Pipeline for Specimen Specific Bone-Ligament-Cartilage Finite Element Models

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ABSTRACT

Specimen-specific finite element (SS-FE) models are becoming more common as their use enables the elucidation of the effects of individual anatomy. However, despite their increased prevalence, they remain laborious to produce. The goal of this study was to develop a method to automatically generate SS-FE models that are representative of the bones, ligaments, and cartilage so that anatomical variation can be represented in models of experimental scenarios. Bones from a template model were morphed to the bone surfaces taken from CT data using an adapted morphing process. Elastic registration was used to map a template FE mesh onto target surfaces taken from CT data. The way this mesh was mapped was used to inform the morphing of the insertions sites of ligaments and cartilage (soft-tissues). In this way, the soft-tissue insertions were also morphed. Ligament wrapping around bony surfaces was added to allow for physiologic mid-substance loading. Cartilage thickness was addressed by checking for penetration between cartilage pairs. Material properties and contact definitions were transferred from the template model to the SS-FE model. Using this methodology, an existing lower extremity finite element model, including 30 bones, 113 ligaments, and 35 cartilage pairs, was morphed to three lower extremities of varying anatomy: a 5th percentile right female lower extremity, a 95th percentile left male lower extremity, and a 50th percentile right male lower extremity. Morphing for each of the specimens took three to four hours. This process from CT to SS-FE model has the potential to leverage the strengths of parametric computation simulation in concert with experimental test setups to a degree not previously achieved.

INTRODUCTION

In recent decades, computational human body models have improved dramatically and have been utilized to understand, quantify, and predict human behavior and injury. However, the time required to create a new model can be extensive. Efforts have been made to address variation in human anatomy through various forms of scaling or through statistical anthropometric data to generate target statistical models with given stature, weight, and age (Vavalle, 2014 & Hwang, 2016). These newly generated anatomies do not reflect any specific person. Instead they aim at covering a range of anatomical variation in order to understand general population response. While these types of models are useful they ultimately lack the ability to represent localized anatomical variations for experimental scenarios.

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Given improvements in computational modeling and imaging technology, SS-FE models have become more prevalent. Previous work has already leveraged these improvements to produce SS-FE of singular bones to produce improved predicted responses of across specimens with varying anatomy (Untaroiu, 2008 & Park 2016). Given the promise shown in predicting individual bone response using SS-FE models, it is possible this method could be expanded to multi-bone systems provided morphing can be expanded to ligaments and cartilage. Since the benefits of using SS-FE models for component level test have already been shown, exploration into validation of multi-component models could prove a useful tool for more complex experimental tests.

The goal of this study was to develop a method to automatically generate SS-FE models that are representative of the bone, ligament, and cartilage structures of their cadaveric counterparts. The lower extremity was selected to develop this method due to its complexity and numerous bone, ligament, and cartilage components.

METHODS

A high resolution FE model of the human lower extremity was created from the CT data of a large male right foot. Care was taken in including all known ligaments and cartilage surfaces. Next, the bony anatomy of three target specimens was created from CT data. Given both the template FE model and the target anatomy from CT an elastic registration approach was used to morph the template model to the SS-FE model using a custom MATLAB script (R2017a, The MathWorks Inc., Natick, MA) (Figure 1).
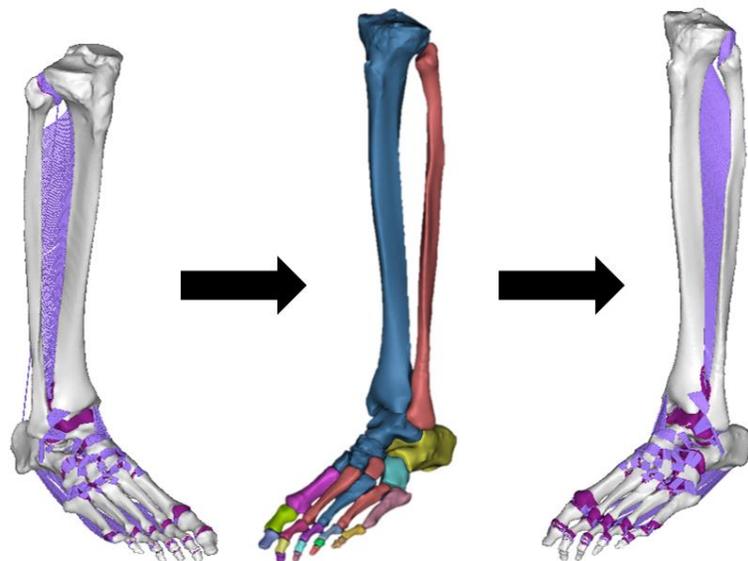

Figure 1: (Left) Template right lower extremity FE model. (Middle) CT data of 95% left male lower extremity. (Right) Morphed SS-FE model of 95% left male lower extremity. Ligaments are colored in a light purple. Cartilage surfaces are colored in a dark purple.

The script is organized to accept the target geometry and first morphs the bones followed by the ligaments and cartilage. The template bones were first best aligned with their respective target bones using an iterative-closest-point (ICP) method. Non-uniform scaling was then applied to the template bones along their principle axes to better approximate the shape of the target bones.

Lastly, elastic registration iteratively diminished the remaining distance between the template nodes and target surfaces until the template mesh had been mapped onto the target bone's surface. Elastic registration is driven by a radial basis function with thin-plate spline as a basis function (Rohr, 1996 & Bookstein, 1989).

The paths the template nodes traveled to the target surface were tracked to interpolate how any point on the template surface would map to the target surface (Figure 2). This was used to map the insertion sites for both ligaments and cartilage, and was achieved by recording the natural coordinates of nodes from the ligaments or cartilage attachments in the element space of the template bones. After morphing was complete, these natural coordinates were used to define the new location of the soft tissue insertion sites. While this new location was not verified against any imaging data, it did produce a representative location and geometry of the soft tissues.
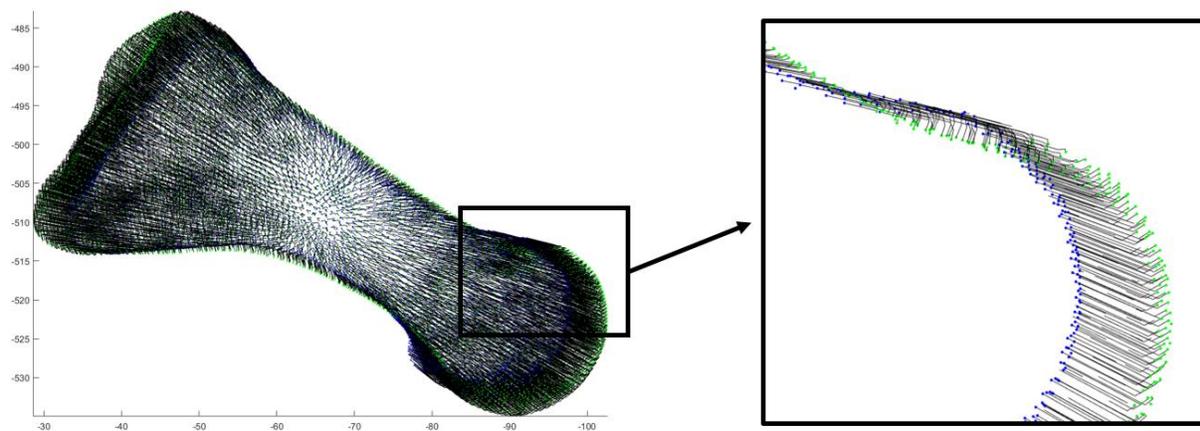

Figure 2: (Left) Paths taken by the template nodes as they are mapped to the target surface of the 1st metatarsal. (Right) Sagittal slice of the distal 1st metatarsal showing the paths (black lines) taken from the starting locations (blue) to the ending locations (green) of the template nodes.

Once the attachment sites for the soft tissues were defined on the target bony surfaces, soft tissues were automatically generated and meshed. Ligaments were represented as parallelized cross-linked discrete beam elements and were wrapped around the bony surfaces by simulating the expansion of the bones forcing the ligaments to form around them. This allowed for a more physiologic ligament response, by providing transverse loading to the bone surfaces (Spratley, 2018). Cartilage surfaces were represented as solid hex elements with a constant thickness. Hypermesh^{TM} (Altair Engineering, Inc., MI, USA) was used to mesh the cartilage surfaces and was automated through tool command language (TCL) scripts. Cartilage thickness was defined by projecting away from the bony surface and checking for penetration between each of the cartilage pairs. Finally, material properties and contact definitions were transferred from the template model to the SS-FE models. This method produces a new SS-FE model with material properties identical to template model.

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RESULTS

Using a right lower extremity FE model as a template this method generated three separate SS-FE models: a 5th percentile right female lower extremity, a 95th percentile left male lower extremity, and a 50th percentile right male lower extremity (Figure 3). The 95% male was selected as a left lower extremity with a plantarflexed foot to demonstrate this method is not sensitive to the initial posture or symmetry of the lower extremity. Morphing for each specimen was run on a contemporary laptop and took 188, 194, and 226 minutes respectively.
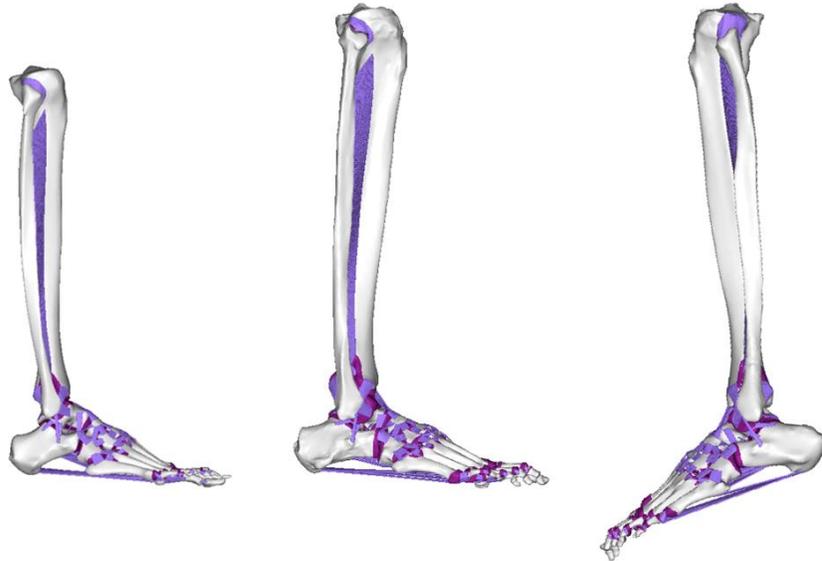

Figure 3: (Left) 5th percentile right female lower extremity SS-FE model. (Middle) 50th percentile right male lower extremity SS-FE model. (Right) 95th percentile left male lower extremity SS-FE model.

DISCUSSION

The automated development of SS-FE models provides a new method to compared to other morphing and scaling methods. This can be achieved by validating against experimental tests just as it was done for single component SS-FE models (Park 2016). This will help demonstrate what level of detail is required to more accurately capture specimen response, and what factors are more or less sensitive in the modeling process. This information can be used to identify factors of low sensitivity that can be ignored to increase model efficiency.

This method is the first of its kind as far as we are aware in that its goal is not to address a general population geometry but the individual specimen geometry. Due to the speed and simplicity of the input this method can and will be used in tandem to experimental tests. This will first be done for the lower extremity in order to evaluate these SS-FE models for injury prediction and the investigation of geometric effects on injury mechanisms. Furthermore, this method, which takes approximately four hours on a laptop can be parallelized through high performance computing to increase the efficiency for larger experimental studies. This method has no bias

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towards shape, symmetry, or initial orientation of geometries and thus has the potential to be expanded to other regions of the body. However, similar evaluations as will be done for the lower extremity should be performed since the sensitivity of different modeling factors may vary in different regions of the body.

Finally, this study aimed to generated SS-FE of varying geometries, and placed high priority on capturing high-resolution of bony geometry and representing the soft tissues required for the foots passive function (i.e. ligaments and cartilage). For this reason, structures such as muscle, adipose, and skin tissues were ignored in order to first evaluate the primary structures of the lower extremity. Further improvement to the method can include the addition of tendons and muscles through the same steps applied for ligaments, but additional consideration will be needed for the incorporation of adipose and skin tissues.

CONCLUSIONS

This method has shown the ability to generate SS-FE models of the human lower extremity quickly and automatically. This capability has the potential to leverage the strengths of parametric computation simulation in concert with experiments to a degree not previously possible. This will be achieved by capturing the initial static positions of bones through Vicon exposures taken just prior to experimental tests and defining the same initial bone positions to the SS-FE model in simulation. Further SS-FE model will continue to be generated using this method to check its robustness against large geometric variations. For now, the models presented here were chosen as bounds of human anthropometry and validation will be conducted on future SS-FE models produced by this method against their cadaveric counterparts.

REFERENCES

BOOKSTEIN, FRED L. (1989). Principal warps: Thin-plate splines and the decomposition of deformations. IEEE Transactions on pattern analysis and machine intelligence, 11.6: 567-585.

HWANG, E., HALLMAN, J., KLEIN, K., RUPP, J., REED, M., & HU, J. (2016). Rapid Development of Diverse Human Body Models for Crash Simulations through Mesh Morphing, SAE Technical Paper, No. 2016-01-1491.

PARK, G., KIM, T., FORMAN, J., PANZER, M. B., & CRANDALL, J. R. (2017) Prediction of the structural response of the femoral shaft under dynamic loading using subject-specific finite element models. Computer methods in biomechanics and biomedical engineering, 20(11), 1151-1166.

ROHR, K., STIEHL, H. S., SPRENGEL, R., BEIL, W., BUZUG, T. M., WEESE, J., & KUHN, M. H. (1996). Point-based elastic registration of medical image data using approximating thin-plate splines. In International Conference on Visualization in Biomedical Computing, pp. 297-306.

SPRATLE, E. M., O'CAIN, C. M., DONLON, J. P., GEPNER, B. D., FORMAN, J. L., KENT R. W. (2018). Ligament Wrapping in a Finite Element Model for Predicting Sprains within the Mid- and Forefoot. In: 2018 IRCOBI Conference Proceedings.

UNTAROIU, C., GENOVESE, D., IVARSSON, J., CRANDALL, J. (2008). A finite element analysis of mid-shaft femoral tolerance under combined axial-bending loading. In 10th Int LS-DYNA® Users Conf.

VAVALLE, N.A., SCHOELL, S.L., WEAVER, A.A., STITZEL, J.D., GAYZIK, F.S., (2014). Application of Radial Basis Function Methods in the Development of a 95th Percentile Male Seated FEA Model. Stapp Car Crash Conf. 58.

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