Journal of Biomechanics 47 (2014) 1548–1553

Contents lists available at ScienceDirect

Journal of Biomechanics

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

Short communication

Non-destructive assessment of human ribs mechanical properties using quantitative ultrasound

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ARTICLE INFO

Article history:
Accepted 25 January 2014

Keywords:
Modulus of elasticity
Maximal strength
Cortical bone
Quantitative ultrasound
Ultrasound velocity

ABSTRACT

Advanced finite element models of the thorax have been developed to study, for example, the effects of car crashes. While there is a need for material properties to parameterize such models, specific properties are largely missing. Non-destructive techniques applicable *in vivo* would, therefore, be of interest to support further development of thorax models. The only non-destructive technique available today to derive rib bone properties would be based on quantitative computed tomography that measures bone mineral density. However, this approach is limited by the radiation dose. Bidirectional ultrasound axial transmission was developed on long bones *ex vivo* and used to assess in vivo health status of the radius. However, it is currently unknown if the ribs are good candidates for such a measurement. Therefore, the goal of this study is to evaluate the relationship between *ex vivo* ultrasonic measurements (axial transmission) and the mechanical properties of human ribs to determine if the mechanical properties of the ribs can be quantified non-destructively. The results show statistically significant relationships between the ultrasonic measurements and mechanical properties of the ribs. These results are promising with respect to a non-destructive and non-ionizing assessment of rib mechanical properties.

This *ex vivo* study is a first step toward in vivo studies to derive subject-specific rib properties.

1. Introduction

Thoracic injuries are frequently observed in automotive collisions and have been reported to be a major cause of automotive related fatalities (van Don et al. 2003; Kent et al. 2005a; Brumbelow and Zuby, 2009). The thorax accounts for approximately 30% of injuries to belted drivers over age 34 who are fatally injured in frontal collisions (Kent et al. 2005b). To improve users' safety, enhanced knowledge of the ribcage biomechanics is needed (Stitzel et al. 2003; Kemper et al. 2005; Vezin and Berthet, 2009). Based on biomechanical knowledge, numerical models have mainly focused on standard individuals (e.g. 50th percentile male) (Ruan et al. 2003; Song et al. 2009). However, there is a need to improve protection for the entire population of transport users. Thus, specific thorax models have been developed for children (Mizuno et al. 2005; Jiang et al. 2012), the small female (Kimpara et al. 2005), and for adults taking into account the aging effect (Kent et al. 2005a; El-Jawahri et al. 2010; Forman et al. 2012).

The global geometry of the ribcage can be obtained from medical imaging, and in particular using biplanar X-rays (Dansereau and Stokes, 1988; Benameur et al. 2005; Mitton et al. 2008; Jolivet et al. 2010), to build these specific models. Detailed geometry (*e.g.* cortical thickness) can be obtained from high-resolution computed tomography. In addition to these geometrical features, the mechanical properties of the bone must be considered to build specific models, as Kemper et al. (2007) concluded .

Variations of the trabecular bone properties produce a negligible influence on rib response (Li et al. 2010). Thus, our study focuses on the cortical bone. The age effect on cortical bone mechanical properties has been assessed at the femoral, humeral, and tibial locations. The failure properties (strength, strain, energy) of these cortical bones were found to decrease with age

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http://dx.doi.org/10.1016/j.jbiomech.2014.01.052
0021-9290

(Lindahl and Lindgren,1967; McCalden et al., 1993; Zioupos and Currey, 1998), whereas no variation (Lindahl and Lindgren,1967; McCalden et al., 1993) or decrease with age (Zioupos and Currey, 1998) was reported for the modulus of elasticity. For the ribs, maximal strength was also found to decrease with age (Stein and Granik, 1976). However, studies which have quantified other material properties of human ribs were either performed on groups of subjects too small (3 to 6 subjects) to draw reliable conclusions regarding the effect of age (Granik and Stein, 1973; Kemper et al., 2005; Kemper et al., 2007) or the age effect was not assessed (Yoganandan and Pintar, 1998; Subit et al., 2013). In addition, the effect of age has not been well documented for children due to the limited availability of pediatric tissue (Agnew et al., 2013; Crandall et al., 2013). Thus, a non-invasive technique applicable in vivo is of interest for the assessment of age effect on the mechanical properties of the rib cortical bone during both growth and aging.

How can the apparent mechanical properties of the ribs be measured non-invasively? Today, quantitative computed tomography is the only clinical modality that could provide a non-invasive estimation of rib mechanical properties based on rib density measurements. This approach relies on the hypothesis that the relationship between bone mineral density (assessed using quantitative computed tomography) and modulus of elasticity, which has been determined for vertebral cancellous bone (Kopperdahl et al., 2002) and femoral cortical bone (Duchemin et al., 2008) can be determined for the ribs (Zhu et al., 2013). One drawback of this approach is the radiation dose of this imaging modality. To overcome this limit, ultrasound techniques offer an interesting alternative. An ultrasound method (*ex vivo* in a water tank) has been applied on rib specimens collected during surgery (Berteau et al., 2012). In the current paper, bidirectional axial transmission was used as it allows bone examination through the skin (Talmant et al., 2009; Kilappa et al., 2011). We assume that this technique, initially developed for peripheral long cortical bones (radius, tibia, phalanges) (Bossy et al., 2004a), can be extended to the ribs. The goal of this study is to assess the relationship between ex vivo ultrasonic measurements (axial transmission) and the mechanical properties of human ribs obtained from three-point bending experiments.

2. Materials and methods

2.1. Specimens

Seventeen human rib specimens (6 and 8 levels), from 9 subjects (67–80 years old) were provided by the Departement Universitaire d'Anatomie Rockefeller (Lyon, France) through the French program on voluntary corpse donation to science. Rib segments (120 mm long) were cut from the midsection of each rib (Fig. 1) to perform three complementary measurements. Specimens were kept frozen (−20 °C) until the experiments. They were thawed at 4 °C for 12 h and at 20 °C for 2 h before the experiments.

2.2. Experiments

First, all segments were scanned using a High Resolution peripheral Quantitative Computed Tomography (HR-pQCT) device (XtremeCT, Scanco Medical AG, Brüttisellen, Switzerland) that provides parallel slices with an isotropic voxel size of 82 μm (Fig. 2). The orientation of the rib in the CT scanner was maintained in a foam in a similar position to the one of the 3-point bending experiment. Gray level images were segmented semi-automatically using a Gaussian filter and a threshold-based algorithm incorporated within the manufacturer's analysis software (μCT Evaluation, Scanco Medical AG, Brüttisellen, Switzerland). The separation of the cortical and trabecular bone compartment was based on a double contouring method of the periosteal and endosteal margins (Burghardt et al., 2010).

The Cortical thickness (Ct.Th) and cross-sectional area moment of inertia needed for the calculation of mechanical properties were computed within the scanner manufacturer's Image Processing Language (IPL V5.16, Scanco Medical AG, Brüttisellen, Switzerland). The Ct.Th was calculated using a direct method (Hildebrand et al., 1999).

Then, ultrasound measurements were performed along the bone surface, using the bidirectional axial transmission extensively described in Bossy et al. (2004b). The ultrasound parameter is the velocity of the first arriving signal (VFAS). Measurements were performed on the central area of the samples, with the probe positioned on the external side of the rib, using a standard ultrasound gel. The average value of triplicate VFAS measurements performed on each specimen with intermediate repositioning was kept for the final analysis.

Fig. 1. The rectangle represents the location of the specimen (120 mm) cut from the rib.

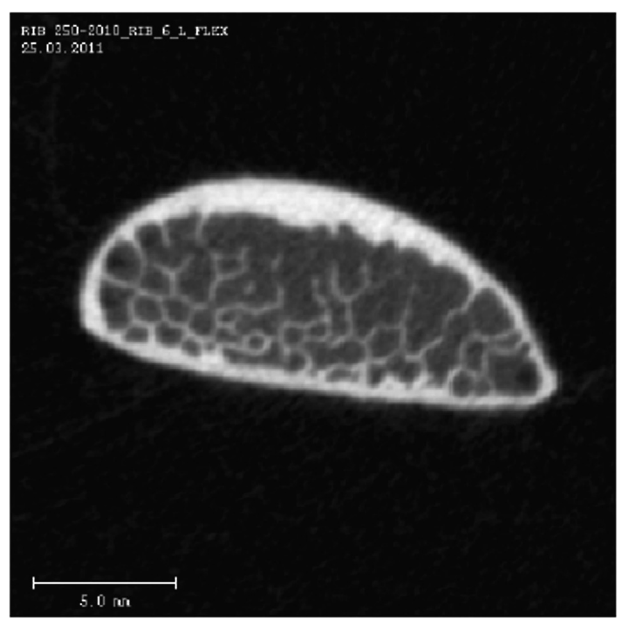

Fig. 2. Gray level image of a cross-section of a rib specimen performed by the HR-pQCT device (voxel size of 82 μm) illustrating bone tissue.