Rib length variation with age and sex - Measurements from high-resolution low-radiation X-ray images of volunteer subjects

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Paper Number 15-0313

ABSTRACT

Research Question: Human surrogates such as anthropomorphic test devices and computational models are common tools used by the automotive industry to characterize injury mechanisms and design countermeasures. The surrogates currently available were designed to be representative of certain sex and percentile of the population, such as the 5th- and 50th-percentile females, and the 50th- and 95th-percentile males. Great improvements were achieved in crash protection thanks to these models, but there is a need for more refined models that take into account a greater variation of the human diversity, such as the geometric variation due to aging. Therefore, the objective of this study was to determine how the length of ribs varies with age and sex.
Methods and Data Sources: A total of 103 asymptomatic volunteer subjects aged 0 to 84 years old were included in the study. First, each volunteer was imaged either with a standard clinical CT-scan, or in a standing position with the EOS imaging system, a low-radiation X-ray system that acquired one frontal and one sagittal high resolution images of the ribcage. Second, a custom-made software toolbox was used to create a subject-specific geometrical 3D model of each subject bony ribcage by registration of a statistical parametric ribcage model. Third, the rib length and mean thoracic index were extracted from the 3D ribcage models.
Results: The two main results were that the thoracic index (depth to width ratio of the thorax) was found to be fairly age-independent, and that the ribs length increased linearly with age between 0 and 20 years old before reaching a plateau. The growth rate of the ribs increased between each rib level from rib 1 (4 mm/year) to rib 10 (10.5 mm/year). This indicates a change in the size and shape of the ribcage during growth.
Conclusion and relevance: The study provides a quantitative characterization of age and sex-induced variation in the ribcage geometry, based on asymptomatic adult volunteer data. This study addresses the need for the geometric data required to build a set of computational models that represent male and female subjects of various age.

INTRODUCTION

A significant research effort has been undertaken in the last four decades to document motor vehicle crashes (MVC) such as vehicle speed, types of occupants, and injury outcomes, and develop typical scenarios for frontal, lateral and oblique impacts. In parallel, models of the human body were developed to estimate the severity of an impact, by determining the mechanical response and strength of the human body during a crash to describe the mechanisms of injury as well as the injury thresholds. Physical and computational human body models, or human surrogates, are used to achieve this goal. The surrogates currently available were designed to be representative of certain sex and percentile of the population, such as the 5th- and 50th-percentile females, and the 50th- and 95th-percentile males. Great improvements were achieved in crash protection thanks to these models, but there is a need for more refined models that take into account a greater variation of the human diversity, such as the geometric variation due to aging, to create human surrogates that represent a larger spectrum of the population. In that effort, the ribcage is of particular interest: older drivers are more likely to die of a chest injury and less likely to die from a head injury compared to the youngest group (Morris et al., 2003). This is a direct consequence of the high rate of seat belt used in this population: in frontal crash, seat belts are designed to load the thorax to limit the forward excursion of the body and, in combination with airbags, prevent the impact of the head and thorax with the vehicle interior structures. However, determining the maximum load that can be safely applied to the thorax without fracturing ribs and how it varies with age has yet to be done. There is a need for geometric and morphologic data to develop a ribcage model that include age-dependent features. Several dataset are available in the published literature and provide valuable information about the age-related changes in the adult (Gayzik et al; 2008) and pediatric ribcage (Holcombe et al, 2013), however they all rely on computed tomography images obtained during routine trauma medical exams. Although, these studies included only subjects that were free of skeletal pathology, CT analysis obtained from hospital databases suffer two important limitations: the subjects are lying on the CT bed, and the resolution of the X-ray images is limited to minimize exposure for the subject for health concerns. Therefore, the goal of the present study was to measure the variations in the length of the ribs as a function of age and sex, based on high-resolution low-dose X-ray images obtained with the EOS system. The EOS system has been developed and used for several years now (Dubousset et al, 2010) to perform follow-up for spine deformity treatments for patients with scoliosis through the creation of subject-specific models of the spine (Humbert et al, 2009). The present study is the first step towards the description of age- and sex-induced variations in the ribcage geometry, and focused on the variation in the rib lengths for a wide range of age.

MATERIALS AND METHDODS

This study uses pediatric data from the literature (Sandoz et al, 2013), and new data for the adult population obtained with the EOS system.

The EOS imaging system

The EOS system is a system approved worldwide for clinical exam. Its main feature is to be a low-dose X-ray imaging system that allows the acquisition of the geometry of the musculoskeletal structure of volunteer subjects in a weight-bearing posture from two 'head-to-toe' X-ray images (Dubousset et al, 2010)(Figure 1). Furthermore, these images are high resolution (0.2 mm/pixel) compared to standard CT images of living patients (typically 2 to 5 mm/pixels). Several statistical models were developed to create subject geometry from the biplanar images obtained with EOS, in particular the spine (Humbert et al, 2009), and the ribcage (Aubert et al, 2014). The subject-specific geometry are created by registering a statistical parametric model of the spine and of the ribcage on the frontal and sagittal images obtained with EOS.

Figure 1.Frontal and sagittal views obtained with EOS and used to create subject-specific spine and ribcage.

Adult morphological data

Fifty five asymptomatic adult volunteers were included in this study (36 men, 19 women), aged 20 to 84 years (mean 38), with a body mass index ranging from 15.4 to 29.5 kg/m² (average: 22.9). Participants were confirmed to be free of spine pathologies or instrumentation anywhere in the upper body. Each participant completed and signed an informed consent form approved by the ethical committee at Hôpital Pitié Salpêtrière (Paris, France) (CPP 6001 and CPP 6036 Ile-de-France VI). The acquisition of the X-ray images took about 20 seconds. No specific instructions about breathing were given to the volunteers.

For each volunteer, a subject-specific geometric model was created: this model included the spine and the ribs 1 to 10. The length of each rib was calculated based on the method described in Aubert et al (2014): the rib length was defined as the length of the centroidal line from the costo-vertebral joint to the costo-chondral junction.

The rib cage morphometry was also described by the mean thorax index that is defined as the mean value of the thorax lateral width to thorax anteroposterior depth ratio calculated for eight horizontal slices equally distributed between the 2nd and the 12th thoracic vertebrae.

Pediatric morphological data

The pediatric data consisted of 960 ribs reconstructed from CT images from 48 children aged 4 months to 15 years (22 girls, 26 boys) (Sandoz et al., 2013). The pediatric data were organized in 16 age groups (less than 1 year-old, 1 year old, 2 years old, …, and 15 years old), and male and female data were combined in a single data set. Similar to the procedure used with the EOS images, the rib length was defined for ribs 1 to 10 as the length of the centroidal line from the costo-vertebral joint to the costo-chondral junction.

RESULTS

Rib lengths

The rib lengths were plotted for each rib level from 1 to 10. The data for the age 0 to 15 years old combine both sex, while the new data generated in this study separates male and female (figures 2 and 3).

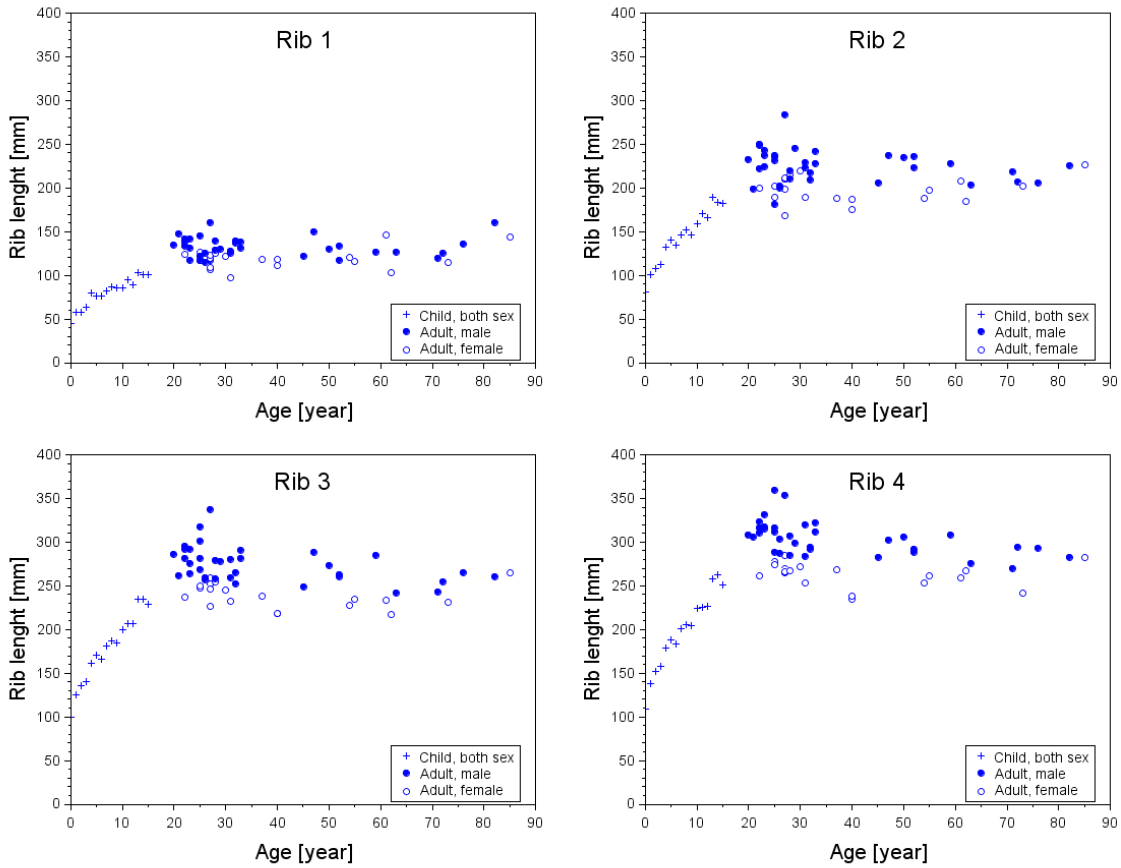

Figure 2. Rib lengths from 0 to 84 years old (ribs 1 to 4).

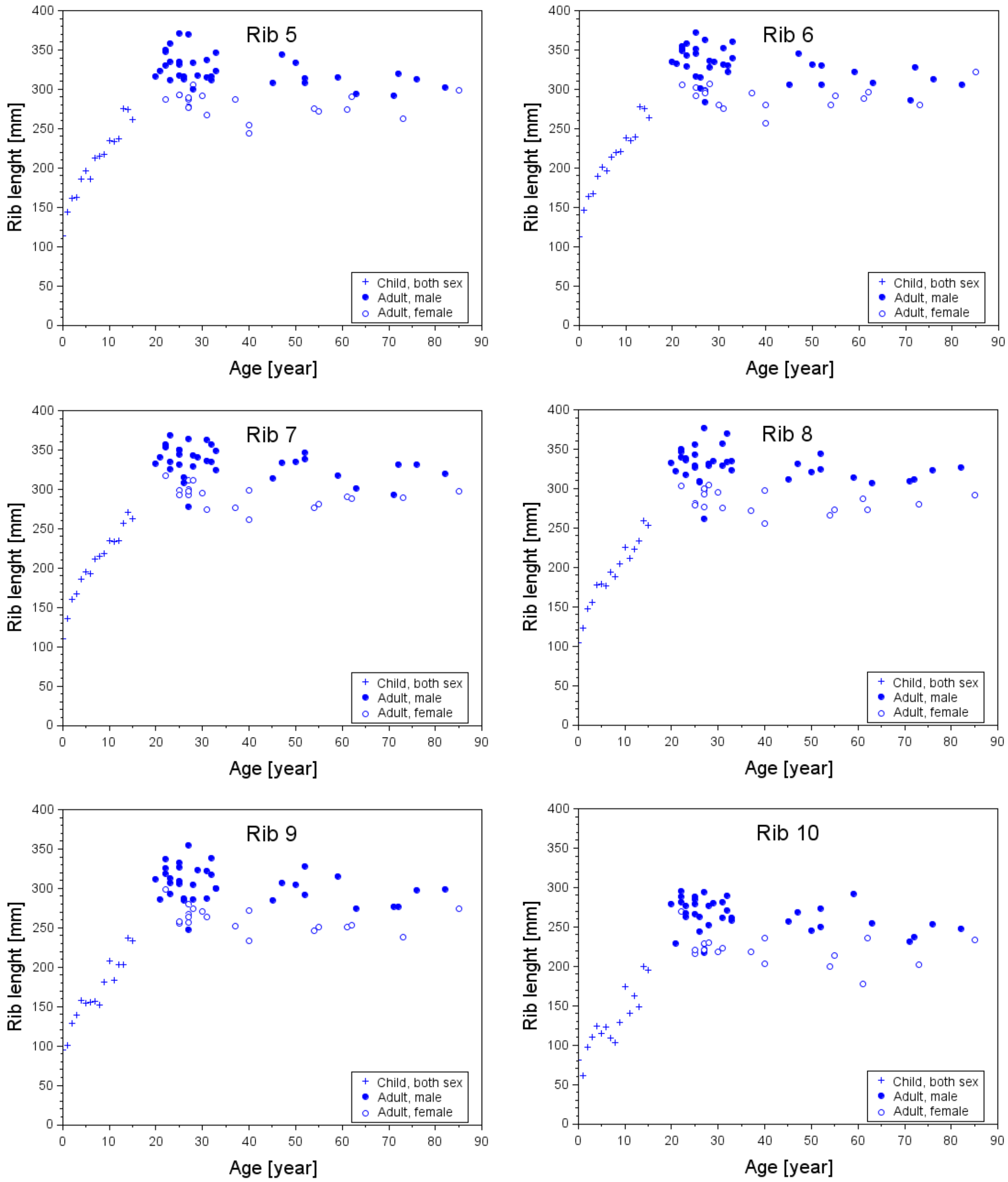

Figure 3. Rib lengths from 0 to 84 years old (ribs 5 to 10).

Mean thoracic index

The mean thoracic index was calculated for the male and female adult subjects (figure 4).

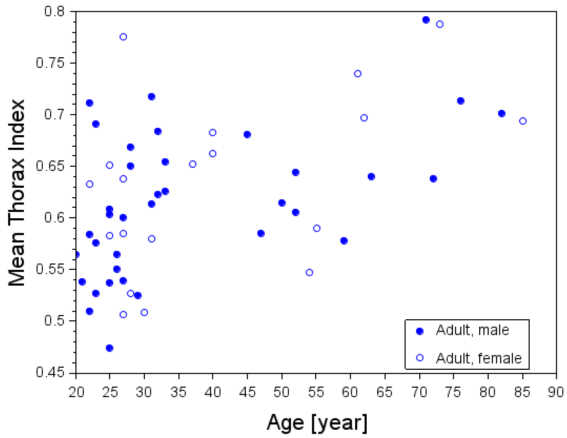

Figure 4. Mean thoracic index.

DISCUSSION

Effect of age

Both the rib length and mean thoracic index were found to vary with age. The rib length increased linearly with age between 0 and 20 years old before reaching a plateau; this trend was common to all rib levels. The growth rate of the ribs before age 20 increased between each rib level from rib 1 (4 mm/year) to rib 10 (10.5 mm/year). This indicates a change in the size and shape of the ribcage during growth. After 20 years of age, the rib length was nearly independent of age. One could have expected the rib to lengthen with age because of the calcification of the costal cartilage, but this trend was not obvious from the data presented in this study. As for the mean thoracic index, it was found to increase with age, indicating that the thorax widens to become ‘rounder”, which is consistent with the results from other study based on CT images (Kent et al, 2005; Weaver et al, 2014). The data provided in Sandoz et al (2013) for the range 0 to 15 years old are averaged (3 subjects in each 1-year age group), while the adult data was not.

Effect of sex

The female ribs were found to be on average per rib level 10 to 17 % shorter than the male’s ribs (figure 5). Conversely, the mean thoracic index was found to be rather insensitive to sex, which suggests that the female ribcage is similar is shape to the male ribcage, but potentially smaller. However, the orientation of the ribs was not reported in this study, although it could be a factor in the overall size and shape of the ribcage.

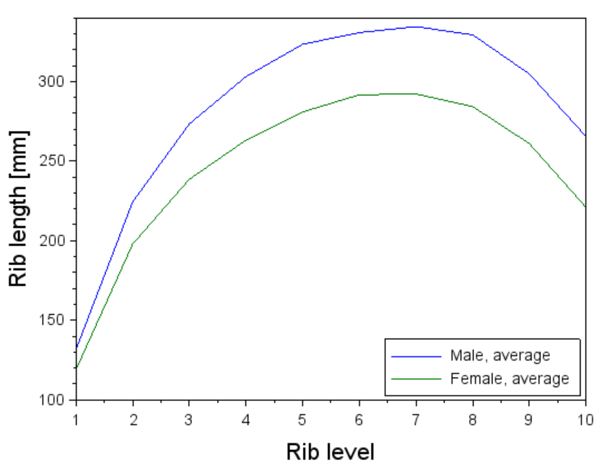

Figure 5. Mean rib length for male and female volunteers.

LIMITATIONS

The analysis presented in this paper is based upon a transversal study, and therefore the inter-individual differences may contribute to the differences that are attributed to age. Furthermore, the data set is biased towards the young adults age group (20 to 35 years of age), and the male subjects.

CONCLUSIONS

The study presented in this manuscript relies on a unique imaging system that can be used to image asymptomatic volunteer subjects with no pathology. In addition, subjects can be imaged in a standing or sitting position. The results presented in this paper focused on the variation of rib length with age and sex, for a relatively small data set. This manuscript provides a first set of results. The analysis is on-going to further established the morphological differences between male and female subjects, as a function of age, to elucidate the link between the geometry of the ribcage and the risk of injury during a motor vehicle crash.

ACKNOWLEDGEMENT

The authors thank the Banque Public d'Investissement for financial support through the French Fonds unique interministériel program (FUI14, project dexEOS), and the ParisTech BiomecAM chair program on subject-specific musculoskeletal modelling, and in particular COVEA and Société Générale. D. Subit thanks the European Union for financial support through the Marie Curie International Incoming Fellowship (FP7-PEOPLE-2013-IIF, project BioAge # 622905). The views expressed in this article are those of the authors and do not necessarily represent the views of the funding bodies.

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