Sex Differences in Knee Valgus Rotation under Unconstrained Single- and Multi-Planar Loading: Implications for Valgus Collapse ACL Injury Mechanism

Ata M. Kiapour, Ph.D.1, Carmen E. Quatman, M.D./Ph.D.2, Samuel C. Wordeman, B.S.2, Vijay K. Goel, Ph.D.3, Constantine K. Demetropoulos, PhD4, Timothy E. Hewett, Ph.D.2.

1Boston Children's Hospital, Harvard Medical School, Boston, MA, USA, 2The Ohio State University, Columbus, OH, USA, 3University of Toledo, Toledo, OH, USA, 4Johns Hopkins University, Laurel, MD, USA.


Introduction: Anterior cruciate ligament (ACL) injuries are common and devastating, particularly among young active individuals participating in sports [1]. In addition to pain and instability, ACL injuries are associated with long-term clinical sequelae that include meniscal tears, chondral lesions, and an increased risk of early onset post-traumatic osteoarthritis [2]. The risk of ACL injury is sex-dependent, with women at a 2-10 fold greater risk than men when playing similar sports [3]. The high risk of injury in women along with their increased rate of sports participation over the last three decades has led to a rapid rise in ACL injuries among women. Prior clinical, biomechanical and video analysis studies show that knee abduction, anterior tibial shear force and internal tibial rotation moments all contribute to the knee joint loading responsible for non-contact ACL injuries [4]. Among these, the tibiofemoral frontal plane loading mechanism has become a recent topic of debate, as a primary factor contributing to non-contact ACL injuries. A recent systematic review reported that more than 80% of the identified ACL injury mechanism studies support frontal plane mechanisms as a contributor to a multi-planar injury mechanism of ACL during landing following a jump [5]. More recently, multi-planar valgus collapse (a combination of knee abduction and internal tibial rotation moments) was shown to be the most probable mechanism for non-contact ACL injuries during jump landing [6]. Hence, this study aimed to investigate the role of sex on knee valgus rotation under physiologically relevant unconstrained single- and multi-planar loading conditions. We hypothesized that female knees would exhibit higher degrees of knee valgus rotation than males under simulated loading conditions.

Methods: Nineteen fresh frozen cadaveric lower extremity specimens (age 45 ± 7 years, 10 female and 9 male) were acquired and checked for any hard and soft tissue pathologies. Specimens were then sectioned at the mid-femur and potted in polyester resin for rigid attachment to the testing frame. The quadriceps (rectus femoris) and hamstrings (semitendinosus, biceps femoris and semimembranosus) tendons were isolated and clamped to allow for the application of simulated muscle loads. Specimens were tested using a custom-designed passive 6-DOF Force Couple Testing System (FCTS). 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 continuous 0-50 Nm knee abduction moment with 400N quadriceps and 200N hamstrings loads at 25° of knee flexion (the most common knee flexion angle at the time of ACL injury [4]). Specimens were also tested under with an additional 20 Nm of internal tibial rotation moment. 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 Optotrak 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 infrared LED markers. Data were collected at 100 Hz over four cycles of abduction-adduction, 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 knee valgus rotation was compared between the sexes at each flexion angle with an a priori level of $\alpha=0.05$.

**Results:** FCTS experiments demonstrated highly consistent and reproducible results. Knee valgus rotation was significantly affected by the magnitude of the applied knee abduction moment for both loading conditions ($p<0.0005$; Figure 1). In both cases, females showed a greater degree of knee valgus than their male counterparts (Figure 1). Sex was a significant predictor of the degree of knee valgus rotation under combined knee abduction and internal rotation moments ($p<0.0005$). Under combined 50 Nm knee abduction and 20 Nm internal rotation moments, females had a $3.2^\circ \pm 1.5^\circ$ (29% increase) greater knee valgus rotation than males. The addition of the internal tibial rotation moment to the knee abduction moment resulted in a significant increase in knee valgus rotation in both males and females ($p<0.0005$; Figure 2). At 50 Nm of knee abduction moment, increased knee valgus rotation due to additional internal rotation moments were $7.3^\circ \pm 2.9^\circ$ (98% increase) for females and $4.3^\circ \pm 2.2^\circ$ (61% increase) for males, respectively. The increased knee valgus rotation was significantly higher in females than males at all applied knee abduction moments ($p<0.0005$; Figure 3).

**Discussion:** These study findings demonstrated that the unconstrained knee valgus rotation differs between males and females primarily under combined knee abduction and internal rotation moments (multi-planar valgus collapse loading mechanism). Females had a greater passive range of knee valgus rotation compared to males. As previously shown [7], the addition of the internal rotation moment resulted in increased knee valgus rotation. Most importantly, females showed a significantly greater increase in knee valgus rotation than males under an additional 20 Nm of internal rotation moment. This coupled valgus response to the applied internal rotation moment may be associated with the interaction between the contour of the tibial plateau (in particular the posterior tibial slope) and the femoral condyles [7]. These combined findings support our primary tested hypothesis, that greater knee valgus rotation would be observed in females than males. The current findings highlight the sex variations in knee valgus rotation as a potential mechanistic contributor to the higher risk of ACL injuries in females than males, especially under consideration of the multi-planar knee valgus collapse as one of the main mechanisms of non-contact ACL injuries [6]. These findings are in agreement with previous studies reporting increased knee valgus rotation at time of ACL injury [8] and significantly greater knee valgus rotation at initial contact (during landing) in athletes who subsequently injured their ACL compared to uninjured control athletes [9].

**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 protocol 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:** Sex differences in knee valgus rotation under single- (LEFT) and multi-planar loading conditions (RIGHT). ITR: Internal tibial rotation moment.

**Figure 2:** Increased (coupled) knee valgus rotation under 20 Nm of internal tibial rotation moment compared to no internal tibial rotation moment (ITR).
Figure 3: Sex differences in increased knee valgus rotation under 20 Nm of internal tibial rotation moment compared to no internal rotation moment through 0-50 Nm knee abduction moments.