Sensitivity of FE-based ACL Injury Risk Prediction to ACL Mechanical Properties and External Loading Conditions

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Disclosures:

Introduction: Over 125,000 anterior cruciate ligament (ACL) injuries occur annually in the United States, mainly affecting the young athletic population \cite{1}. Acute ACL injury can be devastating, and often results in clinical sequelae that include meniscal tears, chondral lesions and osteoarthritis \cite{2}. Among the methods used to study this phenomenon, the use of Finite Element (FE) based computer modeling has become progressively more popular as it allows for detailed analysis of the joint/tissue behavior under complex, clinically relevant loading conditions. Despite model validation, uncertainties due to the in vivo and in vitro kinematic/kinetic acquisition along with variation in soft tissue mechanical properties, could affect the model predictions especially in local outcomes such as ligament strains. Hence, the purpose of this study was to explore the sensitivity of FE-based ACL injury risk assessment to variations in critical biomechanical risk factors (external loadings) and ACL structural properties. The hypotheses tested were that FE-predicted ACL strain would be sensitive to both the biomechanical risk factors and ACL tissue properties and that greater sensitivity would be observed to changes in biomechanical parameters than ACL tissue properties.

Methods: A validated, anatomic non-linear FE model of the knee joint developed from imaging data of a young female athlete was used \cite{3}. A one-at-a-time approach \cite{4} was used to address FE model local sensitivity in prediction of peak ACL strain (as an established measure of ACL injury risk) to three main biomechanical risk factors (anterior tibial shear force, knee abduction and internal tibial rotation moments) and ACL tissue properties. 134 N of anterior shear force, 25 Nm of knee abduction and 10 Nm of internal tibial rotation moments \cite{5} were selected as initial magnitudes. Each parameter was then varied by ±20% of the initial value in order to account for the parameter’s variability and the associated influence on model output \cite{4}. Landing from a 30 cm height in presence of aforementioned biomechanical risk factors (off-axis loads) were conducted using the validated FE model. Further, ACL material model coefficients were optimized to result in ±20% variation in the anterior knee laxity. Landing simulations were then repeated with varied ACL properties in order to quantify model sensitivity to change in ACL mechanical properties. A total of 28 simulations were conducted. The Spearman ranked coefficient of determination was calculated for each of the input parameters in order to determine the influence of each tested parameter on the output variability. Model sensitivity to each parameter was defined as the percent change in FE predicted peak ACL strain with respect to the baseline. Quantified sensitivities were then compared using Analysis of Variance (ANOVA) with a post-hoc Bonferroni correction for multiple comparisons.

Results: FE model prediction of ACL strain was sensitive to variation in all four tested parameters, as measured by the Spearman’s coefficient of determination (\(p^2>0.9\) and \(p<0.01\) for all parameters). Variation in applied anterior shear force, knee abduction and internal rotation moments changed the FE predicted peak ACL strain by 24.6±6.9%, 16.9±1.1% and 13.6±3.8% compared to the baseline, respectively (Figure 1-Right, Green bars). Change in ACL laxity (mechanical properties) resulted in 7.7±2.9%, 9.7±4.5% and 9.1±2.6% change in peak ACL strain compared to the normal ACL condition respectively under additional anterior shear force, knee abduction and internal rotation moments (Figure 1-Left, Green bars). FE predicted peak ACL strain showed significantly lower sensitivity to change in ACL laxity compared to change in biomechanical risk factors (\(p<0.015\) for all comparisons). Finally, FE model sensitivity in peak ACL strain was significantly higher due to variation in anterior shear force compared to changes in knee abduction (\(p=0.005\)) and internal tibial rotation (\(p=0.016\)) moments.

Discussion: These findings illustrate that the FE-based ACL injury risk assessment is sensitive to both biomechanical risk factors (loading) and tissue mechanical properties. However, FE predicted ACL strain was significantly more sensitive to the biomechanical risk factors than the tissue mechanical properties. The model showed significantly higher sensitivity in peak ACL strain to anterior tibial shear force compared to the other loading parameters. This finding is consistent with the ACL being responsible for almost 90% of passive anterior tibial restraint \cite{6}. In addition, variation in knee abduction moment resulted in greater changes in FE-predicted peak ACL strain compared to changes in model output due to the variation in internal tibial rotation moment. This phenomenon may be associated with the role of ACL in restraining knee valgus \cite{7}. The current findings indicate that the applied loading and kinematic boundary conditions may play a more critical role in FE model predictions of overall injury risk compared to the subject-specific material parameters. However, subject-specific anatomical factors (geometry
and material properties) are essential in order to accurately predict individual-based ACL injury risk as previously shown [8]. Combined, these findings support our hypotheses and underline the clinical application of generalized FE models in overall risk assessment and parametric analyses for identification of injury mechanisms and risk factors.

**Significance:** The combination of computer modeling techniques with *in vivo* biomechanics can be used in an *in silico* approach to assess the risk of ACL injury. These models may also be used to better interpret experimental findings and conduct robust parametric analyses under complex, clinically relevant conditions which are challenging if not impossible experimentally.

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**References:**
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[8] Kiapour AM. et al., ASB Annual Meeting

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**Figure 1:** Average FE model sensitivity of peak ACL strain to (left) biomechanical risk factors, and (right) ACL mechanical properties.

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