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Image Segmentation and Registration Algorithm to Collect Homologous Landmarks for Age-Related Thoracic Morphometric Analysis

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ABSTRACT

Adults 65 years of age and older currently constitute more than 12% of the total population and the elderly population is projected to reach nearly 20% by 2030. Previous studies have shown that skeletal and physiological resilience decline with age, resulting in a decreased ability for the body to withstand traumatic insults. In the current study, an algorithm was developed to quantify age and gender-specific variations in the thoracic skeletal morphology. Normal chest CT scans of males and females ages 0-100 were collected from a radiological database. Image segmentation and subsequent image registration was used to collect landmark data from the ribs. Rigid and affine transformations were used to morph segmented ribs from different subjects to a "rib atlas". The atlas consists of a normal chest CT scan from an average male with over 100 landmarks placed per rib. The transformation matrices will be used to map landmarks from the atlas coordinate system to the coordinate system of each CT scan, effectively allowing for collection of homologous (or comparable) rib landmarks across all subjects. Geometric morphometrics will be used in future work to analyze the landmark data to formulate age and gender-specific shape and size variation functions. These functions will be used to create a scalable finite element model of the thorax that will be used to predict thoracic injury response for different ages and genders.

INTRODUCTION

In motor vehicle crashes, thoracic injury ranks second only to head injury in terms of the number of fatalities and serious injuries, the body region most often injured, and the overall economic cost (Cavanaugh 2002; Ruan et al. 2003). Thoracic injuries account for 13% of all minor to moderate injuries, 29% of all serious to fatal injuries, and are attributed to up to 25% of traumatic deaths (Dougall et al. 1977; Galan et al. 1992; Allen et al. 1996; Ruan, El-Jawahri et al. 2003). While motor vehicle crashes are associated with 60-70% of blunt chest trauma, 20% is attributed to falls that are more commonly seen in the elderly (Galan, Penalver et al. 1992; Allen and Coates 1996).

Adults 65 years of age and older currently constitute more than 12% of the total population and with increases in life expectancy, the elderly population is projected to reach nearly 20% by 2030 (U.S. Census Bureau 2008). Motor vehicle crash is a common source of trauma among the elderly population, with the elderly having the second highest crash-related death rate compared to all age groups (National Center for Health Statistics 2003). The incidence of thoracic injury increases with age for both belted and unbelted occupants (Hanna 2009). Skeletal and physiological resilience are known to decline with age, resulting in a decreased ability for the body to withstand traumatic insults (Burstein et al. 1976; Zioupos et al. 1998). Thoracic injury tolerance in the elderly has been shown to decrease by 20% for blunt loading and up to 70% for concentrated belt-loading (Zhou 1996).

Thoracic morbidity and mortality also increase with age. Older patients sustaining a thoracic injury present with more comorbidities, develop more complications, remain on a ventilator longer, and require longer stays in the intensive care unit (ICU) and hospital (Finelli et al. 1989; Shorr et al. 1989; Perdue et al. 1998; Holcomb et al. 2003; Hanna 2009). Complications from thoracic injury include pneumonia, atelectasis, acute respiratory distress syndrome (ARDS), and respiratory failure. Elderly patients with rib fractures have two to five times the risk of mortality of younger patients with increases in risk observed as the number of rib fractures increase (Bergeron et al. 2003; Stawicki et al. 2004). Each additional rib fracture results in a 19% increase in mortality and 27% increase in pneumonia (Bulger et al. 2000).

Age and gender-specific variations in the geometry and mechanics of the thoracic skeleton are expected to relate to thoracic injury. Previous studies have found statistically significant changes in the rib cage geometry with age (Kent et al. 2005; Gayzik et al. 2008). However, these studies had several limitations. Geometrical changes such as the shape, size, and angle of the ribs were quantified using a limited number of landmarks or measurements that were collected manually from two-dimensional (2D) images of a computed tomography (CT) scan. Also, the pediatric population was not analyzed in either of these studies and some other age groups were under-represented. The objective of the current study is to quantify age and gender-specific variations in the thoracic skeletal morphology for both genders and across the entire age spectrum (ages 0-100). This goal will be accomplished using a semi-automated image segmentation and registration algorithm to collect homologous (or comparable) landmarks from the ribs.

METHODS

An algorithm was developed to collect landmark data from the ribs for the purpose of quantifying age and gender-specific variations. The main steps of the algorithm are: 1) Scan Collection, 2) Image Segmentation, and 3) Image Registration.

Scan Collection

Normal chest CT scans of males and females ages 0-100 were collected from the radiological database at Wake Forest University Baptist Medical Center. To identify exclusion criteria and ensure normal scans were collected, a musculoskeletal radiologist was consulted. Exclusion criteria included, but was not limited to: congenital abnormalities, infections, fractures, and cancers of the ribs, scoliosis, kyphosis, sternotomy, thoracotomy, and osteopenia/osteroporosis in individuals younger than 50. During scan collection, radiology reports and other patient medical records were reviewed and scans were visually inspected. A minimum of 10 male and 10 female scans were collected for the following age groups: newborns, 3 month, 6 month, 9 month, 1 year, 3 year, and 6 year olds. Beginning with 10 year olds, 10 scans for each gender were collected by decade up to age 100.

Image Segmentation

A semi-automated method was used to segment the 24 ribs on each subject. A bone threshold was applied, followed by a region growing operation. Minimal manual editing was used to ensure the entire rib was selected and the surrounding soft tissue was excluded. A hole filling operation was used to enclose the rib interior. Results of the segmentation include a mask and a three-dimensional (3D) model for each rib (Figure 1).

Image Registration

An image registration algorithm was developed for the purpose of collecting homologous landmarks from the ribs for all subjects in the study. An atlas was created from segmentation of a normal chest CT scan of an average male. The atlas contained the 24 ribs with over 100 landmark points placed on each rib. For every subject in the study, each segmented rib was registered with the corresponding rib in the atlas (i.e. the left first rib in each subject is registered with the left first rib in the atlas). Rigid and affine transformations were used in the registration algorithm to morph the atlas to the rib of each subject (Figure 2, Steps 1 and 2). Following the registration, the 100 landmark points on each rib will be transformed to the subject-specific coordinate system of the CT scan (Figure 2, Step 3). Effectively, this allows for collection of homologous rib landmarks across subjects of all ages. Geometric morphometrics, particulary the Procrustes superimposition method, can then be used to analyze the landmark data to formulate age and gender-specific shape and size variation functions.

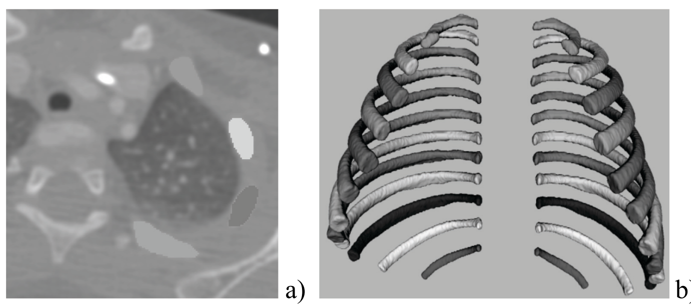

Figure 1: Rib segmentation results. a) Masks of the segmented left ribs 1-4 overlaid on an axial chest CT image. b) 3D models of the 24 segmented ribs of a pediatric subject.

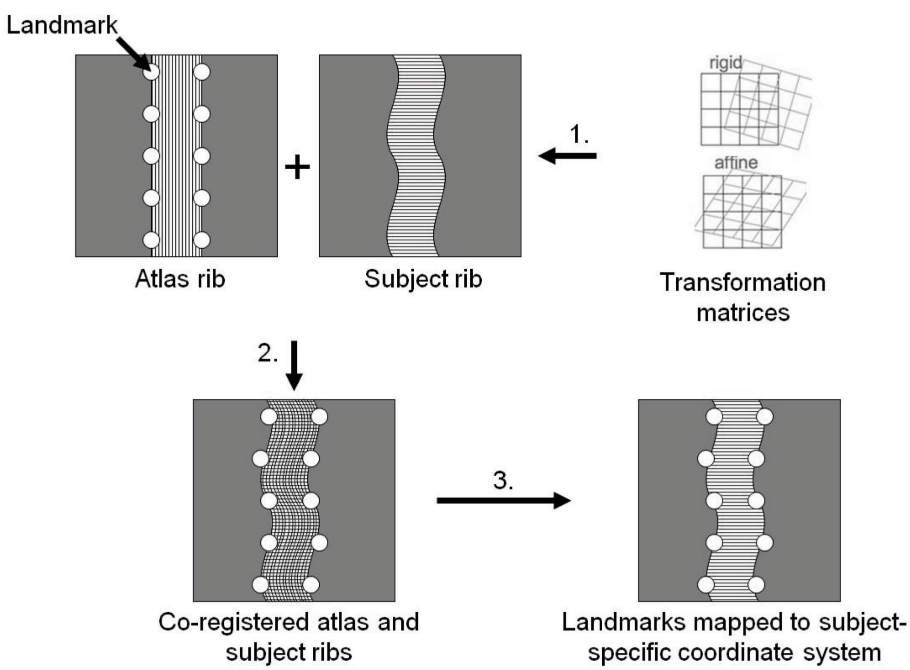

Figure 2: Image registration process. 1) Rigid and affine transformations are applied to register a subject's rib with the atlas. The atlas rib is depicted with only 10 landmarks for simplification. 2) The co-registered atlas rib and subject rib in the subject-specific coordinate system with landmarks shown. 3) Depiction of 10 landmarks in the subject-specific coordinate system.

RESULTS

An example of the results of the registration algorithm is provided in Figure 3. In this example the left fourth rib from a 16 year old male (termed "subject rib") was registered with the left fourth rib of the average male (termed "atlas rib"). The rigid transformation (Figure 3, Step 1) translates and rotates the atlas rib to align three landmarks on the atlas rib with three landmarks on the subject rib. The affine transformation (Figure 3, Step 2) applies translation, rotation, scaling, and shearing operations to morph the atlas rib to the subject rib.

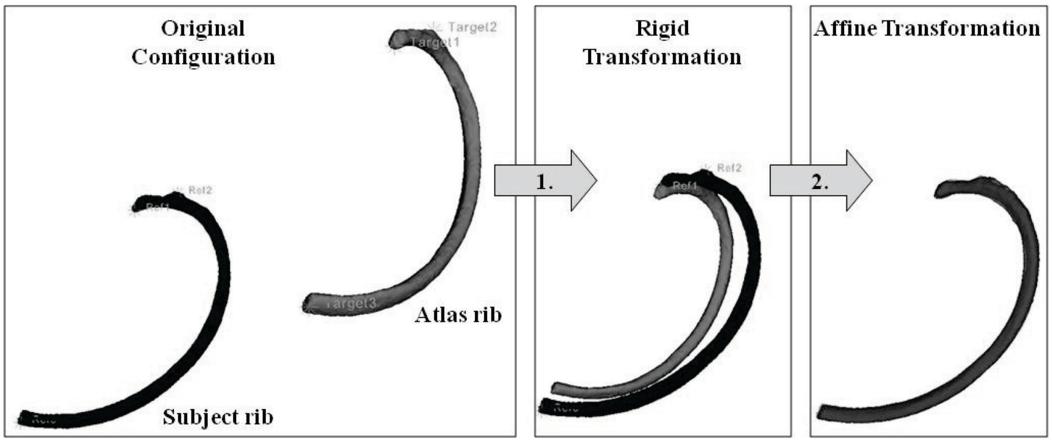

Figure 3: Image registration example. 1) Rigid transformation applied to rigidly align three landmarks on the atlas rib with three landmarks on the subject rib. 2) Affine transformation applied.

CONCLUSIONS

The image segmentation and registration algorithm developed in the study provides a method for collecting landmark data from the ribs. The algorithm improves on the previous methods of measuring rib geometry by utilizing the full 3D information in the scan to collect landmarks (Kent, Lee et al. 2005; Gayzik, Yu et al. 2008). The algorithm requires little user interaction, allowing landmarks to be collected in an automated fashion for a large number of subjects and reducing intra-observer and inter-observer error. Landmarks on the ribs can be classified as: true anatomical landmarks representing a homologous structure, pseudolandmarks defined by relative locations such as the most lateral point, or semilandmarks defined relative to other landmarks. Previous methods that have relied on the manual landmark identification and this method may not result in selection of homologous landmarks, particularly for pseudolandmarks or semilandmarks (Gayzik, Yu et al. 2008). Automatic selection of landmarks through image registration eliminates error in landmark identification and improves the ability to select a large number of homologous landmarks on the ribs.

Limitations include the possible introduction of error since some manual interaction was required to segment the ribs. The CT scan resolution presents a limiting factor on the rib cage variation that can be detected as differences less than the maximum voxel length cannot be accurately measured. We made efforts to select higher resolution CT scans with a slice thickness of 0.625 mm to address this limitation.

Image registration has been widely used to study injuries, disease, and cancers of the brain (Maldjian et al. 2001; Lee et al. 2010; Long et al. 2010). The image segmentation and registration algorithm developed in the current study could be modified and used in subsequent research studies to collect landmark data from other bony and soft tissue anatomy. Similar to the current study, geometrical variation in the anatomy could be characterized for different ages or genders. The algorithm could also be used to study pathology and volumetrically characterize the extent and location of injured or diseased tissue.

Future efforts will focus on refining the image segmentation and registration algorithm and collecting homologous landmark data for all subjects in the study. Landmark data will be input into a geometric morphometrics analysis to formulate age and gender-specific shape and size variation functions of the rib cage. Additional research will be conducted to quantify changes in bone mineral density and cortex thickness with age and gender. The morphological functions developed will be used to create a parametric finite element model of the thorax that will allow vehicle crashworthiness to be evaluated for all ages and genders and will lead to improvements in restraint systems to better protect children and elderly in a crash.

In conclusion, an image segmentation and registration algorithm was developed to collect homologous rib landmarks from normal CT scans of males and females ages 0-100. The algorithm uses rigid and affine transformations to morph segmented ribs from different subjects to a "rib atlas". The collected landmarks will be analyzed to formulate age and gender-specific shape and size variation functions. Results of this study will lead to an improved understanding of the complex relationship between thoracic geometry, age, gender, and injury risk.

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