Prediction of the Structural Response of the Femoral Shaft under Dynamic Bending Loading using Geometric Subject-Specific Finite Element Models

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ABSTRACT

The goal of this study was to predict structural responses of the femur under dynamic three point bending using the geometric SS-FE models, and to evaluate the prediction accuracy of the models, compared to that of various conventional techniques: mass-based and structure-based scaling. Geometric SS-FE models of the fifteen femur specimens were developed using a morphing technique. Dynamic three-point bending tests of fifteen bare femurs were simulated using the developed geometric SS-FE models - the distal and proximal ends of the femur specimens were potted into cups, and the mid-span of the specimens were loaded in latero-medial direction by an impactor at 1.5 m/s. The geometric SS-FE model captured the response variations of the PMHS better than the scaling techniques; mass-based scaling technique even increased the prediction error. This result suggests a benefit of using geometric SS-FE models to capture the response variance shown from anthropometric variability compared to current scaling techniques.

INTRODUCTION

While the automotive safety field has made remarkable improvements in occupant safety over several decades, new approaches are required to overcome the present challenges facing the field. In particular, future initiatives must address the limited range of population represented by anthropometric test devices, the limited ability of scaling techniques to capture the complexity of the human body, and the limited number of cadaveric specimens available.

Given contemporary computational modeling and imaging technology, subject-specific finite element (SS-FE) models have been increasingly employed in the field of biomechanics. Since subject-specific finite element models can incorporate detailed skeletal geometry of specimens as well as spatial distribution of bone density, they have the potential to predict the response of each specimen. If accurate subject-specific modeling techniques can be further developed and validated, they may facilitate the development of parametric statistical finite element models that can capture the effects of anthropometric and compositional differences throughout the population.

The SS-FE models have gotten attention, especially in the field of orthopedic biomechanics. The studies in the field of orthopedic biomechanics mainly focused on proximal femurs since they were attempting to predict the risk of fracture in falls or were interested in an implant design (Helgason, 2008). However, the SS-FE models focusing on the femoral shaft, in which important region of the automobile safety field, haves not been addressed. In the field of injury biomechanics, the subject-specific FE modeling technique has gotten attention by researchers focusing on how to develop morphed human body FE models (Vavalle, 2014). While previous studies in the field of injury biomechanics studying on SS-FE models give insights into how to develop whole-body level SS-FE models, validation of component-level test data would be a useful supplement for those studies to identify the important validation points to develop SS-FE models. One research addressed the SS-FE models of the femoral shaft to demonstrate the benefit of using subject-specific FE models for the prediction of response in component level impact tests (Untaroiu, 2008); however, the number of specimens used in the study was limited.

The goal of this study was to predict structural responses of the femur under dynamic bending loading using the geometric SS-FE models and to evaluate the prediction accuracy of the models, compared to that of various conventional techniques: mass-based and structure-based scaling. First, Geometric SS-FE models of the fifteen femur specimens were developed using a morphing technique. Using the developed geometric SS-FE models, FE simulations were conducted under the same loading condition as the tests. To evaluate current scaling techniques, the response of one of the randomly picked geometric SS-FE model response was scaled to the others using the mass-based scaling and structure based scaling techniques. The impact force time history was used as the reference curve for the comparison, and the root mean square (RMS) error between scaled responses, model responses, and tests were calculated to quantify the prediction error.

METHODS

First, the template FE model of the femur was developed based on the geometry of the Global Human Body Model Consortium-owned GHBMC M50 Seated Occupant Model (GHBMC) (Figure 1). Next, the geometry of each femur specimen was reconstructed from the computed tomography (CT) data by the segmentation with thresholding method (Hounsfield Unit=500). Given the developed template FE model and the reconstructed subject geometry, 768 control points for morphing were selected using an in-house MATLAB scripts (R2015a, The MathWorks Inc., Natick, MA), focusing on the inner and outer surface shape of the femoral shaft (Figure 1); 19 sections, from the 25%ile to the 75%ile along the longitudinal direction of the femur were selected, and each section had evenly distributed 40 pseudo-landmarks around the outer and inner outlines of the section. Also, eight mathematical landmarks were selected to take into account the proximal and distal region of the femur.

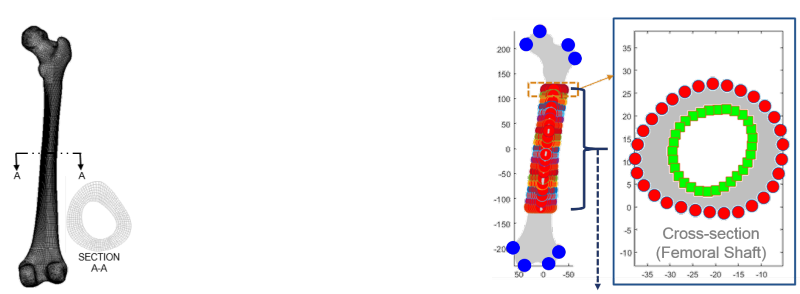

Figure 1: Developed template femur FE model (left) and selection of control points for morphing (right)

Given the selected control points, the geometry of the template femur FE model was mapped to the target subject geometry of each specimen using the morphing technique, implementing a radial basis function with thin-plate spline as a basis function (Rohr, 1996). Finally, using the developed geometric SS-FE models, FE simulations were conducted under the same loading condition as the tests (Figure 2).

Figure 2: Biomechanical tests (left) and FE simulations (right): three-point bending test conducted by Forman et al.

To evaluate current scaling techniques, one of the geometric SS-FE model responses was randomly picked as the baseline model response and that baseline model response was scaled to the others using the mass-based scaling (Eppinger, 1984) and structure based scaling (Nie, 2016) techniques. For mass-based scaling, the scaling factors were derived from the ratio of mass between the target specimen and the baseline model (Eq. 1). This scaled response using the mass-based scaling technique is, hereafter, referred to as "the mass-based scaled response". The scaling factors for structure-based scaling were obtained using the ratio of mid-section area and femur length between the baseline model and target specimen (Eq. 2). This response is referred to as "the structure-based scaled response."

$$\lambda_{\text{force}} = \lambda_{\text{mass}}{}^{2/3}, \qquad \lambda_{\text{time}} = \lambda_{\text{mass}}{}^{1/3} \qquad \textit{E}\text{q. 1}$$

$$\lambda_{\text{force}} = \frac{\lambda_{\text{Area}}{}^{3/2}}{\lambda_{\text{length}}}, \qquad \lambda_{\text{time}} = \lambda_{\text{length}} \qquad \textit{Eq. 2}$$

The linear elastic material model was used for the material model of the femur in this study (Table 1). Since a wide range of elastic modulus of a cortical bone has been reported (McCalden, 1997), material parameter identification was conducted to assign the general material properties to the geometric SS-FE models.

Table 1: Material parameters for the geometric and heterogenized SS-FE models

	Elastic Modulus [GPa]	Poisson's Ratio	Density [kg/mm3]

Geometric SS-FE	15	0.3	2000

The impact force time history was used as the reference curve for the comparison, and the average root mean square (RMS) error between the response of models and that of the test was calculated to quantify the prediction error; the RMS error was calculated until a fracture occurred in the test data. The RMS errors of the baseline response, the mass-based and structure based scaled responses, and the geometric SS-FE model responses were compared to evaluate the structural response prediction capability of the models. Also, a paired Student t-test was performed to check statistical differences between the responses. All model and responses were shifted to match that time zero. All the test and model responses were filtered using the same filter class (CFC180) (SAE, 2003).

RESULTS

The RMS errors between the baseline, mass-based scaled, structure-based scaled, and the geometric SS-FE model responses were compared (Figure 3). The geometric and heterogenized SS-FE models showed a statistically significant ($p < 0.05$) reduction of the RMS error compared to that of baseline models. The mass-based scaled response increased the RMS error compared to the baseline model, while the structure-based scaled response reduces the RMS error.

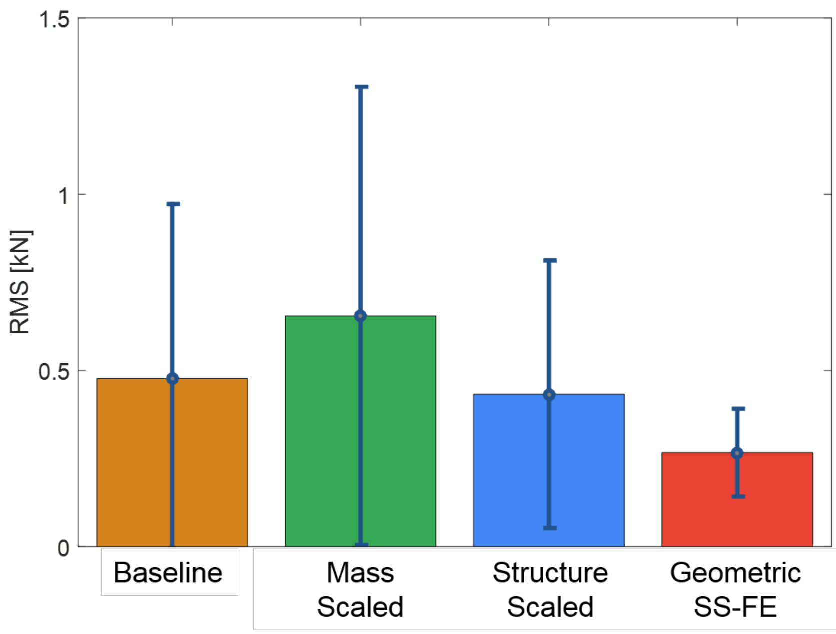

Figure 3 Comparison of structural prediction capability between the responses

Figure 4 compared the impact force time histories between the geometric SS-FE models and PMHS specimens from the tests conducted by Forman et al. The average and the standard deviation of the RMS errors of the geometric SS-FE models for all the 15 cases were 0.16 kN and 0.21 kN, respectively.

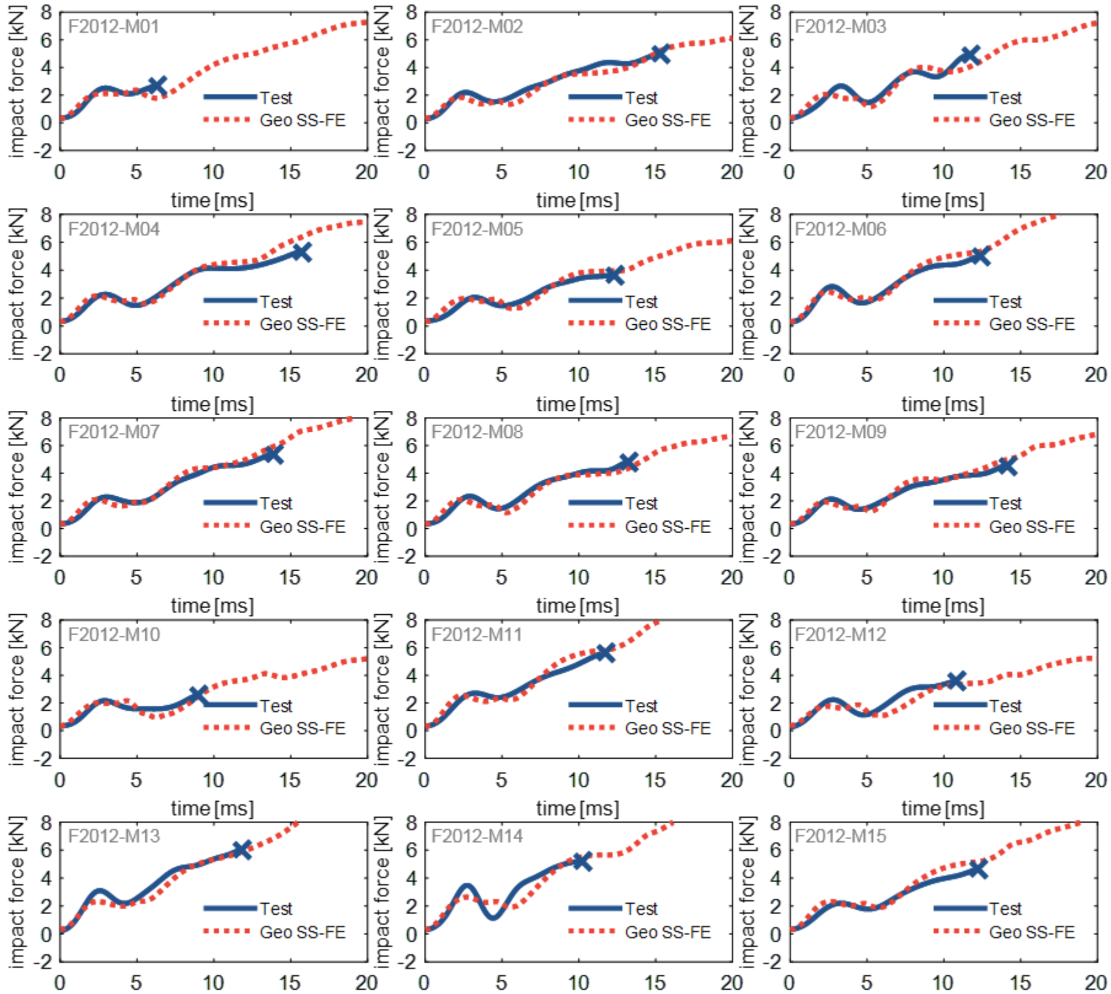

Figure 4 Comparison of impact force time histories between the geometric SS-FE models and PMHS specimen from Forman's test

DISCUSSION

The developed the geometric SS-FE models showed a statistically significant improvement in the prediction capability of structural response compared to the baseline model (Figure 3). This result demonstrated the advantage of incorporating all aspects of geometric variability into the model using the subject-specific modeling over using the baseline model. On the other hand, using the scaled response or scaled models to predict the response of each specimen would not be acceptable. The result showed that the mass-based scaling technique even increased the prediction error (Figure 4). It means that just relying on scaled models, or a scaled response of a baseline model is limited in the ability to capture the complex geometric variability in the human body; at worst, even further from that of using a baseline model.

The reason for increased error in scaled responses might arise from a violation of the fundamental assumption of scaling techniques: geometric similarity. Scaling techniques try to represent complex geometry with one or two parameters with the assumption of geometric similarity. If the geometric similarity is not applicable for femur specimens, those techniques would not be acceptable.

If accurate subject-specific modeling techniques can be developed and validated, this may facilitate the development of parametric statistical FE models that can capture the effects of variabilities throughout the population. Since the responses of developed geometric SS-FE models showed a good correlation with those of the femur specimens, the next step is to develop parametric statistical FE models.

This study aimed at prediction of the structural response of femoral shaft. Thus, the fracture prediction was not taken into account in this study. Prediction of fracture of the femoral shaft or cortical bone would require more detailed information than the prediction of a structural response does. Zioupos (2001) claimed that factors related to the quality of collagen deteriorate with age, and it affects the toughness of cortical bone. On the other hand, those collagen related factors show less correlation with the stiffness of the cortical bone. Hence, to predict the fracture of the femoral shaft, small length scale structure information or an FE model is likely to be required.

In addition, this study needs to be extended to apply to various loading rates, types, and various body regions. It is well known that cortical bone is rate dependent and an anisotropic material. Also, bone has a different structure according to its function in the body. For example, the proximal region of the femur consists of trabecular inside and thin cortical outside to offer stability against compressive force. For different body regions and loading conditions, a different level of model complexity is likely to be required.

CONCLUSIONS

The geometric SS-FE model captured the response variations of the PMHS better than the scaling techniques; mass-based scaling techniques even increased the prediction error. This result suggests a benefit of using geometric SS-FE models to capture the response variance shown from anthropometric variability compared to current scaling techniques.

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