial test, and the varus stress test were considered in the simulation.

Methods: Bone models of human knee were reconstructed using computed tomography (CT) images of a 26-year-old male subject. The cartilage layers on femur and tibia and meniscus were also reconstructed. The developed bone and soft tissue models were imported into the dynamic analysis software, RecurDyn ver.7 (Function Bay Inc., Korea). The viscoelastic contact applied between the femoral and tibial cartilages was based on multi-body contact model with elastic contact stiffness (500 N/mm) and damping coefficient (5 Ns/mm) given in a previous study [6]. The contact between the meniscus and cartilages was also defined using the parameters (20 N/mm of elastic stiffness and 5 Ns/mm of damping coefficient) obtained from discrete element technique [7]. The major ligaments, ACL, PCL, MCL, and LCL, were included in the knee joint model. Subsequently, the deep capsular fibers of MCL and the posterior knee capsule were also developed. Finally, the PLT and PFL within PLC structures were modeled based on avialable material properties and information of anatomic locations [8]. To validate the knee model, three types of clinical tests were considered: 1) posterior drawer test under a 134 N of posterior tibial force, 2) dial test under a 5 Nm of external tibial moment, and 3) varus stress test under a 3 Nm of varus moment. First, the posterior tibial translations of the intact and PCL deficient knees in the posterior drawer test at 0°, 30°, 60°, and 90° of knee flexion were compared to previous studies. The dial test and varus stress test were performed as a sequential ligament sectioning study [9]. The external and varus rotaions of the tibia at 0°, 30°, 60°, and 90° of knee flexion were compared to values from the experimental study [9]. Finally, the posterior drawer test under a 134 N, the dial test
under a 5 Nm, and the varus stress test under a 5 Nm were simulated for the developed model which had the PLC structures, and the model in which the PFL and PLT were removed. In order to evaluate the contribution of the PLC structures to the knee joint stability, the posterior translation, external rotation, and varus rotation were investigated.

**Results:** For the validation, the posterior translations in the posterior drawer test were within the ranges of values from previous experimental studies in both intact and PCL deficient cases [10-12]. For the sequential ligament sectioning, the dial test results were similar to the experimental results except when all three components were removed [9]. The varus stress test results also showed similar trend in the varus rotation even though the average difference between our results and the experimental results was 2.1°. For final laxity test with and without PLC structures, All the posterior translations, external and varus rotations were increased when the PFL and the PLT were removed regardless of the degree of knee flexion (Figure 2).

**Discussion:** A knee model that included the PLC structures was developed and validated by comparison to previous experimental studies in the posterior drawer test, dial test, and varus stress test. The posterior translation, the external rotation, and the varus rotation were then predicted to quantitatively investigate the contributions of the PLC structures to the translational and rotational stabilities. Our result indicates that PLC structures, including the PFL and PLT, could significantly contribute to the posterior translational and external rotational stabilities, as the clinical observation suggested. Therefore, inclusion of the PLC structures in knee joint models might be helpful to improve the utility of the models.

**Significance:** This study presents that PFL and PLT in PLC structures should be considered to computational knee joint model for more reliable kinematic and kinetic analysis.
**Figure 1.** Model of the knee joint: A. anterior view; B. posterior view; C. medial view; and D. lateral view.
Figure 2. Translations or rotations for posterior drawer test under a 134 N, dial test under a 5 Nm, and varus stress test under a 5 Nm with and without the PFL and PLT.