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A parametric ribcage geometry model accounting for variations among the adult population

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ABSTRACT

The objective of this study is to develop a parametric ribcage model that can account for morphological variations among the adult population. Ribcage geometries, including 12 pair of ribs, sternum, and thoracic spine, were collected from CT scans of 101 adult subjects through image segmentation, landmark identification (1016 for each subject), symmetry adjustment, and template mesh mapping (26,180 elements for each subject). Generalized procrustes analysis (GPA), principal component analysis (PCA), and regression analysis were used to develop a parametric ribcage model, which can predict nodal locations of the template mesh according to age, sex, height, and body mass index (BMI). Two regression models, a quadratic model for estimating the ribcage size and a linear model for estimating the ribcage shape, were developed. The results showed that the ribcage size was dominated by the height ($p=0.000$) and age–sex-interaction ($p=0.007$) and the ribcage shape was significantly affected by the age ($p=0.0005$), sex ($p=0.0002$), height ($p=0.0064$) and BMI ($p=0.0000$). Along with proper assignment of cortical bone thickness, material properties and failure properties, this parametric ribcage model can directly serve as the mesh of finite element ribcage models for quantifying effects of human characteristics on thoracic injury risks.

1. Introduction

Crash injury data analyses have shown that thoracic injuries are the second leading cause of fatalities and severe injuries in motor vehicle crashes (MVCs), and the risks of thoracic injuries are significantly associated with occupant characteristics, such as age, sex, height, and body mass index (BMI), a parameter measuring the obesity level.

As age increases, the human thorax experiences both morphological changes and material property changes (Gayzik et al., 2006, 2008; Kent et al., 2005). Field data analyses, computer simulations and cadaver tests have all shown that the incidence of AIS 2+ thoracic injuries increased with age (Carter et al., 2014; Ridella et al., 2012; Zhou et al., 1996). The risk of ribcage injuries in crashes also differs significantly between men an women (Bellemare et al., 2003; Cerney and Adams, 2004; Kimpara et al., 2005; Kindig et al., 2010). In particular, the risk of being seriously injured in crashes is higher for women than men (Bose et al., 2011; Parenteau et al., 2013), and the increase of thoracic injury risk with age is greater for women than men (Carter et al., 2014; Parenteau et al., 2013; Ridella et al., 2012). In addition, obese occupants are at increased risk of thoracic injuries compared with non-obese (Cormier, 2008; Forman et al., 2009a, 2009b; Shi et al., 2015; Turkovich, 2011).

Morphological variations in the human ribcage, such as the shape, size and cortical bone thickness, as well as the material and failure properties of the ribcage, are expected to affect the impact response and injury tolerance of the thorax, especially among vulnerable populations such as the elderly, women, and the obese. These variations in ribcage geometry could be evaluated through statistical shape analysis (SSA), a common technique to assess the size and shape variations in human skeleton and organs, such as femur (Bredbenner and Nicolella, 2008; Bryan et al., 2009; Zhu and Li, 2011), tibia (Baka et al., 2014; Bredbenner et al., 2010), liver

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(Lamecker et al., 2004; Lu and Untaroiu, 2014) and spleen (Yates et al., 2016). Gayzik et al. (2008) quantified the age-related shape change of human ribcage using rib landmarks through morphometric and multivariate regressions. Weaver et al. (2014a, 2014b) analyzed a larger set of landmarks on the ribcage obtained from analysis of CT scans from 339 subjects aged 0–100 years. The size and shape of all the ribs and sternum were significantly affected by age in both male and female. Based on CT scans from 89 adult subjects, Shi et al. (2014) developed a statistical model to predict ribcage geometry accounting for age, sex, height and BMI using principal component analysis (PCA) and regression.

To improve the model reported by Shi et al. (2014) and allow the ribcage geometry model to be used directly for assessing the effect of morphological variation on chest injury risk, the objective of this study is to build a parametric ribcage model accounting for the age, sex, height, and BMI effects on the ribcage morphology, including all 24 ribs, sternum, and thoracic spine.

2. Methods

Anonymous clinical ribcage CT scans ($n=101$) were obtained from University of Michigan Health System using a protocol approved by an institutional review board at the University of Michigan. All subjects were adult female ($n=47$) or male ($n=54$) patients without skeletal pathology. The age, sex, height and BMI distributions of the subjects are shown in Fig. 1. Except the high correlation between the height and sex, no significant correlation was found among these four parameters.

Fig. 2 shows the overview of the method for developing the parametric ribcage model accounting for morphological variations among the adult population. First, the ribcage geometry for each subject was collected through a series of image analyses, including threshold-based image segmentation, landmark identification on each rib, sternum and spine, landmark re-processing through B-spline, and landmark symmetry adjustment. After the landmarks were identified, a template ribcage finite element (FE) model from Total Human Model for Safety (THUMS) version 4.01 (Hayashi et al., 2008; Iwamoto et al., 2002) was morphed into the geometry of each subject using a mesh morphing method. The ribcage model of THUMS, including 24 ribs, sternum and the thoracic spine, consists of 26,180 shell elements and 26,139 nodes. Generalized procrustes analysis (GPA), PCA, and regression analyses were then used to develop a parametric model that used age, height, BMI and sex to predict nodal locations of the FE ribcage mesh.

2.1. Landmark identification

All the CT data were collected using a resolution of 512×512 pixels with 1.25 mm between slices. Selected scans were imported into Mimics (Materialise, Plymouth, MI) for image segmentation. A semi-automated threshold method was used to segment the thoracic skeleton, including the 24 ribs, the sternum, and the thoracic vertebrae from the CT scans.

Landmarks were collected at ten cross-sections along each of the 24 ribs for each subject. Four landmarks were identified on each cross-section following the method used by Shi et al. (2014). To ensure the cross-sections being evenly distributed along the rib, B-spline interpolation was used to generate curves along the rib top and bottom ridges, and these curves were divided equally into nine segments with ten cross-sections. As a result, 960 (40×24) landmarks were identified on the ribs. For the sternum, a pair of landmarks were identified at each sternocostal joint and sternoclavicular joint, which resulted in 32 landmarks on the sternum. Two landmarks were identified at the tips of the spinal process on each of the T1–T12 vertebrae. As a result, a total of 1016 landmarks on the ribcage, including 960 landmarks on the ribs, 32 landmarks on the sternum and 24 landmarks on the spine, were identified for each subject. Fig. 2 shows an example of identified landmarks on the ribs, sternum, and thoracic spine.

2.2. Spine lateral curvature adjustment

In general, the landmarks identified from each subject were not perfectly symmetric due to the spine lateral curvature and the biological difference between the two sides of the ribs. Relative speaking, the spine lateral curvature generated much greater differences between the left and right sides of the ribcage than the biological differences between the corresponding ribs on the two sides. The spine lateral curvature also varied significantly among subjects, which introduced errors/variations that are unrelated to the subject age, sex, stature, and BMI. Therefore, in this study, we adjusted the spine lateral curvature, so that the two sides of the ribcage are symmetric in terms of the rib positions. In addition, with the goal of building parametric FE models, a symmetric model was also developed for each subject by averaging the rib geometries

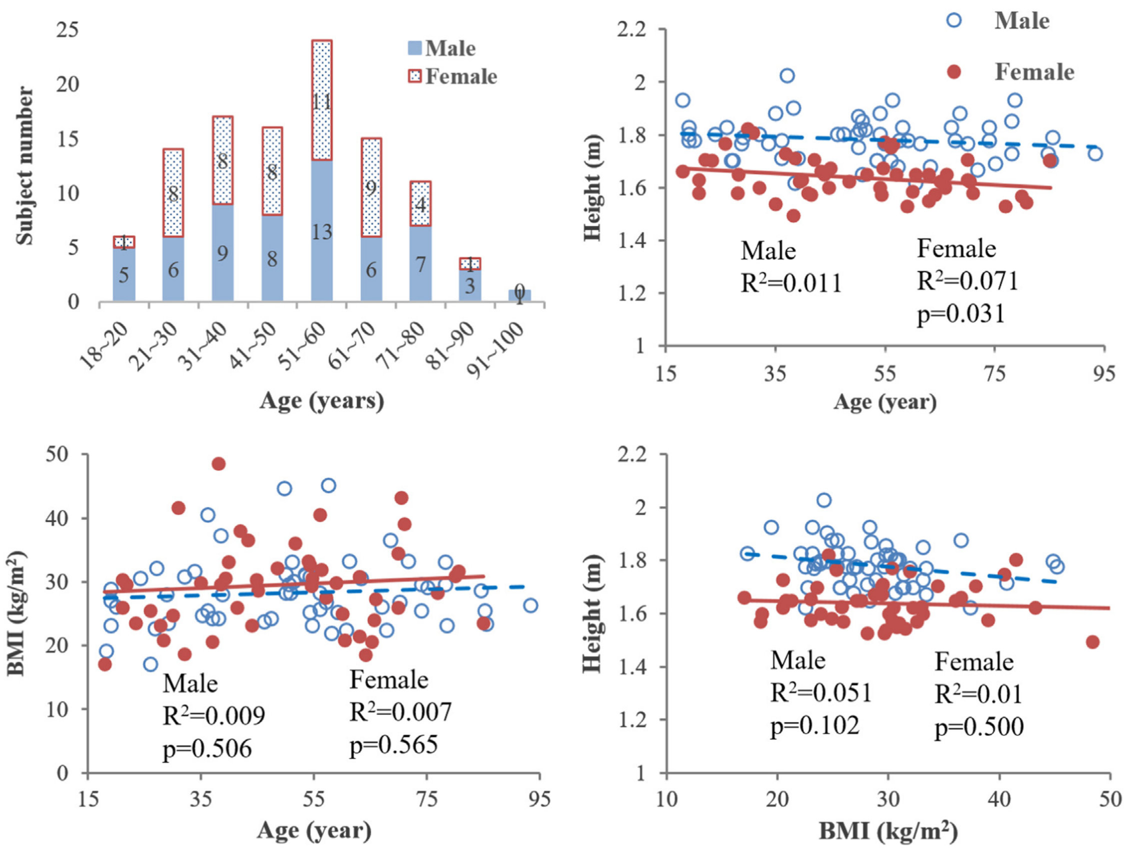

Fig. 1. Age, sex, height and BMI distributions of all sampled subjects.

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