A Parametric Skeleton Model of Human Upper Extremities Accounting for Morphological Variations Among the Diverse Population

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Objective: To develop parametric skeleton models of human upper extremities, including the humerus and clavicle, and investigate morphological variations, specifically the effects of age, stature, sex, and BMI, on those skeletal geometries.

Problem to be solved: Based on CIREN data, ~25% of motor-vehicle crash injuries are upper extremity-related, and upper extremity injuries are common in vulnerable road users, such as bicyclists and motorcyclists. However, the current safety regulations and consumer information crash tests have not yet considered upper extremity injuries. Virtual testing using human body models (HBMs) may provide opportunities to consider upper extremity injuries in the safety design evaluation process, and parametric HBM representing the morphological and biomechanical variations of the population may further enhance safety equity among the diverse population. However, to the best of our knowledge, a parametric upper extremity skeleton model is not yet available, limiting the capability of HBMs to evaluate the variations of upper extremity injuries in motor-vehicle crashes.

Methodology: Computed Tomography (CT) scans of the upper extremities were obtained from the University of Michigan Health System following protocol approved by the University of Michigan Institutional Review Board (HUM00004842). The 3D skeletal geometry of the right humerus and clavicle were extracted from CT scans using Mimics. Anatomical features were identified using landmarks in Hypermesh. A template mesh of the humerus and clavicle of a midsize male was mapped onto the segmented skeletal geometries for each subject using previously developed mesh morphing and projection methods. The resulting homologous meshes were analyzed using Generalized Procrustes Analysis (GPA) and Principal Component Analysis (PCA) to illustrate the morphological variations among the population for each bone. Multivariate regression analyses were performed to identify the associations between subject covariates (age, stature, sex, BMI, bone length) and PC scores of each bone, so that for a given set of subject covariates the 3D geometries of the upper extremity geometry can be predicted.

Data to be included: The study population consisted of 105 patient CT scans. 55.2% were female (n=58), and mean age was 40.8 (SD=13.2).

Preliminary Results: The statistical humeral model (n=89) accounts for 66% of morphological variations in bone geometry (R^2=0.38), and the clavicular model (n=58) accounts for 62% of morphological variations (R^2=0.26). Top 3 PC scores in the humeral model represent cross-sectional area, shape of the proximal and distal ends, and curvature along the deltoid tuberosity. Top 3 PC scores in the clavicular model represent length, curvature along the subclavian groove, and cross-sectional area. There is a statistically significant association between sex and humeral length ($p<0.05$) and sex and clavicular length ($p<0.05$).

Conclusions: This study identified a methodology for creating robust statistical geometry models of the upper extremity skeleton. The models developed could serve as a geometrical basis for future development of parametric HBMs for upper extremity injury assessment representing a diverse population. Future research will focus on improving model accuracy, exploring the effects of interactions between subject covariates and upper-extremity bone geometry, and incorporating the scapula to develop a complete model of the upper extremities.