Gender Differences in Knee Laxity and Stiffness: An In Vitro Study of Age Matched Specimens from a Younger Population

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Introduction: Female athletes suffer non-contact anterior cruciate ligament (ACL) injuries at a rate 2 to 8 times greater than their male counterparts [1]. Increased joint laxity and reduced knee stiffness in female knees have been suggested as a possible explanation for higher ACL injury rates in women [2, 3]. Prior in vivo studies have examined male-female differences in stiffness and laxity using anterior-posterior (AP) [3, 4], varus-valgus (VV) [3, 5], and internal-external (IE) modes of testing [3, 5]. However fixation of the tibia and femur, possible influence of muscular contractions, and attachment of transducers to the lower limbs can introduce errors to the testing system that prevent accurate measurements of inherent structural properties of the joint itself. These errors are minimized during in vitro testing in a controlled laboratory environment. To our knowledge, there has been only one cadaveric study that has examined male-female differences in joint stiffness and laxity [6]. This study applied a combined valgus moment + internal torque at 15° and 30°of flexion only. Straight anterior-posterior tibial force at 0° and 30° of flexion was also evaluated. The objective of our cadaveric study was to measure male-female differences in knee stiffness and laxity at multiple flexion angles for three modes of testing: AP force vs. displacement, IE torque vs. rotation, and VV moment vs. rotation.

Methods: Forty-seven fresh-frozen cadaveric knees were used for this study (22 male, 25 female). The mean age was 34.6 years for males (range of 19 to 45 years) and 28.4 years for females (range 16 to 42 years). Specimens were potted in PMMA for fixation. The tibia was clamped to a force-moment sensor mounted on the end of a six DOF robot, with the femur secured to a baseplate. The robot performed force controlled AP, IE, and VV tests, measuring the corresponding tibial motion. Testing was performed at fixed knee flexion angles in 10° increments from 0° to 50°. Additional AP tests were also performed between 60° and 90° flexion. The applied loading levels were ± 134 N AP force, ± 10 Nm VV moment, and ± 5 Nm IE torque. Laxity was defined as the amount of tibial translation or rotation at the maximum applied load. Knee stiffness was determined from the slope at the terminal end of the force vs. displacement or moment vs. rotation curve; calculated between 67 N and 134 N of applied AP force, between 2.5 Nm and 5 Nm of applied IE torque, and between 5 Nm and 10 Nm of applied VV moment. Stiffness and laxity values were compared between male and female test groups at each flexion angle using an unpaired two-sample t-test. The significance level was p < 0.05.

Results: Anterior-Posterior (Figure 1): There were no significant male-female differences in posterior knee laxity (and total AP laxity). However, from 50° to 90° flexion female knees showed significantly greater anterior laxity (p < 0.03), with a maximum difference of 1.3 mm at 50° flexion. There were no significant male-female differences in anterior or posterior stiffness.
Internal-External (Figure 2): There were no significant male-female differences in external rotation laxity or stiffness. Female knees had significantly greater internal laxity (and total IE laxity) from 0° to 50° flexion (p < 0.03), with a maximum difference of 8.3° at 50° flexion (Figure 1). On average, internal stiffness for males was 42% greater than females from 0° to 30° flexion (p < 0.03).

Varus-Valgus (Figure 3): Females had significantly greater valgus knee laxity from 0° to 50° flexion (p < 0.05), while total VV laxity was greater between 10° and 50° flexion (p < 0.03). The maximum male-female valgus laxity difference was 1.6° at 50° flexion. There were no significant male-female differences in varus laxity. Male knees had 35% greater valgus stiffness at 10° flexion (p < 0.03) and 19% greater varus stiffness at 50° flexion (p < 0.03).

**Discussion:** Increased joint laxity in women is thought to be a risk factor for ACL injury. As forces and moments are applied to the knee during athletic activities, tibiofemoral displacements and rotations occur. The resulting AP, VV and IE motions are resisted in part by the ACL and in part by activated knee musculature. It has been suggested that a knee with increased laxity and reduced stiffness would require greater muscular control to stabilize the joint [7-9]. This could affect the timing and activation sequence of the knee musculature compared to a stiffer joint. If muscular accommodations are not met, larger joint motions (produced in a more lax knee) would produce higher ACL forces.

Markolf et al. [10] have shown that when tibiofemoral force (joint load) is applied to a cadaveric knee, condylar contact on the posteriorly sloping lateral tibial plateau causes the tibia to translate anteriorly and rotate internally, thereby loading the ACL. This has been proposed as a mechanism for noncontact ACL injury [7]. Female knees have been shown to have a steeper posterior lateral tibial slope than male knees [11], so theoretically a female knee should be more susceptible to this ACL injury mechanism, especially after fatigue sets in and neuromuscular control is diminished. The increased valgus and internal rotations associated with a more lax knee would further increase the risk of ACL injury from this loading condition.

Hsu et al. [6] reported no gender differences in AP stiffness and laxity at 15° and 30° flexion. We also found no gender difference in these parameters between 0° and 30° flexion. In addition, female knees showed significantly greater internal and valgus laxities than males between 0° and 50°. This was similar to the in vivo results of Shultz et al. [3], who found increased total VV laxity and total IE laxity in females at 15° and 30° of flexion. These findings were particularly interesting with regard to possible ACL injury mechanisms. It has been shown that both applied internal torque and valgus moment generate force in the ACL [12]. Consequently, increased internal and valgus rotations within the more lax female knees could produce higher forces on the ACL.

It is believed that increased knee laxity is more demanding on leg musculature to maintain joint stability. After fatigue sets in and the muscles are unable to adequately stabilize the joint, greater laxity could leave the knee more vulnerable to injury. The increased knee laxity seen in female knees in this study, in association with other risk factors such as tibial plateau and femoral notch geometry, muscular imbalance, neuromuscular control, and hormonal variations, may contribute to the gender differences in ACL injury rates.

**Significance:** Female knees showed significantly greater anterior, internal, and valgus laxity than male knees over specified ranges of knee flexion. In combination with other gender specific risk factors, increased knee laxity may be a contributing factor associated with the higher rate of female ACL injuries.
Figure 1. AP knee laxity from 0° to 90° of knee flexion (mean ± SD). Significant male-female differences were observed for anterior laxity from 50° to 90° degrees (* p < 0.03). There were no male-female differences in posterior or total AP laxity.
Figure 2. IE knee laxity from 0° to 50° of knee flexion (mean ± SD). Significant male-female differences were observed for both internal (* p < 0.03) and total IE laxity († p < 0.03). There were no male-female differences in external laxity.
Figure 3. VV knee laxity from 0° to 50° of knee flexion (mean ± SD). Significant male-female differences were observed for both valgus (*p < 0.05) and total VV laxity (†p < 0.03). There were no male-female differences in varus laxity.