6 DOF Kinematics of Human Knee Joint in Response to Full Body Weight
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Introduction: Six DOF kinematics of the knee joint has been extensively studied in-vitro. Recently, various imaging methods have been applied to investigate the in-vivo knee joint kinematics with the improved accuracy compared to traditional motion analysis method. However, the in-vivo kinematics of the knee in response to controlled loading conditions is still a challenge to determine. This information is important for further investigation of in-situ forces of different tissue structures, such as the ACL or PCL, when the knee is under physiological loading conditions. In this study, we investigated the 6 DOF tibiofemoral joint kinematics of knee joint caused by full body weight.

Materials and Methods: Nine subjects, 4 males - 5 females, aged 23 to 48 years old, with healthy knees were recruited under the guidance of the Institutional Review Board (IRB). Each knee (chosen randomly, 5 right and 4 left knees) was scanned in a relaxed, full extension position using a 3.0 Tesla MR Scanner (Trio, Siemens, Malvern, PA) in both sagittal and coronal planes based on an existing protocol established in our laboratory [1]. The 3D anatomic models of the tibia and femur were created using these MR images.

The same knee was then imaged at four different flexion angles (0°, 15°, 30° and 45°) using the dual-orthogonal fluoroscopy technique [1] under two different in-vivo axial tibial loading: (i) minimum load <10N, (ii) full body weight (BW). A force plate, which has been constructed using a 6 DOF force sensor (JR3, San Francisco, CA), was mounted on top of the performing platform. The value of the load applied to the subject’s leg was displayed on a monitor and simultaneously recorded during the experiment.

Next, the 3D models of the bones were matched with Fluoroscopic images in a solid modeling software in 6 DOF to reproduce the in-vivo positions of the tibia and femur at each position (Fig. 1). Finally, the kinematics of the knee joint in 6 DOF could be determined by using the series of matched bony models and relative position of their corresponding coordinate systems. A joint coordinate system formulated by the transepicondylar axis of the femur and longitudinal axis of the tibia was used to measure the 6 DOF knee kinematics [2]. In this paper, we reported the anterior/posterior and medial/lateral femoral translation and internal/external tibial rotation of the knee at different flexion angles. The knee joint motions under the full BW were specifically compared to those measures under no load.

Results: Anterior/Posterior: Increasing axial tibial load from no load to full BW caused increase in posterior femoral translation (Fig. 2a) For example, at 30° of flexion, the full BW increased the posterior femoral translation from -1.5±1.9 mm to -3.7±2.4 mm (p<0.05).

Medial/Lateral: At 0° and 15° of flexion, the femur moved medially by increasing the tibial load (Fig. 2b). Full BW caused little change in medial/lateral femoral translation.

Internal/External: Full BW caused the tibia to rotate externally at full extension from -1.8±3.4° to -4.9±4.2° (p<0.05) (Fig. 2c). At higher flexions, tibia rotated internally with respect to femur. At 45° of flexion, the internal tibial rotation was 4.2±2.6° under no load, but was 5.6±3.2° under the full body weight.

Discussion: This study investigated the 6 DOF living human knee kinematics under increasing tibial load at different flexion angles in-vivo. Applying axial tibial load on the knee form no load to full body weight leads to an increase in posterior femoral translation in all flexion angles and increase in medial femoral translation at low flexion angles. However, the full body load only caused change in femoral translation about 2 mm. Interestingly, the full BW load increased external tibial rotation at low flexion angles, but increased internal tibial rotation at higher flexion angles. This may be due to the different function of the complicated knee joint geometry as well as the internal soft tissue constraints at different range of knee flexion. This data may be valuable for future investigation of injury mechanisms of the knee structures such as the ACL or meniscus.


Figure 1: Matching the 3D bone model with fluoroscopic images to reproduce the in-vivo knee position in space.

Figure 2: In-vivo kinematics of the knee: a) Anterior/Posterior, b) Medial/Lateral translation of femur, and c) Internal/External rotation of Tibia.