NOVEL FRAMEWORK TO PERSONALIZE VALIDATED GENERALIZED FINITE ELEMENT MODEL: IMPLICATION FOR INDIVIDUAL-BASED ACL INJURY RISK ASSESSMENT

1Ata M. Kiapour, 1Ali Kiapour, 1Constantine K. Demetropoulos, 2Carmen E. Quatman, 2Samuel C. Wordeman 2Timothy E. Hewett, 1Vijay K. Goel

1Engineering Center for Orthopaedic Research Excellence (ECORE), University of Toledo, Toledo, OH 2OSU Sports Medicine, Sports Health and Performance Institute, The Ohio State University, Columbus, OH email: ata.kiapour@utoledo.edu, web: http://www.eng.utoledo.edu/ecore

INTRODUCTION
The anterior cruciate ligament (ACL) is one of the most frequently injured ligaments of the knee, with a prevalence estimated to be 1 in 3000 in the U.S. population. Current approaches to biomechanical finite element (FE) modeling of the knee are at a crossroads. While the ideal scenario for clinically applicable FE modeling would be a subject-specific approach with detailed, image-based anatomic reconstruction of the joint, the computational intensity of such an approach would almost certainly preclude its clinical applicability. The assumption that an accurate assessment of an individual’s ACL injury risk profile can be attained through generalized FE models also has yet to be tested. The current study aims to test a novel framework in which the developed, validated generalized FE model can be customized to each specimen based on ACL structural properties (mechanical and anatomical), posterior slope of the lateral tibial plateau and femoral intercondylar notch width as the most critical anatomic risk factors for ACL injury [1]. We hypothesized that personalized FE models using the proposed framework would result in more accurate predictions of ACL strain (as an established measure of injury risk) compared to the generalized FE model. Thus, these models may serve as individual-based injury risk assessment tools.

METHODS

1) Model Customization Approach: An anatomical non-linear knee FE model, developed from a healthy, young female athlete (25 yrs, 170 cm, 64.4 Kg) was used (Figure 1). The model has been extensively validated against direct cadaveric measurements of joint kinematics, ligament strains and cartilage pressure distribution under quasi-static and dynamic loading conditions [2].

Five normal cadaveric legs (41±5 yrs) were acquired, imaged and instrumented with a DVRT displacement transducer across the ACL AM-bundle. A-P knee joint laxity of each specimen was determined using a CompuKT Knee Arthrometer. The 3D ACL geometry of each specimen was generated and meshed following the same technique used in development of the validated generalized FE model. Five personalized FE models were developed by changing the native ACL geometry/mesh to the subject-specific ones. Further, tibial slope and intercondylar notch width of each specimen were measured. In order to modify the lateral tibial slope of each personalized model, tibial plateau was rotated about an axis located above the tibial tuberosity, 2 cm distal to the tibial plateau and normal to the long axis of the tibia to match the measured lateral tibial slope [3]. Finally, the regional nodes/elements across the intercondylar notch of each model were manually manipulated to match the measured intercondylar width of the specimen. Subsequently, personalized FE models were used to simulate instrumented knee laxity tests. Finally, ACL material model coefficients of each personalized model were optimized to reproduce the subject-specific force-displacement curve obtained from knee arthrometry.
II) Approach Validation and Accuracy Evaluation:
Model predictions of ACL strain during simulated A-P laxity tests for each personalized FE model were compared to experimentally measured data. Further, cadaveric experiments of bi-pedal landing from a 30 cm height [4], conducted on the specimens, were simulated in the personalized FE models. Finally, FE predictions of peak ACL strain were compared to experimentally measured values to test the reliability/validity of this novel approach for prediction of individual-based ACL injury risk. Additional simulations were conducted using the generalized FE model to further verify the accuracy of the personalized models. Pearson’s correlation coefficient (r), root-mean-square errors (RMSE) and ANOVA with a post-hoc Bonferroni for multiple comparisons were used for statistical analyses.

RESULTS AND DISCUSSION
Applied anterior drawer load resulted in elevated ACL strain levels as shown by 4.4±1.4%, 3.2% and 4.2±1.3% in cadaveric experiments, generalized and personalized FE models, respectively. Simulated landings resulted in peak ACL strain of 6.8±1.6%, 5.7±0.9% and 6.5±1.3% in cadaveric experiments, generalized and personalized FE models, respectively. Although both generalized and personalized FE models resulted in similar trends as cadaveric experiments, personalized FE models resulted in more accurate predictions compared to the generalized model.

Strong correlations (Laxity Test: r=0.97, p=0.006; Landing: r=0.94, p=0.01) with low deviation (Laxity Test: RMSE=0.4%; Landing: RMSE=0.7%) were observed between personalized FE models predictions and experimental measurements of ACL strain. However, a lower correlation (r=0.42 p=0.48) with greater deviation (RMSE=1.9%) was observed between generalized FE model predictions and experimental measurements under the similar landing condition (Figure 2). No significant differences were observed between average peak ACL strain reported by cadaveric experiments, generalized FE and personalized FE models (p>0.55). The absence of significance differences between generalized FE model predictions and experimental data highlights the potential application of this modeling approach in overall risk assessment (identification of risk factors and mechanisms) and parametric/sensitivity analyses. However, low correlation and large RMS error, are indicatives of the relatively low accuracy of this approach in individual-based risk assessment. Whereas, personalized FE models resulted in more accurate predictions of ACL strain supported by strong correlations with the RMS error minimized.

Figure 2: Personalized and Generalized FE models predictions of ACL strain Vs. cadaveric measurements.

CONCLUSIONS
The current findings demonstrate the validity of the proposed novel, computationally efficient approach to generate personalized models and thus supported our hypothesis. This highlights the clinical utility of such personalized models for prediction of an individual’s risk of ACL injury (as reported by ACL strain) especially in large-scale clinical studies where subject-specific modeling is not practical.

REFERENCES

ACKNOWLEDGEMENTS
Funded by NIH/NIAMS (R01 AR056259 & R01 AR049375).