Average male and female rib cross-sectional shapes via PCA

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I. INTRODUCTION

Over the last several decades, fatalities per driven mile have been steadily decreasing due to modern vehicle safety advances, yet the thorax has remained consistent as the most injured region in motor vehicle crashes (MVCs) [1]. The ribs are structurally important under all forms of thoracic loading and rib fractures make up the most common type of thoracic injury [2,3].

Human body models (HBMs) are increasingly used throughout the vehicle safety field to understand the biomechanics of the chest under loading. As such, it is important that these tools are as accurate as possible, particularly within key mechanical components like the ribs. Geometry defined in common HBMs in current use has generally been developed via 3D segmentation of a chosen subject's computed tomography (CT) scan, followed by various processes to transform this data into a 3D finite element mesh. Overall adult rib shapes are many centimeters in size and are generally captured faithfully by such processes. For smaller structures like rib cross-sections, however, mesh size choices and original geometry acquisition constraints can lead to differences between the final HBM cross-sectional shape and that of the actual underlying subject.

Rib cross-sectional size and shape differs not only between different ribs of the same subject, but it also changes along the length of a rib. While these changes in shape are often described graphically or qualitatively, there is currently no definitive source for typical rib cross-sectional geometry which might be used for the development of human rib FE meshing.

Here we present a method to define such a source by calculating a geometric average from across multiple ribs within a sample population. The population is a set of ex-vivo 6th ribs which have previously had their periosteal borders identified using a Cortical Bone Mapping (CBM) technique validated against high resolution histology images [4]. Here, we further perform a shape-based principal component analysis on the cross-sectional geometry of these ribs, and interpret the result to reproduce statistically average male and female cross-sectional rib geometry.

II. METHODS

Study population and prior work

A set of 33 sixth ribs were obtained from anatomical donors in Ohio, USA. The 16 male and 17 female ribs were harvested and underwent computed tomography (CT) scanning at an axial resolution of 0.15 mm per pixel with slice spacing of 0.67 mm per pixel. The periosteal surfaces of each rib were obtained using threshold-based techniques, and these surfaces were refined using a cortical bone mapping (CBM) methodology implemented in MATLAB. The CBM technique was validated [4] to reproduce cross-sectional area within 5%.

Cross-sectional geometry pre-processing

The resulting surface was digitized into 300 successive rings of 80 coordinates, with each ring representing the geometry of a single cross-sectional rib shape. Cutaneous, pleural, inferior, and superior rib aspects were positioned at the intersections between each cross-sectional shape and its primary and secondary inertial axes, with smoothing applied along each rib so as to improve continuity of these directions along each rib's length. The 80 points were aligned to these rib aspects, with 20 points equally spaced in each quadrant of the rib's cross-sectional shape.

This produced 9900 individual 2D cross-sectional shapes (300 shapes along 33 ribs). All shapes were offset such that their centroid lay coincident with the origin. All shapes were then rotated so as to maximize the absolute Y-coordinates of the inferior and superior aspect points and the absolute X-coordinates of the cutaneous and pleural coordinates.

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Cross-sectional shape PCA

Principal component analysis (PCA) was then performed using the X- and Y-coordinates from each cross-sectional shape observation as features (160 features from 80 XY coordinate pairs). In general, shape-based PCA reduces this large feature space down to a more manageable set of principal components (PCs) that still encapsulate the spatial variation (in XY coordinate positions) seen in the collection of original shapes. Here, we have explored the geometric effect of each principal component (PC1, PC2, etc.) in two ways.

Firstly, we highlight the differences in cross-sectional rib shape obtained when an average shape is varied by between -3 and +3 standard deviations along that component's direction. Secondly, profiles of PC values along each of the 33 ribs were plotted, showing how each rib's shape varied along its length. Using just 8 principal components, the average male and average female PC values were computed along the full length of the rib. The PCA results then allow for new rib cross-sectional shapes to be calculated using each of these sets of 8 PC values. These statistically average male and female rib shapes were displayed along the length of the rib.

III. INITIAL FINDINGS

The PCA serves to represent spatial changes in the original feature space (160 features) in as few principal components as possible. Figure 1 shows that over 90% of all positional variance is captured by the first 4 PCs, and 99.5% is captured by the first 20 PCs. We will highlight results here using the first 8 PCs which together explained 98% of all spatial variance.

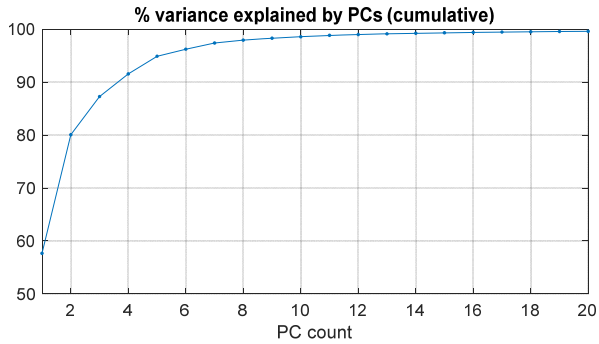

Figure 1: Variance in XY coordinates of all cross-sections explained by each principal component (PC)

The individual effect of each PC on an average rib shape is illustrated in Figure 2, wherein adjustments to rib section coordinates along each PC direction are viewed relative to the average shape measured across all positions of all subject ribs (black line). Figure 3 then shows the extracted PC values by rib position, represented as PC value curves plotted along the length of each of the 33 subject's ribs. The average PC values along rib lengths for males and females is included in Figure 3. Using these average PC values for the top 8 PCs, average rib sectional shapes can be reproduced, and these are shown in Figure 4 for males and females. For comparative reference, Figure 5 shows exemplar sections taken directly from one of the individual male and female subjects.

Figure 2 shows PC1 is very strongly associated with the overall size of a rib's cross-sectional shape. Viewing the profiles of PC1's value along all subject ribs it is clear to see that, on average, males have higher PC1 than females along the length of the rib. Also, clear trends can be seen along the lengths of all subject ribs whereby this overall size component follows a gentle trough towards the mid-rib region and increases sharply towards the sternal end. These features are correspondingly represented in Figure 4 average male and female shapes. PC2 largely controls the aspect ratio of the ribs, ranging from rounder sectional shapes to highly elongated shapes. Again, Figure 3 shows clear trends in aspect ratio along rib lengths that are shared between both sexes. PC3 largely represents the prominence of a costal groove, which appears in most subjects between 15%-50% along the rib's length. PC4 and PC5 tend to modulate separate rotational aspects of the rib shape. Each successive PC is responsible for smaller and smaller total changes in coordinate positions, with lower priority PCs (6 and beyond) modulating only local protrusions or zones of the rib shapes.

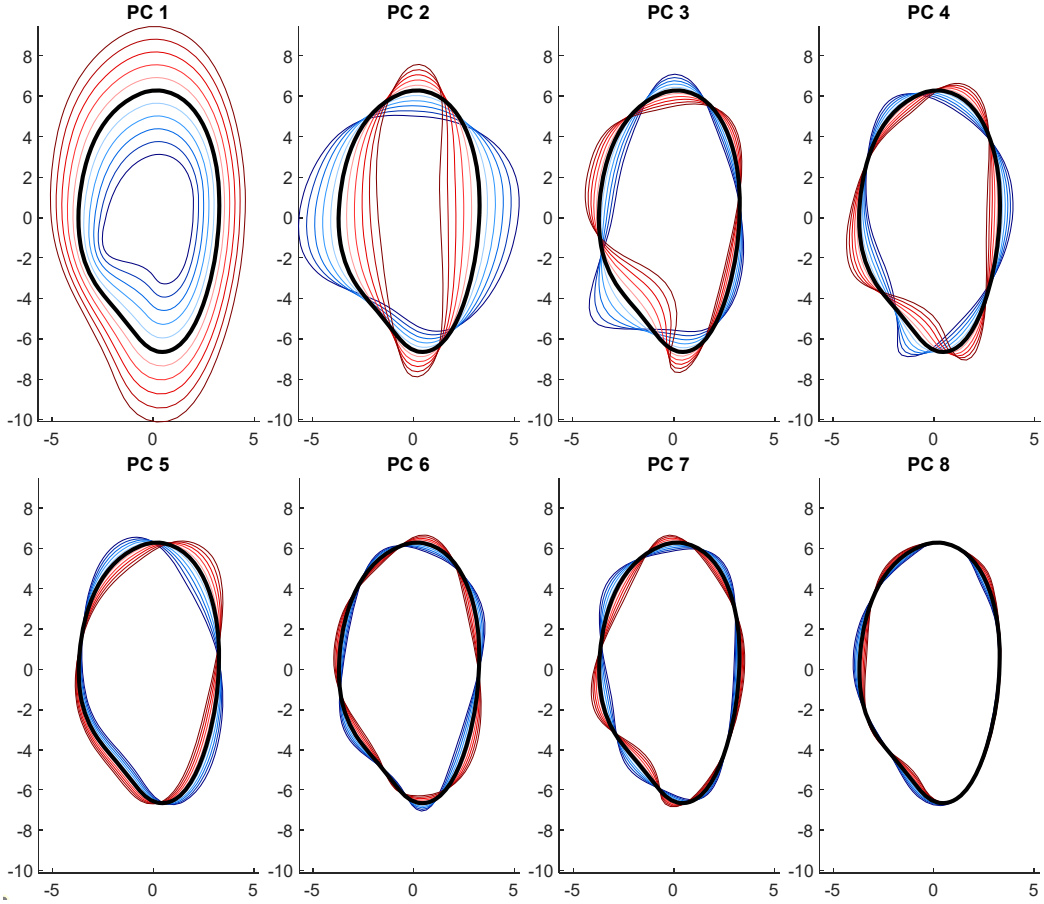

Figure 2: Effect on cross-section shape of independently modifying each PC value from -3 to +3 standard deviations (blue to red). The average cross-sectional shape (solid black) is the same in all subfigures. Clear physical associations are seen for overall cross-section size (PC1), aspect ratio (PC2), and costal groove prominence (PC3). Units are in mm.

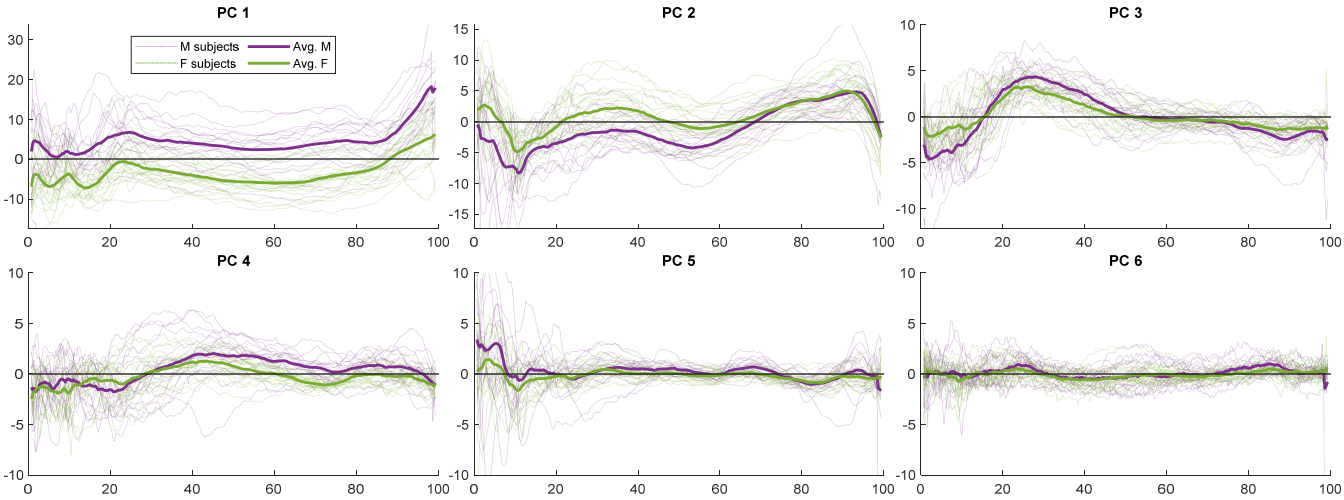

Figure 3: First 6 PC values by position along rib length. PCs 1-4 show clear trends along the lengths of ribs shared by all subjects. These indicate how typical rib shapes change along their length. PCs 1 & 2 also differ by sex, with males having consistently larger PC1 (size) and females having larger PC2 (aspect ratio) towards the first 60% of a rib's length.

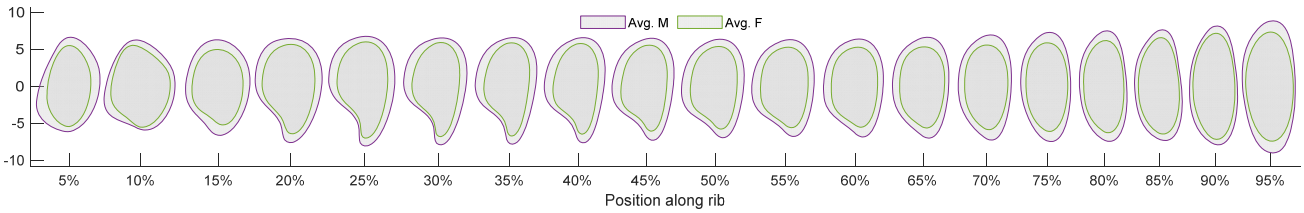

Figure 4: Statistically average male and female rib cross-sectional shapes along the length of 6th ribs. Each shape is produced using the average PC value at a given rib location from just the top 8 PCs.

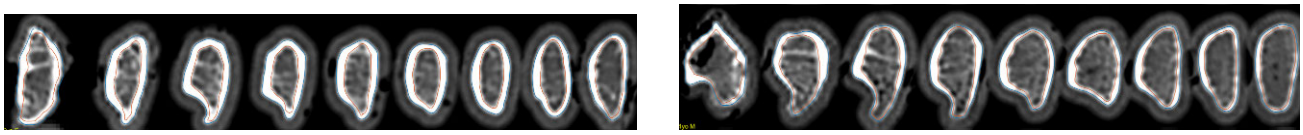

Figure 5: Exemplar cross-sections from a 66yo female (left) and a 54yo male (right) subject, ranging from the 10th to 90th percentile rib locations (left to right). Thin blue lines represent the periosteal (outer) rib border.

IV. DISCUSSION

Here we have shown the feasibility of a method to characterize rib cross-sectional shapes. It collects rib sections from all along full 6th ribs, and analyses the general forms of variation to those shapes using shape-based PCA.

Many of the higher principal component directions of change show clear associations with physically meaningful properties such as cross-sectional size, elongation, and a distinct costal groove protrusion. For example, Holcombe et al [4] quantified average rib cross-sectional areas and inertial moments as a function of rib position. The average value trends along the rib for PC1 largely match those area trends reported previously. Similarly, PC2 trends show changes in total aspect ratio that match previous reports of major vs. minor inertial moment ratios.

One advantage of the current methodology over previous work is that the rib shapes themselves can be reported, rather than merely scalar geometric properties derived from those shapes. The ability to take the PCA results and then recapitulate ribs based on statistical analysis (in this case, mean values from 8 components) gives the potential to synthesize statistically-generated ribs that retain the primary characteristics of real human ribs. One direct use of this technique could be to generate FE mesh ribs that more accurately represent the geometry of a target demographic than you would otherwise obtain from the specific geometry of a chosen single subject.

One general criticism of PCA methods is that the principal component directions themselves can be difficult to explain or understand. This comes from the fact that they are essentially uncontrolled, emerging only as output from the input data provided. As above, it is promising to see physically meaningful component directions emerge from this analysis. One important factor in ensuring this occurs is to properly process the input data such that as much undesirable variation in shape as possible is removed from the data prior to PCA. For example, in this study we centered all rib sections to a common origin and aligned all data along inferior/superior directions to reduce rotational variation. When placing results from the current study into the larger context of ribs of full bodies in which rotation of rib sections along the rib does in fact occur, it will be important to adequately capture this twist (or camber) as an independent property.

In its current preliminary form, this study is further limited by its use of only 6th rib data, and only describes outer rib border geometry. For general applicability to HBMs it would be desirable to extend the technique to cover all rib levels, and to couple this outer border information with other aspects of rib global shape [5] and cortical bone thickness [4]. Furthermore, the underlying population is relatively small and not strategically chosen for this current study's purpose. Therefore, only simple statistical averages for males and females have been calculated as a proof-of-concept. Given a larger data pool, it would be possible to derive population-based average PC values for a more refined demographic target (such as 5th percentile females to match many current HBMs), or even to investigate changes in rib cross-sectional shapes that are associated with age or other demographic factors.

V. REFERENCES

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