Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Modeling female and male rib geometry with logarithmic spirals

Sven A. Holcombe [a,b,*], Stewart C. Wang [b], James B. Grotberg [a]

[a] Department of Biomechanical Engineering, University of Michigan, Ann Arbor, MI, USA
[b] International Center for Automotive Medicine, University of Michigan, Ann Arbor, MI, USA

ARTICLE INFO

Article history:
Accepted 20 July 2016

Keywords:
Rib
Model
Geometry
Shape
Spiral
Gender
Thorax
Bone

ABSTRACT

In this study we present a novel six-parameter shape model of the human rib centroidal path using logarithmic spirals. It provides a reduction in parameter space from previous models of overall rib shape, while simultaneously reducing fitting error by 34% and increasing curvature continuity. Furthermore, the model directly utilizes geometric properties such as rib end-to-end span, aspect ratio, rib "skewness", and inner angle with the spine in its parameterization, making the effects of each parameter on overall shape intuitive and easy to visualize.

The model was tested against 2197 rib geometries extracted from CT scans from a population of 100 adult females and males of uniformly distributed ages between 20 and 70. Significant size and shape differences between genders were identified, and shape model utility is demonstrated by the production of statistically average male and female rib shapes for all rib levels. Simulated mechanical loading of the resulting model rib shapes showed that the stiffness of statistically average male and female ribs matched well with the average rib stiffness from each separate population. This in-plane rib shape model can be used to characterize variation in human rib geometry seen throughout the population, including investigation of the overall changes in shape and resultant mechanical properties that ribs undergo during aging or disease progression.

1. Introduction

Rib fractures are a significant problem for trauma patients, and their presence increases the risk of fatality in motor vehicle collisions (MVCs) (Kent et al., 2008). Rib fractures are of particular concern in elderly populations, where higher rates of fracture result in longer periods in care, longer stays on ventilation, and increased risk of pneumonia and mortality (Kent et al., 2008; Holcomb et al., 2003; Bulger et al., 2000).

The rib cage itself forms a primary structural component within the chest that is subjected to external loading during traumatic events such as MVCs or falls, and the ability of the ribs to withstand deformation is influenced by both their material properties and also their geometry (Kent et al., 2005). This geometric rib shape varies both by rib level, and also between individuals across the population (Kindig and Kent, 2013; Hu and Reed, 2012; Weaver et al., 2014; Shi et al., 2014). Variation in material properties, rib cross-section, and the overall rib centroidal path each serve to affect the mechanical response of ribs to loading and their sensitivity to fracture (Kemper et al., 2007; Li et al., 2010; Cormier et al., 2005; Stitzel et al., 2003; Kindig et al., 2011). Experimental studies conducted on isolated ribs under mechanical loading with the aim of understanding the biomechanics of ribs show variation in a number of mechanical properties (Agnew et al., 2015; Beadle et al., 2015).

Computational modeling of the human ribs and thorax offers the potential to incorporate this variation and build models representing the breadth of geometric variance of a given population. To do so, however, accurate models of rib shape are needed that can adequately quantify this variation both within the rib cage and across the population.

A primary component of rib shape is its centroidal path (i.e., the sequence of centroids connecting adjacent cross-sections), and previous studies have quantified aspects of this shape using the characteristic measures of one or more geometric primitives. Examples include measures derived by representing rib shapes with a circular ring (Kent et al., 2001), an arc (Schultz et al., 1974), an ellipse (Margulies et al., 1989), and a pair of superimposed arcs (Roberts and Chen, 1972; Roberts, 1977).

Kindig and Kent (2013) developed a seven-parameter rib shape model that used two geometric primitives (a circle and a semi-ellipse) connected via shorter patches (two lines and a parabola) to represent the centroidal rib path with C_1 continuity (i.e., a piecewise curve where all connecting pieces meet with position and slope continuity). It was the first model whose parameters acted both as measurements of rib shape and also as the blueprint to

* Corresponding author.
E-mail address: svenho@umich.edu (S.A. Holcombe).

http://dx.doi.org/10.1016/j.jbiomech.2016.07.021
0021-9290/

Please cite this article as: Holcombe, S.A., et al., Modeling female and male rib geometry with logarithmic spirals. Journal of Biomechanics (2016), http://dx.doi.org/10.1016/j.jbiomech.2016.07.021

independently build the full centroidal path. Its parameterization was also flexible enough to accurately model the varying overall shapes seen at different rib levels, which earlier models were unable to do. One potential drawback of the Kindig and Kent model comes from the requirement of mathematical constraints on the placement of its primitives. When fitting individual ribs these constraints are easily satisfied, however statistical operations on multiple ribs (such as using average parameter values to reflect typical rib geometry) can, in some cases, lead to new sets of parameter values that no longer meet those same criteria.

In this study we introduce a novel six-parameter model of the in-plane shape of a rib's centroidal path. It aims to provide a more efficient and accurate model of the various rib shapes seen by rib level and across the population. Further, the model parameters are designed to directly match characteristic geometric properties such as rib length, aspect ratio, and skewness. This model was fit to 2197 ribs from computed tomography (CT) scans, and used to generate typical and representative ribs for adult males and females. The individual effect of each parameter is demonstrated, along with the direct application of the model to computational analyses of rib stiffness under end-to-end compression.

2. Methodology

A total of 2197 unfractured ribs were analyzed from CT scans of 50 females and 50 males in the International Center for Automotive Medicine (ICAM) CT database. Subjects were chosen at random from those who met age criteria (20–69 years with 10 subjects per gender per decade), were free of skeletal abnormality (including scoliosis, kypohosis, bifurcating ribs or abnormal rib counts), were not pregnant at the time of scan, and had at least 9 rib levels fully visible within the scan window. All subject data was obtained under Institutional Review Board approval.

2.1. Centroidal path extraction

Rib centroidal geometry was extracted for all ribs using semi-automated routines written in MATLAB R2015b (The Mathworks, Natick, MA) to firstly place landmarks at each rib end and then determine a series of 3D centroidal path points joining those end landmarks.

The distal (from the spine) rib end landmark was placed at the apex of the cup-shaped transition from bone to cartilage at the costo-chondral junction, consistent with past literature (Lau et al., 2011). Resliced views of the CT image volume that highlight this region were used as shown in Fig. 1(a). The rib end landmarks at the end proximal to the spine were placed using resliced views perpendicular to the spine as illustrated in Fig. 1(b). This proximal landmark was placed on the rib cortical surface at the articulation point between each rib and the vertebra of its same number.

Using an algorithm adapted from Staal et al. (2007), an initial rib path template was built linking these two end landmarks through the CT image space. This path was then iteratively refined by reslicing the CT image volume perpendicular to the rib as seen in Fig. 1(c). The centroidal path points were set to match the 2D centroid of a filled segmentation of its cross-section.

Finally, a plane is fitted to each rib's centroidal path with a primary axis (the rib's local x-axis) passing from the proximal to distal rib end points, and a secondary axis (the local y-axis) that is chosen so as to minimize the total out-of-plane deviation of all points along the rib's path.

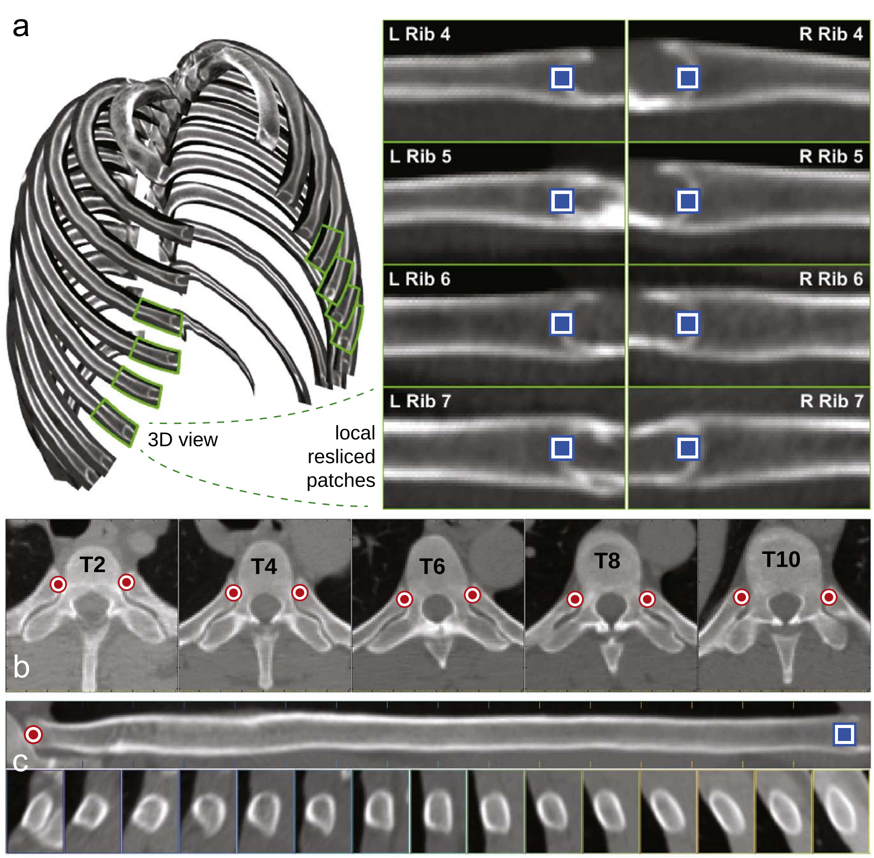

Fig. 1. Resliced views for landmark placement of (a) the distal rib end at the costo-chondral junction, and (b) the proximal rib end at the spine articulation point, with (c) resliced cross sectional views along the rib (upper) and perpendicular to the rib (lower) where the 2D centroids of rib pixels provide the 3D centroidal path.

Please cite this article as: Holcombe, S.A., et al., Modeling female and male rib geometry with logarithmic spirals. Journal of Biomechanics (2016), http://dx.doi.org/10.1016/j.jbiomech.2016.07.021