The Effect of Anterior Knee Laxity on Multi-Planar Passive Knee Kinematics during Dynamic Landing: An In Sim Study of Human Knee Joint

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Introduction: Excessive laxity of the knee joint appears to increase overall joint stability and increase the risk of anterior cruciate ligament (ACL) injury during high risk activities [1]. Despite the frequent clinical use of knee arthrometry in ACL injury risk assessment, the relationship between increased knee laxity and elevated injury risk during high-risk activities is unclear. The purpose of this study was to evaluate the relationships between anterior knee laxity and multi-planar passive knee kinematics during landing using a novel in sim approach, which included cadaveric experiments and computer modeling. We hypothesized that increased knee laxity would elevate ACL strain by increasing joint motion in all three anatomical planes. We also hypothesized that this effect would be greater in the sagittal and coronal planes than the axial plane.

Methods: 12 normal cadaveric legs (45±4 years, 6 female and 6 male) were tested for A-P knee laxity using a CompukT Knee Arthrometer [2]. Specimens were sectioned and potted at mid-femur for attachment to a validated drop-stand used to simulate landing from a jump [3]. The quadriceps (Q) and hamstrings (H) tendons were then isolated and clamped for application of muscle loads. Specimens were mounted to simulate lower extremity posture during ground strike, while landing from a jump. Landing was simulated by vertical impact of approximately half body mass from 30 cm with the knee at 25° of flexion under simulated muscle forces (Q: 1200 N, H: 800 N).ACL strain was calculated from a DVRT transducer arthroscopically placed across the AM-bundle. Tibiofemoral joint motion was captured by an Optotrak 3020 motion capture system. In order to better interpret experimental findings, additional parametric studies were conducted using a validated anatomic finite element (FE) model of the knee joint [4]. Simulations were conducted in a controlled fashion to isolate the effect of joint laxity by keeping the anatomy and loading factors constant. This model was developed from anatomical data of a healthy, skeletally mature young female athlete. The model consists of 3D representations of the lower extremity bony structure in addition to soft tissue structures of the knee joint. The model was extensively validated against cadaveric measurements of tibiofemoral kinematics, ACL and MCL strains, and tibiofemoral cartilage pressure over a wide range of static, quasi-static and dynamic loading conditions. Dynamic pivot landing was simulated under 25 Nm of knee abduction and 10 Nm of internal tibial rotation moments in presence of muscle loads (Q: 1200, H: 800 N) and axial impact load of 4000 N over 70 ms. The simulations were repeated with decreased ACL stiffness (increased anterior joint laxity) from 100% to 25% of normal value with 25% increments. Multiple linear regression models were used for statistical analyses.

Results: Average anterior knee laxity of 2.6±1.2 mm was generated under 134 N of anterior drawer load. Simulated landing resulted in an average axial impact load of 4212±676 N over a period of 72.9±10.8 ms. Load generated by axial impact significantly increased anterior translation (ATT) by 6.8±2.5 mm (p=0.003), average knee abduction by 1.6±1.3°(p=0.001) and average internal tibial rotation by 2.2±2.7° (p=0.015), sequentially. The resultant change in tibiofemoral kinematics along with axial impact load significantly increased average ACL strain by 4.8±2.9% (p=0.031). Simulated landings resulted in a peak angular velocity of 68±22.8 deg/s (knee abduction) and 69.±28.5 deg/s (internal rotation), and peak anterior tibial acceleration of 120.6± 53.8 m/s². A strong, statistically significant correlation was observed between quantified anterior knee laxity and peak ACL strain (r=0.65, p=0.03) with greater knee laxity lead to higher ACL strain levels. Also, specimens with greater anterior knee laxity demonstrated a general trend towards higher peak ATT, knee valgus and internal tibial rotation. However, these correlations were not significant (r<0.4, p>0.3). Similar relationships with stronger correlations were observed between anterior tibial acceleration, valgus angular velocity and internal rotation angular velocity with anterior knee laxity (r<0.5, p>0.1). However, gender-specific analyses resulted in good to strong correlations between anterior tibial acceleration (r=0.75, p=0.04), valgus angular velocity (r=0.74, p=0.04), and internal rotation angular velocity (r=0.63, p=0.14) with anterior knee laxity in female specimens (Figure 1). FE simulated pivot landings demonstrated a strong and significant correlation between increased ATT (r=0.97, p=0.001), knee valgus (r=0.93, p=0.008), internal tibial rotation (r=0.86, p=0.011), and peak ACL strain (r=0.98, p=0.001) with decreased ACL stiffness (greater anterior knee laxity). The fold change increase in measured kinematics were 82.5% (ATT), 67.6% (valgus), and 42.4 (internal rotation) under decreased ACL stiffness from 100% to 25%.

Discussion: As previously reported, quantified anterior knee laxity using knee arthrometry is a strong predictor of risk of ACL injury, measured by peak ACL strain, during landing [2]. Cadaveric simulation of landing demonstrated no strong relationships...
between knee multi-planar kinematics and anterior knee laxity. However, FE predictions resulted in strong and significant correlations between altered ACL stiffness (anterior knee laxity) and knee kinematics in all 3 anatomical planes. This may be due to the wide range of intra-specimen variability in both joint anatomy and tissue structural properties during cadaveric testing, while the FE analysis isolated the effect of joint laxity by keeping all other variables constant. This is further supported by the enhanced correlations obtained by changing translations and rotations to linear acceleration and angular velocity, which has taken into account the timing variations between specimens. This is in agreement with our previous findings that joint velocity and acceleration are stronger predictors of ACL strain than pure rotations and translations. While these correlations were not significant, analyses of female samples alone demonstrated strong and significant correlations. This is in line with previous findings of females being at 4-6 times higher risk of ACL injury compared to males [5]. Observed correlations were highest for anterior tibial acceleration and valgus angular velocity, and lowest for internal rotation angular velocity. These findings are in agreement with FE analysis results demonstrating maximum changes in ATT and knee varus, and minimum changes in internal tibial rotation due to altered ACL stiffness. These differences in knee multi-planar response can be explained by the role of ACL as passive restraint against ATT and knee abduction. These combined findings support our hypotheses, highlight the importance of ACL injury frontal and sagittal plane mechanisms, and underscore valgus collapse as a sex-specific ACL injury mechanism [5]. Findings may also provide a better explanation for greater risk of ACL injury among females than males, given that females having significantly higher knee laxity than males.

**Significance:** Intervention programs that address multi-planar knee biomechanics with special focus on knee frontal and sagittal plane mechanics are essential to effectively mitigate the risk of ACL injury.

**Acknowledgments:** Supported by NIH/NIAMS

**References:**
[1]. Myer et al, AJSM 2008
[2]. Kiapour et al, AJSM 2013
[3]. Levine et al, AJSM 2013

![Graphs showing correlations with anterior knee laxity](image)

**Figure 1:** Correlations between (Left) anterior tibial acceleration, (Middle) abduction angular velocity, and (Right) internal rotation velocity with anterior knee laxity for female specimens.