6

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A Finite Element Study of Age-based Size and Shape Variation of the Human Rib Cage

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ABSTRACT

To fully understand the effects of aging on the integrity of the normal skeleton, detailed geometric models are needed to complement material property data. The purpose of this research is to develop a predictive model for age-related changes in rib-cage geometry using the generalized Procrustes approach, an advanced method of shape analysis. This predictive model is coupled with the finite element method to isolate the effects age-related size and shape change have on the structural response of the rib cage. Using a relatively small sample set (n=12), trends in the age-related size and shape change of the human thorax consistent with clinical observations are identified. Finite element models constructed from landmark datasets generated via the generalized Procrustes approach demonstrate a decrease with age in the energy absorbing capacity of the thorax during a blunt impact.

INTRODUCTION

The normal aging process is associated with a number of well-documented skeletal changes that can negatively impact quality of life, and increase susceptibility to disease and trauma. Of particular interest is how age-related size and shape change of the human thorax relates to clinical outcomes following trauma. The increase in the size of the elderly population has raised questions on the safety of elderly motor vehicle occupants. The chest is the most commonly injured body region in fatal frontal impacts of drivers over the age of 64 (Kent, Lee et al., 2005), and rib fractures were the most serious injury sustained by 40% of patients over 60 who died of chest injuries following an automobile crash. This shift in population demographics, coupled with a higher susceptibility to thoracic trauma with age motivates a better understanding of age-related changes in thoracic biomechanics.

Bone mineral density, elasticity, and energy absorbing capacity all decline with age (Frost, 1997; Zioupos and Currey, 1998). However the mechanical properties of bone are determined not just by material characteristics, but also by geometry. For a particular mode and rate of loading, the strength of a bone is a product of (1) shape and size, and (2) the strength or stiffness of the material within (Martin, 1991). An unresolved question is to what extent mechanical characteristics of bone versus overall geometry affect skeletal strength of the rib cage. It is known that the large-scale geometric structure of the rib cage is influenced by age and factors such as sex and disease state (Bellemare, Cordeau et al., 2001; Bellemare, Jeanneret et al., 2003); yet this has not been well quantified.

We developed a predictive model for age-related changes in rib-cage geometry using an advanced method of shape analysis known as the Procrustes method. This method is based on direct analysis of landmark coordinates and has been used extensively in anthropology to study size and shape differences between populations of people (Rohlf and Slice 1990; Slice and Stitzel, 2004). A landmark is a physical location common in each individual in a shape analysis study. The Cartesian coordinates of anatomical landmarks (in two or three dimensions) encode all of the distances, angles, or ratios that could be defined using those landmarks. The Procrustes method can be used to create a function from landmark coordinates which describes where in space a landmark is located based on an extrinsic variable, such as age. We have coupled this technique with the finite element method to isolate and analyze the effect age-related size and shape changes have on the structural response of the rib cage.

METHODS

The methods are presented in two parts, the first describing the shape change analysis, and the second describing the accompanying finite element analysis.

Age-Related Shape Change Analysis

Landmark coordinate data were collected to characterize a portion of ribcage geometry. The data were then subjected to a generalized Procrustes analysis (GPA) and a regression of size and shape on to age. The coordinates were obtained from twelve recent clinical chest and abdominal CTs using Analyze (Biomedical Imaging Resource, Minneapolis, MN). All individuals were males from 20 to 78, without skeletal pathology. The coordinates of five landmarks were recorded for each individual for each of the first seven right ribs. The landmarks were the most posterior point of contact at the costovertebral joint, the most posterior point on the rib shaft, the most lateral point on the shaft, the most anterior point of the attachment of the rib to the costal cartilage, and the most anterior point of attachment of the costal cartilage to the sternum. The total sample included 35 landmarks for each individual. Points of attachment were located by stepping through the CT volume from a superior perspective until the attachment point was first visible. Posterior/lateral points were located by moving through the volume until the visible segment of the rib was at its most extreme position. Each landmark is identified by an x,y,z coordinate triplet. A lateral view of the landmarks is illustrated in Figure 1.

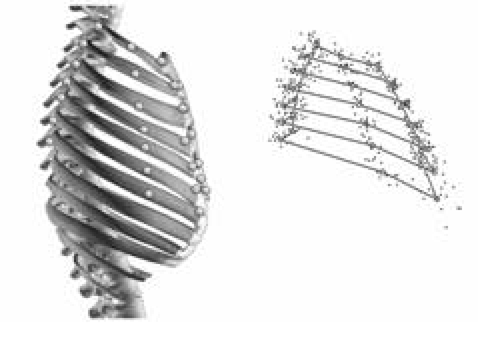

Figure 1: Landmark points shown for geometric model development (left) and superimposed landmark points from CT scans (right).

If two data sets consisting of p landmarks are organized into [px3] matrices X_1 and X_2, their geometric relationship can be described mathematically in Equation 1 (Slice and Stitzel, 2004; 2005).

$$r(X_2 - 1t)H = X_1 + E \quad (1), \qquad (X_2 - 1t)H = r^{-1}(X_1 + E) \quad (2)$$

Here, t is a translation vector, H is a rotation matrix, and r is an isometric scaling factor. Each of these variables represents an operation performed on the landmark datasets to isolate real shape differences, E. The translation moves the average coordinate location of the landmarks in a set to a common origin, the rotation matrix rotates each point set rigidly about the origin so that datasets are in least squares agreement and the scaling is a dilatation or compression of the dataset. What remains is *E*, which is the real shape difference between X_1 and X_2. If data sets are translated and rotated, they should then reflect both size and shape differences, as shown in Equation 2. This scenario is used in this study.

The landmark datasets are used to look for age-related changes of a geometric measure, T1 through T7 height. A second analysis uses a multivariate regression technique to regress landmark location onto age. The resulting function gives the location of the 35 landmark coordinates as a function of age; effectively describing a ribcage of a normal male at that age. The coordinate data were processed using the program *Morpheus et al*. (Slice, 1998).

Finite element model development

Finite element model construction employed the landmark sets generated from the multivariate regression analysis. We employed data representing three males ages 20, 50, and 80 years-old. Model generation was performed using two preprocessor applications, FEMB (Finite Element Model Builder, Engineering Associates, Troy, MI) and LS-PrePost (Livermore Software Technology Corporation, Livermore, CA). Individual landmarks were connected along both the posterior to anterior directions and the superior to inferior directions using splines, Figure 2B. Sagittal and transverse dimensions of each rib at each landmark coordinate, as well as material properties were taken from the Total Human Model for Safety (THUMS, Toyota Central R&D Labs, Inc.). The number of shell elements employed along the costal cartilage and the ribs were the same for each of the age models, Figure 2C. Shells were projected inward creating solid elements, which were then mirrored about the sagittal midplane. The sternum was modeled with solid elements. All the elements representing bone were coated with shell elements to model cortical bone (shells) surrounding cancellous bone (solids). The posterior-most nodes at the costovertebral junction were locked. A 23.4 kg impactor was placed 0.3 mm away from the midline node between the 4th and 5th rib, and rotated parallel to the sternum. A summary of model parameters is shown in Table 1. Impacts were simulated at 3.4 m/s using LS-Dyna finite element software (Livermore Software Technology Corporation, Livermore, CA). Contact force and nodal displacement data were filtered to 60 Hz using the SAE J211 standard filter in Matlab (The Math Works, Natick, MA). Total amount of energy absorbed during the impact was calculated from force versus displacement data.

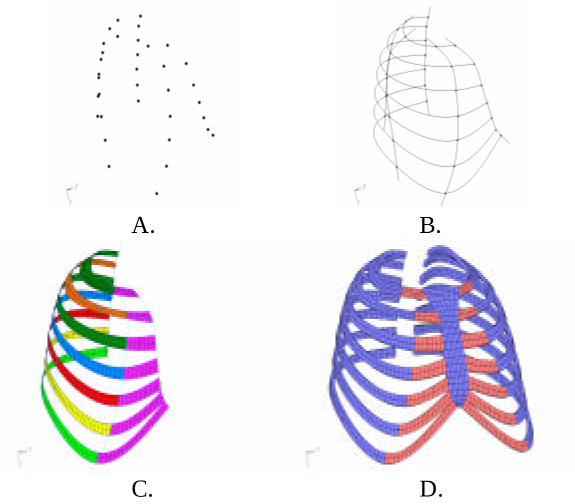

Figure 2: Finite element model development. A. Nodes imported from GPA, B. Splines outlining nodes, C. Shells of each rib, D. Model is mirrored and solids added. Solids representing bone are coated with shells (not shown).

Table 1. Finite element model parameter summary.

Structure	Bone Type	Section	? (kg/m^3)	E (MPa)	?
Rib	Cancellous	Solid	862	4.00x10^1	0.450
	Cortical	Shell	2000	1.02x10^4	0.306
Sternum	Cancellous	Solid	862	4.00x10^1	0.450
	Cortical	Shell	2000	1.15x10^4	0.301
Cartilage	-	Solid	1000	4.90x10^1	0.400

RESULTS

Age-related shape change analysis

The data resulting from the GPA was used to determine if significant geometric changes with age could be discerned. Figure 3 shows the results for the T1-T7 height study. Regression of vertebral height onto age using all data is not significant (p=0.65) even disregarding the outlying fifty year old (p=0.61). Separately regressing size onto age for individuals under fifty and those over fifty (omitting the fifty year old) results in a mildly statistically significant regression for the younger group (p=0.09, R2=0.68) and a significant regression for the older group (p=0.03, R2=0.72).

To model age-related effects on geometry of the rib cage, the landmark sets were regressed onto age of the individual. In Figure 4, predicted three-dimensional configurations are shown for 20, 50, and 80 year old individuals. The arrows show the path of each landmark from its position on the 20 year old, identifying a clear change in the shape of the structure with increasing age.

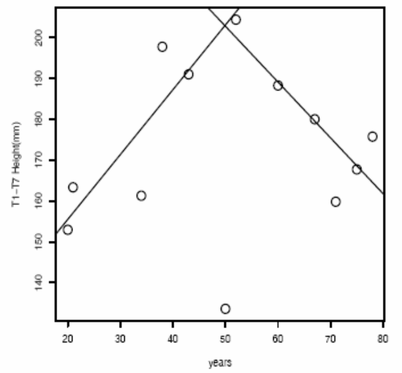

Figure 3: T1-T7 height versus age showing separate regressions of size onto age for younger (age < 50) and older (age > 50) individuals.

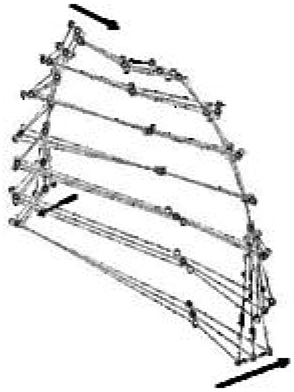

Figure 4: 20, 50 and 80 year-old landmark node sets generated from the regression of size and shape on age. Arrows indicate the direction of motion of a landmark.

Finite element model

The results of the finite element analysis are summarized in Figure 5 through Figure 7. Figure 5 shows force versus normalized displacement of the sternum. Displacement was normalized based on the distance from the point used to center the impactor and a point midway between the posterior and inferior-most nodes of the 7th rib. The maximum contact force produced throughout the impact as well as the energy is shown in Figure 6. Figure 7 shows chest displacement.

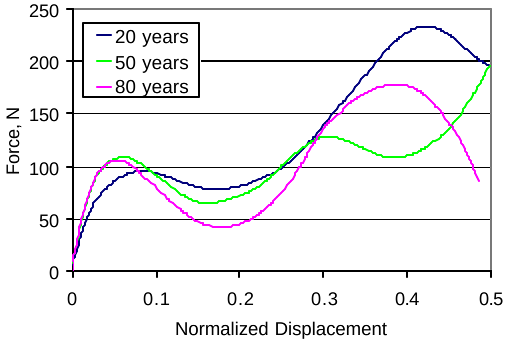

Figure 5: Force vs. Normalized displacement for each of the generated rib cage models.

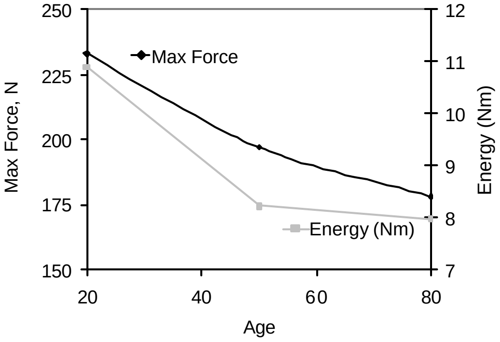

Figure 6: Max force registered during impact (right axes) and total energy absorbed (left axes) during the impact simulations for all three age groups.

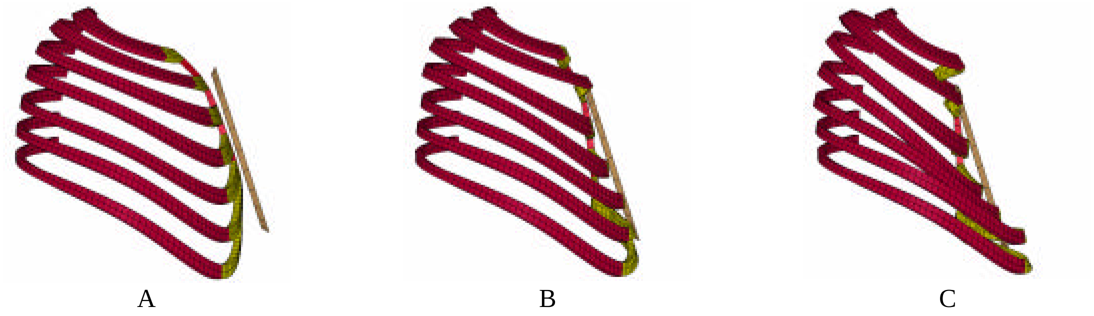

Figure 7: Progression of impact simulation, 20 year old rib cage. (A) time = 0, (B) 20% chest compression, (C) 40% chest compression.

CONCLUSIONS

Age-related shape change analysis

Statistically significant and clinically relevant findings can be drawn from the GPA incorporating a relatively small sample size (n=12). The analysis of T1-T7 height vs. age demonstrated a mild significance for the younger age group (age<50) and a significant relationship (p=0.03) for the older age group (age>50). The general trend shows that this measure increases until age 50, and afterwards begins to decrease. The outlier at age 50, may be a result of the nature of this study. Landmark sets were translated and rotated to minimize least squares error between coordinates, but were not scaled. This outlier may have shown greater agreement with this trend if scale were included in the GPA. Gender, age and absence of skeletal pathology were considered when selecting individuals for the study. Scaling the individuals to minimize least squares error of each landmark coordinate may remove differences occurring due to factors such as differences in weight and individual health. Such research is reserved for later studies. Trends continue to emerge when looking at more than a single metric. Referring to Figure 4, the vectors describing the motion of an individual landmark, especially on the anterior of the sixth and seventh rib are suggestive of the posteroanterior increase in this dimension associated with age. Vectors describing the motion of the landmarks at the costovertebral junction are suggestive of kyphosis. Furthermore, the vectors at the lateral most points (though not apparent in this view) indicated a reduction in lateral dimension also found to be associated with aging (Bellemare, Cordeau et al., 2001). Together these could describe the development of the “barrel chest” often observed in elderly individuals.

Finite element analysis

Age-related trends are evident in the finite element analysis results as well. While it is known that age plays a role in changes in the material properties of the cartilage and bone comprising the rib cage (Stitzel, Cormier et al., 2003; Kemper, McNally et al., 2005), the results of this finite element study are meant to isolate the effects of size and shape differences only. Figure 6 shows both the maximum force generated throughout the impact as well as the total energy absorbed by the rib cage decrease with age.

When exploring the mechanical behavior of any skeletal component, it is important to acknowledge the material properties and the geometry of the structure as separate entities. Additionally, it should be made clear whether the results of a particular study are analyzing one or the other, or if the measured quantities are really a product of both. In the majority of the literature devoted to car crashes the strength of the bone being measured is a product of both the geometry of the specimens and the materials within them, i.e., the cortical and cancellous bone. This research demonstrates the ability to generate predictive models of the human thorax from a relatively small sample size that isolate how the size and shape of the rib cage affects its mechanical response.

Other methods have been published to study the geometry of the human thorax employing medical imaging modalities. A stereoradiographic method was presented where points are digitized from plain film x-rays in 2 dimensions and lined up via a direct linear transformation (Dansereau and Stokes, 1988). Measurements in this case were taken directly from the xray film. Research has also been conducted studying rib angle change with age, measuring the rib angle directly from a two-dimensional screen capture of a full three-dimensional reconstruction (Kent, Lee et al., 2005). While statistically significant change in rib angle was detected in the latter study, the sample size used was much larger than the present study (n=152 vs. n=12). Rib angle measurement, which was given relative to table position, was not presented in terms of overall shape change, as rib angle relative to table position is not an intrinsic shape measurement. In both of these techniques the amount of data that can be drawn from the study is limited since one or two geometric measures were recorded in each case. The GPA is a powerful alternative to this practice since each landmark dataset preserves all the geometric measures which can be taken between them. While this study only took 5 landmarks per rib, there is no limitation on the number of landmarks one wishes to include in the set.

There are some limitations of the present work. In an effort to demonstrate the capability of the GPA while preserving the true geometry of the rib cage, this analysis was performed preserving size and shape of the landmark data. Future studies will be conducted eliminating the question of size by applying the univariate scale factor r (Equations 1 and 2). This scale factor will further minimize the least squares difference between landmarks via either a bulk dilatation or compression of the dataset about the centroid. Such scaling should mitigate differences between individuals owing to frame size and may eliminate the presence of outliers as seen in Figure 3. The finite element model lacks thoracic viscera and musculature; however this study is intended to demonstrate the feasibility of the technique. Future studies will also include greater sample sizes to provide more confidence in the accuracy of the trends isolated by the GPA. However, these limitations aside, this study illustrates the power of the GPA to develop better predictive models of how the architecture of the human thorax changes with age. This method ultimately can be extended to account for variation and changes to any level of detail and include factors such as gender, size and other variables.

A novel approach to the analysis of the age-related size and shape change of the human thorax is presented. The generalized Procrustes method is used to quantify age-related changes in the size and shape of the human thorax. Finite element models constructed from the shape change analysis results demonstrate a decrease with age in the peak force resisting compression and the amount of energy absorbed during a blunt impact.

ACKNOWLEDGEMENTS

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DISCUSSION

PAPER: ***A Finite Element Study of Age-based Size and Shape Variation of the Human Rib Cage***

PRESENTER: ***Scott Gayzik, Wake Forest University School of Medicine, Virginia Tech – Wake Forest Center for Injury Biomechanics and Institute of Anthropometry, University of Vienna***

QUESTION: *Guy Nusholtz, Daimler Chrysler*
Did you do any statistical tests on the differences? I noticed you had a lot of scatter from your data. Is all the differences that you see the migration, in terms of motion of points, statistically significant? That's one and the second part of that is: Did you look at the distributions and are they the same regardless of age? In other words, is there as much variation at 20 years old as there is at 50 and 80 years old?

ANSWER: I have done or looked at the variation in age. As far as statistically, you're asking about whether or not there are, because of the scatter, if you can actually look at differences between, like, a 20 year-old and a 50 year-old and find that there is actually a statistically significant difference between those landmarks?

Q: That's the first part of the question.

A: For this study, there were 12 individuals of age and we used Procrustes analysis to develop a spline to fit, to develop a function based on age for where those points were in age. So I guess the answer to your question is really only one individual at each age so that would not be—You can't say, like, "Okay. Take all the 20 year-olds and see what the scatter is."

Q: The obvious point, the obvious question, then, is how do you know it's not just due to variation between individuals and a function of age? If you only got one point, one point at each thing, how do you know it's age? I mean it could be something else. I mean, you can think about that for a while.

A: Okay.

Q: The second issue is: You're only looking at geometry and material changes.

A: Right.

Q: Which could be much more dominant so whatever you get from the geometry could be easily swamped out by whether there were material changes.

A: That's a point that's well taken. We understand, but the purpose of this study was really to look and see if we could isolate, first of all, use this method, which wasn't previously used in automotive safety research. It's actually a method that was developed for anthropology sort of track changes, evolutionary changes between people to use a new method to sort to quantify shape change and to make more biofidelic models based on age. So—

Q: I think the only thing there is you have to deal with human variability before you start attributing to a single variable.

A: Right, but we wanted to, you know, keeping everything the same and changing only shape, could we show any differences?

Q: Okay. Thank you.

Q: *Richard Kent, University of Virginia*
This is a really great presentation and extremely elegant method. One question: Did you look at, sort of, the obesity range of your folks, your subjects?

A: We did not and again, I think that goes back to the limitations of how many subjects we had. And, this is really kind of like a preliminary look to see if this could be done across an age range, but that would be interesting and obviously that's gonna change because of bone remodeling based on weight that a 20 year-old who's, you know, a certain stature is gonna be different than a 20 year-old who could be morbidly obese.

Q: Yeah.

A: That's definitely something to think about.

Q: Okay. Yeah, I love the technique. Maybe a word of caution as you move forward: We did a similar thing maybe, you know, we've looked at 160 CTs now and just looking at one parameter, which is the angle of the 7th rib in a lateral plane, and it's hard to pick it out in age. It's there, but it's subtle. I see about maybe, like, 7° from age 18 to 85. And so, to say you have an age effect here, again, I sort of would agree with Guy that maybe but probably not. But like I said, about 160, we're seeing it I think and so there is huge variability. But in terms of applying this technique, kudos! I think this is a really great idea.

A: Thanks.

Q: So thanks.