Sex-Specific Variations in Passive Knee Rotation under Unconstrained Axial Plane Torques

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Introduction: Knee rotation plays a critical role in the kinetic chain of the lower extremities and its normal function \cite{1}. Excessive rotational torque to the knee can lead to major soft tissue injuries, resulting in rotatory instability. Excessive axial tibial torque has been widely shown to be associated with the anterior cruciate ligament (ACL) injury risk \cite{2}. Moreover, these injuries can lead to knee rotational instability even after surgical reconstruction \cite{3}, which may contribute to the long-term degenerative changes frequently seen after ACL injuries such as post-traumatic knee osteoarthritis \cite{4}. Despite well-documented sex-specific movement patterns and their reported role in ACL injury rates, little is known on the role of sex on passive tibiofemoral joint motion. This is of critical importance as the variation in passive joint restraints and range of motion can be a major mechanistic contributor to ACL injury and therefore partially address the discrepancy in the injury rates between sexes. Many previous in vitro and in vivo studies investigated how the sexes may differ in knee axial rotation. However, they are largely limited by use of non-physiologic and constrained loading conditions (in vitro), and limited loading conditions and inaccurate kinematics measurements (in vivo). Therefore, the current study aimed to investigate the sex differences in passive knee rotation under a range of physiologically relevant unconstrained axial plane torques. We hypothesized that females exhibit greater knee rotation than males in the axial plane.

Methods: Eighteen fresh frozen cadaveric lower extremity specimens (age 44 ± 8 years, 10 female and 8 male) were sectioned at the mid-shaft of the femur and potted in polyester resin. The quadriceps (rectus femoris) and hamstrings (semitendinosus, biceps femoris and semimembranosus) tendons were isolated and sutured inside metal tendon grips for the application of simulated muscle loads. Specimens were tested using a custom designed passive six-degree of freedom Force Couple Testing System (FCTS), shown in Figure 1. This system utilizes servo-electric actuators to drive a low friction compliant cable-pulley system with two closed loops that generate an unconstrained pure moment. An external fixation frame was attached to the tibia such that the centers of the pulleys were located about the knee center of rotation. Specimens were all tested under a 400N quadriceps and 200N hamstrings loads through knee range of flexion (0-90°; Baseline Loading). Specimens were additionally tested under a range of ±15Nm axial tibial torque (with the increments of 5Nm) to simulate a range of physiologic loadings exerted on the knee joint during daily activities. The applied muscle and external forces were applied to specimens using a combination of static weights and compliant cable-pulley systems. Additional pulley systems were used to maintain the physiologic muscle line of actions during the range of motion. An Optotrac 3D motion tracking system (Northern Digital Corporation, Waterloo, Ontario, Canada) was used to track the position of the femur and tibia in 3D space using two rigid arrays of non-collinear irLED markers. Data were collected at 100 Hz over four cycles of flexion-extension, and data from the third
cycle were used for analysis. The effect of sex on knee axial plane rotation through range of flexion was investigated using a multivariate analysis of covariance (MANCOVA). The degree of tibial rotation was compared between the sexes at each flexion angle with an a priori level of α=0.05.

**Results:** Axial tibial rotation was significantly affected by knee flexion angle under all 7 modes of loading (p<0.0005)-Figure 2. Sex was a significant predictor of axial rotation under baseline (p=0.006), 5-15 Nm of internal tibial rotational moment (p<0.25). Under baseline and internal rotation moments, the tibia went to more internal rotation from 0-25° of knee flexion, replicating the “screw-home” mechanism (Figure 2). Internal tibial rotation was then reduced by moving the knee from 25° to 90° of flexion, with males showing up to 3° of external tibial rotation at deep flexion angles under baseline and 5 Nm of internal rotation moment. Under external rotation moments, all specimens started with an externally rotated tibia with continuous reduction in degrees of external tibial rotation as the knee moved from 0° to 90° of knee flexion (Figure 2). No significant differences were observed between internal tibial rotation under 15 Nm of internal torque and external tibial rotation under 15 Nm of external torque compared to the baseline for both the males (p=0.289) and females (p=0.794)-Figure 3.

**Discussion:** These results demonstrate that unconstrained tibiofemoral axial rotation differs between males and females under neutral conditions and externally applied axial torques. For all loading conditions, females had a greater range of passive axial tibial rotation than males. This discrepancy in passive knee rotation may potentially be attributable to increased joint laxity and smaller, weaker knee ligaments in females than males [5,6]. A number of in vivo studies have shown similar sex differences in knee axial rotation using clinical external measurement devices under a limited range of loadings and flexion angles [7]. Despite the ultimate clinical utility of these in vivo studies, challenges in accurate in vivo quantification of multi-planar knee kinematics have hindered the ability of such studies to detect the sex differences in such sensitive measures. Biomechanical testing on human cadaveric tissue, if properly designed, offers a practical means to enhance our knowledge of joint biomechanics and tissue functions by providing direct and accurate measurements that are challenging, if not impossible to obtain in vivo. Further, these techniques provide a standard framework in which to conduct robust parametric studies. Combined, findings support our hypothesis, showing greater passive knee rotations in females than males. Interestingly, the sex differences were substantially greater under internal torques than external torques. Considering the internal tibial rotation as a major component of non-contact ACL injury mechanism [2], these findings highlight the sex variations in internal tibial rotation as a potential mechanistic contributor to the higher risk of ACL injuries in females than males. Further, this discrepancy in knee rotation can result in greater post-injury knee rotational instability among women, which may in turn put them at higher risk of developing post-traumatic knee osteoarthritis in long-term.

**Significance:** The current findings highlight the importance of further optimization of the current prevention and rehabilitation strategies to better fit each sex instead of a “one fits all” approach. This may in turn lead to a decreased risk of injury, improved surgical outcomes and a decreased risk of post-traumatic osteoarthritis in females.
Figure 1: Force couple testing system (FCTS).

Figure 2: Sex-specific differences in knee axial rotation under baseline (Top), internal torques (ITR; Middle) and external torques (ETR; Bottom).
Figure 3: Increased axial tibial rotation under 15 Nm of internal tibial torque (ITR) and 15 NM of external tibial torque (ETR) for both males and females.