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

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I. INTRODUCTION

Biomechanical response corridors from Post Mortem Human Subjects (PMHSs) are commonly used as the target responses for assessing biofidelity of anthropomorphic test devices (ATDs) and computational models. As the responses from biomechanical test data usually have large variations due to the anthropometric differences and physical characteristics, the first step in developing the target response corridors is to normalize subject responses to a standard size subject using scaling techniques. Although various methods have been proposed and widely used to scale the responses [1-2], the effectiveness of those methods has been questionable [1].

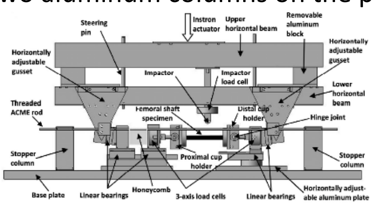
With the recent development of computational technology and the radiology, the subject-specific finite element (FE) modeling has been increasingly employed in the clinical biomechanics field, to predict personalized responses [3-4]. If the subject-specific FE models could capture the inter-subject response variance effectively, in the end, given the target subject information enables us to develop directly the target response corridors from the predicted response from the subject-specific FE models.

The goal of this study was to predict structural responses of the femoral shaft under the dynamic combined (compression and bending) loading condition using the subject-specific FE models and to evaluate the accuracy of a subject-specific FE models to predict the response of the target subject compared to that of the scaling technique.

II. METHODS

Experimental Testing

The biomechanical test responses from three-point femur bending with or without axial compression tests [5] were used as the reference data for the current study. Femoral shafts from PMHSs were subjected to combined loading conditions of axial compression and bending (Fig. 1). The distal and proximal ends of the specimen were potted into cups, and the mid-section of the femoral shaft was loaded with 1 *m/s* rate in either posterior-anterior (PA) or anterior-posterior (AP) direction by an impactor covered by a foam. The constant axial compression was imposed by the geometrical constraint of the text fixture with a honeycomb piece inserted between the two aluminum columns on the proximal side horizontal slider bearing.



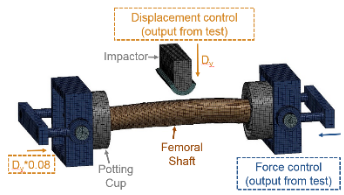


Fig. 1. Schematic of the experimental test set-up (left) [8] and its finite element model (right)

Subject-Specific Finite Element Models

The geometry of each specimen was reconstructed from the computed tomography (CT) data by segmentation using the thresholding method (Hounsfield Unit (HU) = 500). The FE model of each reconstructed geometry was developed using the same number of hexahedral elements. This FE model is referred to as the *homogenized subject-specific (HM-SS)* models. The material model 'MAT124_plasticity_compression_tension' in LS-DYNA was used. Only elastic property of the model was considered for the purpose of prediction of structural response (E_t = 8 *GPa* and E_c = 10 *GPa* were assigned for all specimens which were optimized to give the best prediction results). Also, the *heterogenized subject-specific (HT-SS)* models were developed by mapping the HU scale from the CT data to each element of the FE model. The relationship between HU and the density of

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bone as well as the empirical relationship between the bone density and the Young's modulus has been established [6]. The different Young's moduli were assigned to elements depending on the HU scales based on the relationships among HU, bone density, and Young's modulus. Each element searched the voxels inside its volume from CT data, and an average HU value of those voxels was used for assigning the Young's modulus to each element. Finally, the template FE model was developed based on the geometry of the Global Human Body Model Consortium owned GHBMC M50 Seated Occupant Model (GHBMC), and the response of the template model was scaled to each subject using the mass-based scaling technique [2]. This scaled template model response is referred to as the *scaled* model.

The impact force time histories of the scaled, HM-SS, and HT-SS models were compared to the PMHS responses from the biomechanical test. In total, twelve different subject responses were used for the comparison.

III. INITIAL FINDINGS

Fig. 2 shows the result of HU mapping for the HT-SS model from one of the subjects. On average, the HU mapping gave less than 5% error regarding area and moment of inertia of mid-section along the longitudinal direction of the femoral shaft. In general, the models were able to capture time histories of impact forces until fractures; Fig. 3 shows the comparison of impact force time histories of two of the subjects, the subject information of two cases is presented in TABLE II. The HM-SS and HT-SS model showed less prediction error (defined as the root mean square error in impact force time history between the model and the PMHS) than that of the scaled model (TABLE I).

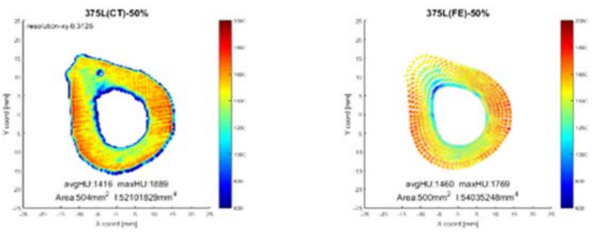

Fig. 2. Results of HU mapping in mid-section for HT-SS model (375L): HU distribution from CT scan (left), heterogenized FE model (right).

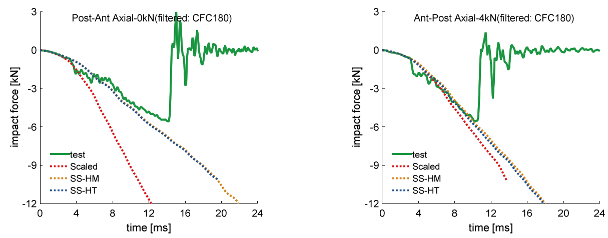

Fig. 3. Comparison of impact force time histories from two of the subjects: 392R(left), 375L(right)

TABLE I

SUMMARY OF RESULTS: ROOT MEAN SQUARE ERROR IN RESPONSE PREDICTION

	Scaled Response	HM-SS	HT-SS
Average (1 STD)	0.70 (0.76)	0.48 (0.24)	0.43 (0.24)

TABLE II

SUBJECT INFORMATION FOR TWO SUBJECTS IN FIG.3

	Age	Gender	Height [cm]	Weight [kg]	Mid-section Area [mm^2]	Mid-section Avg. HU
379R	58	M	182.9	141	619	1488
375L	59	M	177.8	81.8	504	1416

IV. DISCUSSION

The subject-specific FE models captured the response variations of the PMHS better than the mass-based scaling technique (TABLE I). This result implies that the benefit of the subject-specific FE modelling for predicting the responses of a target subject instead of relying on the scaling methods.

The empirical relationship between the mechanical property and the bone density, in general, shows large variance among references and the relationship could be further optimiszed in additional studies. The effect of heterogeneity on the structural response prediction was not significant for the considered loading condition (TABLE I). Further analysis needs to be done on the effect of heterogeneity on fracture responses.

V. References

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