Multi-planar Segmental Angular Velocity and Linear Acceleration during Dynamic Landing: Strong Predictors for Risk of ACL Injury

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Introduction: Over 125,000 anterior cruciate ligament (ACL) injuries occur annually in US, often (>70%) via non-contact mechanisms during landing [1-3]. Non-contact ACL injury mechanisms are multi-planar in nature, involving tibiofemoral joint articulation in all three anatomical planes [4]. Despite considerable efforts to characterize high-risk motions that lead to ACL injury, relationships between segmental velocity and acceleration (as a measure of loading rate), ACL loading, and the potential risk of ACL injury remains unclear. These factors are of critical importance as the ACL, like other soft tissues, exhibits time and rate dependent characteristics that indicate the importance of tissue multi-axial loading rate as dictated by multi-planar segmental angular velocity and linear acceleration during high-risk dynamic activities. Hence, the current study aims to investigate the relationships between knee joint multi-planar motion, and velocity and acceleration with ACL strain (an established measure of injury risk) during landing in a cadaveric model. We hypothesized that: I) segmental velocity and acceleration would be strong predictors of ACL strain and provide more reliable estimates of injury risk compared to joint motion; and II) anterior tibial translation/acceleration and knee abduction angular velocity would be stronger predictors of risk of ACL injury compared to internal tibial rotation/angular velocity.

Methods: 12 normal cadaveric legs (45±4 years, 6 female and 6 male) were sectioned and potted at the mid-femoral shaft with all soft tissues dissected up to 15 cm proximal to the joint. The quadriceps and hamstrings tendons were then isolated, and clamped inside metal tendon grips to allow for the application of simulated muscle loads. The remaining musculature, along with the skin, was maintained intact. Dynamic landing following a jump was simulated using a custom-made drop-stand [4] designed to maintain specimens in an orientation that simulated lower extremity posture as during ground strike while landing from a jump. Each specimen was positioned inverted and rigidly fixed at the proximal femur with the tibia orientated vertically and the knee at 25° of flexion. Landing following a jump was simulated by vertical impact of half body weight (350 N) from a height of 30 cm in the presence of the pre-tensioned quadriceps (1200 N) and hamstrings (800 N). ACL strain was calculated using a DVRT displacement transducer, arthroscopically placed on the distal third of the ACL AM-bundle. Tibiofemoral kinematics were captured using an Optotrak 3020 motion capture system. Paired-sample t-test and linear regression analysis were used for statistical analyses with an a priori alpha level of 0.05. Correlations were classified as poor (<0.4), good (0.4 to 0.74) and strong (≥0.75) based on Pearson’s correlation coefficient (r) [5].

Results: Simulated landings 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 average anterior tibial 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 68.4±22.9 deg/s (knee abduction) and 69.0±28.5 deg/s (internal tibial rotation), and peak anterior tibial acceleration of 120.6±53.8 m/s². No significant difference was observed between peak abduction angular velocity and peak internal rotation angular velocity (p=0.866). No tissue failure was observed following testing. Specimens with higher impact-induced ATT, knee abduction and internal tibial rotation demonstrated a general trend towards greater ACL strain. However, these correlations were mainly weak to good and not statistically significant. The strongest correlation was between ATT and ACL strain (r=0.65, p=0.030), while similar correlations were observed between knee abduction and ACL strain (r=0.52, p=0.090), and internal tibial rotation and ACL strain (r=0.49, p=0.091). Similarly, specimens with higher angular velocity (knee abduction and internal tibial rotation) and higher anterior tibial acceleration demonstrated greater levels of ACL strain during landing. However, reported segmental velocity and acceleration demonstrated higher correlations with ACL strain (Figure 1). These correlations were strong and statistically significant for anterior tibial acceleration versus ACL strain (r=0.84, p=0.001) and knee abduction velocity versus ACL strain (r=0.76, p=0.004). The correlation between internal tibial rotation velocity and ACL strain was not strong and significant (r=0.55, p=0.068).

Discussion: To the authors' knowledge, this is the first study to demonstrate the significant association between multi-planar knee segmental velocity and acceleration, and ACL strain during dynamic landing. Significant increases in ATT, knee abduction
and internal tibial rotation lead to increased ACL strain during simulated bi-pedal landing. This is in agreement with previous in vivo clinical and biomechanical studies showing the multi-planar knee articulation during landing, and the contribution of these loading conditions towards an increased risk of ACL injury. The strong and statistically significant correlations (not significant for internal rotation angular velocity) between quantified segmental angular velocity and linear accelerations highlight the critical importance of these kinematical parameters as strong predictors of ACL injury risk during landing, supporting our first hypothesis. Further, segmental angular velocity and linear acceleration showed substantially higher correlations with ACL strain (risk of ACL injury) compared to measured joint kinematics in all three anatomical planes. This finding highlights the clinical importance of segmental velocity and acceleration relative to joint rotation and translation in the assessment of an individual's ACL injury risk. In addition, these findings support the use of multi-axial rate meters and accelerometers in biomechanical evaluation of ACL injury risk and mechanism, specifically during dynamic activities, where accurate in vivo quantification of multi-planar joint kinematics is challenging. The current findings also underline the critical role of knee frontal and sagittal plane kinematics as the main contributors to potential ACL injury, as the maximum, and only significant correlations observed between knee kinematics and ACL strain occurred in sagittal and frontal planes, supporting our second hypothesis. Together, these findings indicate that although internal tibial rotation contributes to increased ACL strain, it is secondary to anterior tibial translation and knee abduction in affecting ACL strain and potential injury risk.

**Significance:** A better understanding of ACL injury risk factors may provide insight to improve current prevention strategies intended to decrease the risk of ACL injury. Intervention programs that address multi-planar loading including knee abduction are essential to effectively mitigate the risk of ACL injury.

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**References:**