METHODOLOGY TO PREDICT THRESHOLDS FOR LOADING CORRIDORS OF HUMAN RIBS

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ABSTRACT

Bone properties are changing during a human life, e.g. bone mineral density is decreasing. Hence, bones of elderly people do not withstand loads which are still manageable by young people. The objective of the study was to establish a methodology to predict and adjust thresholds for force-deflection curves according to gender, age, rib cross-section and rib mineral density. Specimens of five fresh post mortem human surrogates were examined. Bone mineral density was measured and specimens were subjected to 3-point-bending tests. The findings could be used to limit loading corridors of ribs in human body models according to gender aspects.

Keywords: Thorax, Bones, Restraint Systems, Safety Belt, Models

A certain number of publications have been identifying bone properties. Mainly femur (Ashmann et at., 1988), tibia (Choi et al. 1990), pelvic (Dalstra et al. 1993), or vertebra (Nicholson et al. 1997) bones were examined. Other studies were investigating the properties of iliac crest (Kuhn et al. 1989) or mandible (Ashmann et al. 1987) bones. Within these studies specimens were dissected and separated into cortical and cancellous bone. Specimens were subjected to tension and/or compression tests. In other research activities bone properties were evaluated without fracturing specimens (Rho et al. 1993). Though a number of publications on the mechanical properties of these body parts exist, human ribs haven't been investigated in such detail:

Granik (1973) and Stein (1976) used specimen from lateral sixth and seventh rib subjected to a three-point bending test. Schultz et al. (1974) showed that there is no difference in strength of different ribs. Cormier (2003) studied the mechanical properties of specimens taken from the thoraces of four cadavers, using anterior, lateral and posterior parts from rib two to twelve. In total 59 specimens (two males, two females) including periosteum were analysed. Prior to the tests bone mineral density (BMD) was measured. Kemper et al. (2007, 2006) separated cortical bone from cancellous bone of six cadavers between 42 and 81 years old. Specimens from first to twelfth rib of anterior, lateral and posterior section were prepared as dog-bones and bone mineral density was measured. In total 117 specimens were dissected. No differences in material properties were reported for different positions of the ribs. The authors reported that bones become more brittle with increasing age. Laporte (2008) used five rib cages (30 ribs in total from level 4 to 9) in dynamic tests. Prior to the tests the ribs were scanned by computer tomography (CT) technique for geometric analysis. The loading curves and CT scans were used in a finite element model. No information is given on the bone mineral density but the author concludes that simulations showed a strong sensitivity of the mechanical properties to rib geometry.

Rib fractures are serious injuries and are sustained by almost 40% of elderly passengers (Kent et al. 2005). Stein and Granik (1976) reported that mechanical characteristics of human ribs change with age. Kemper et al. (2007) found a difference in the local mineral density of ribs, although this difference (between the anterior and lateral thorax) was found to be small. The provision of a balanced protection for occupants being different in age and gender is a huge challenge for restraint systems. For the development of new restraint systems appropriate loading limits as a function of age and gender are highly needed in order to further mitigate severe injuries to the thorax and the thoracic content.

The goal of this research is to show up the possibility to predict loading corridors for people being different with respect to age and gender based on force-deflection curves of fresh rib specimen. These force-deflection corridors should border upper and lower loading limits of human ribs according to gender or age groups. Force -displacement curves from approximately 140 specimens were analysed.

METHOD

Ribs from five fresh post mortem human surrogates (PMHS), three male and two female, were examined. Ethical approval was provided by the research ethics committee at the Medical University Graz. Three subjects (one young male, two elderly female) were studied in 3-point bending tests. The thoraces of the other two elderly males were exclusively used for measuring bone mineral density. The ribs were separated into specimens of seven centimetres in length, distinguishing between anterior, lateral and posterior thoracic position, resulting n a total of 140 specimens. Bone mineral density of each specimen was determined by Dual-X-Ray-Absorptiometry (DXA), where "density" is defined as mass per cross-sectional area (g/cm²). (Remark: This unit is widely used in clinical examination to quantify and identify osteoporosis.) In addition the geometry (height, width, radius of costal arch) of all specimens were measured.

It is evident, that human ribs form a three-dimensional arch reaching from the vertebra to the sternum. Hence, a test set-up was designed to ensure equal test conditions for all specimens. For the adjustment and fixation of the bones in the test setup (3-point-bending tests) both ends of the specimen were anchored with bone cement in metal cylinders. These cylinders are suspended in prismatic brackets (see Figure 1). The specimens were positioned such that the impactor loads the top of the arched specimen. The prismatic brackets are rigidly connected to the subframe. Such the movement (expansion) of the specimen in x-axis is constrained. The dynamic loading to the rib specimen were applied by a Testmatic Z3-X500 testing machine with loading rates at 10 mm/min (100 Hz), 100 mm/min (200 Hz) and 500 mm/min (1.000 Hz). Load cell and displacement transducers were directly attached to the impactor. Due to the low loading rates signals were smoothed rather than filtered.

Previous studies were investigating the mechanical behaviour of ribs by three-point-bending tests of the whole rib (Charpail 2006, Laporte 2008) or smaller rib-sections (Cormier 2003, Granik et al. 1973, Kepmer et al. 2007, Yoganandan et al. 1998). They performed the test by loading the specimen up to failure in one single loading cycle. Here, the specimens were loaded several times starting at a low loading level, working up in small steps until the specimen failed. The loading levels were defined by using specimens in pre-test. Attention was paid to the selection of the specimens, such that the dependency of load- rates is available for each region of the thorax. However, load rates were applied to specimens that in total each region of the rib is loaded with the defined rates.

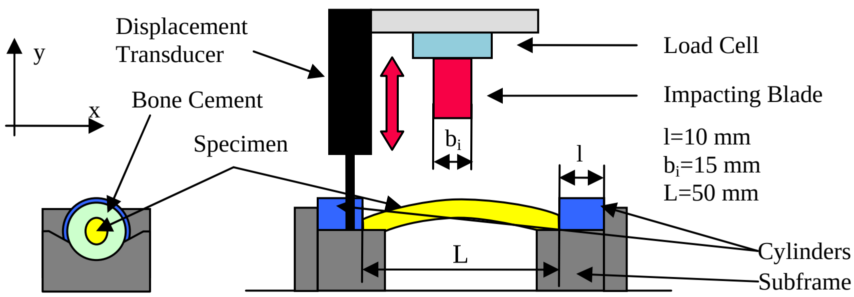

Figure 1: Test set-up

RESULTS

It was found that bone mineral density is not constant throughout the arch. Density is increasing from sternum towards to the vertebra. This tendency was identified for males and females (Table 1) as well as for young and elderly people (Table 2). A Pearson Correlation analysis was used and it was found that young male (r=0,778) and female (r=0,677) subjects have a highly positive correlation. It has to be pointed out that only one young subject was analysed. Considering the two elderly males, the correlation between BMD and specimen position resulted in a lower correlation coefficient of r=0,233.

ANOVA test of BMD showed a significant difference between specimens taken from the sternal vicinity (anterior section) compared with specimens taken from the vertebraic vicinity (posterior section, p=0,001). A significant lower BMD (p=0,034) was identified for anterior sections compared with the lateral sections. The difference in BMD between lateral and posterior sections was not found to be significant (p=0,256).

For the comparison of BMD in males and females only specimens of the elderly subjects were used, such that the results of the young subject do not influence the analysis (see Table 2). BMD of males and females show a significant difference (p=0,000).

Table 1: BMD according to position of the specimens within a rib and gender (elderly people)

	anterior section BMD [g/cm²]	lateral section BMD [g/cm²]	posterior section BMD [g/cm²]	Mean BMD BMD [g/cm²]
Male	0,290 (SD=0,103)	0,332 (SD=0,101)	0,363 (SD=0,112)	**0,308 (SD=0,104)**
Female	0,173 (SD=0,025)	0,264 (SD=0,064)	0,296 (SD=0,057)	**0,246 (SD=0,072)**
Mean BMD	**0,268 (SD=0,104)**	**0,312 (SD=0,096)**	**0,317 (SD=0,081)**	**0,291 (SD=0,100)**

Table 2: BMD according to position of the specimens within a rib and age

	anterior section BMD [g/cm²]	lateral section BMD [g/cm²]	posterior section BMD [g/cm²]	Mean BMD BMD [g/cm²]
Young	0,406 (SD=0,061)	0,568 (SD=0,051)	0,591 (SD=0,064)	**0,516 (SD=0,103)**
Elderly	0,268 (SD=0,104)	0,312 (SD=0,096)	0,317 (SD=0,081)	**0,291 (SD=0,100)**

It was found that specimens have similar force-deflection curves when selecting those with more or less identical geometry (width, height and radius) and bone mineral densities. The left diagram in Figure 2 shows force-displacement curves of specimens taken from different rib locations of one single subject. The right diagram shows force deflection curves of specimens taken from different subjects but being similar w.r.t. geometry and BMD.

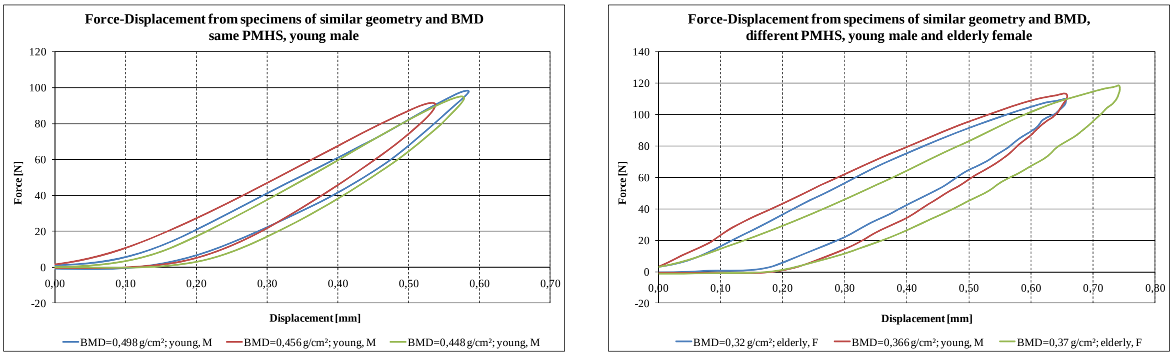

Figure 2: Force Displacement Graphs for different specimens

In the next step, a parameter is identified in order to adjust the mechanical properties of ribs to age, gender and thoracic section. The deflection of each single test curve was linearly scaled with the BMD in order to eliminate this parameter (see Figure 3 left hand side). In this figure the force-deflection curves of three different specimens are shown: one young PMHS, 37 years old with a bone mineral density of 0,539 g/cm² and two elderly PMHS (58 years, BMD=0,28 g/cm²; 65 years, BMD=0,369 g/cm²). Using these three normalised curves, an arithmetic mean curve was created. In a second step the mean-curve was scaled with a factor according to age and appropriate rib section (see Figure 3 right hand side). This factor is the reciprocal of the mean BMD for a specific age group (as found for the investigated cadavers). Applying the reciprocal factor (RF) for elderly subjects (RF=3,15) the lower limit of force-deflection curves is determined and with the reciprocal factor for young subjects (RF=1,69) the upper limit is determined.

DICSUSSION

Examination of BMD indicated an increasing tendency from sternum towards to the vertebra. This behavior was noticed for males and females as well as for young and old subjects. From force-deflection graphs it was found that all of the tested specimens with their individual geometries and bone mineral densities showed diverse characteristic. However, specimens with equal parameters (BMD, geometry) show similar behavior even when comparing PMHS of different age groups. This pilot study indicates that it is possible to identify parameters for determining upper and lower limits of force-deflection curves.

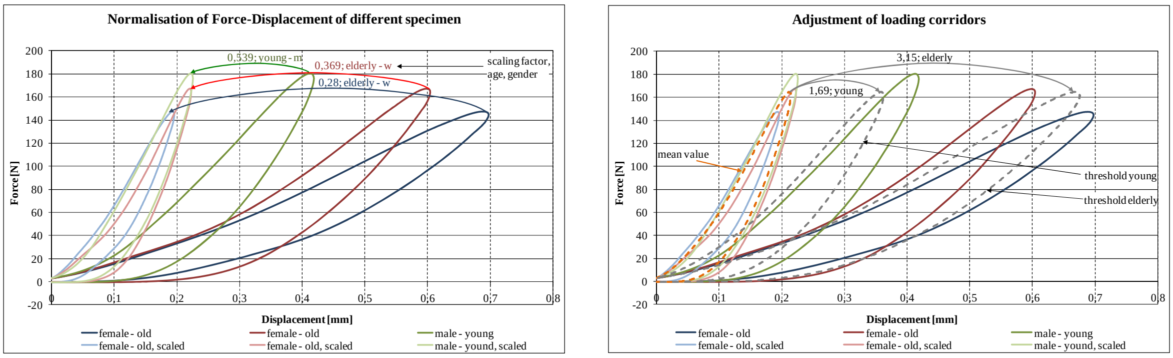

Figure 3: Scaling methodology for Force Displacement Graphs

LIMITATIONS

A major limitation is the low number of different subjects. Only three PMHS were used for the scaling methodology. It would be an important impact to validate this method with rib specimens from younger females and elderly males. Another sample should reflect the age group between 20-30 years.

The DXA method is widely used in clinical examinations, however, only areal densities can be obtained. No information is given on the interior of the bone. Appropriate data can be provided by using Peripheral Quantitative Computed Tomography (pQCT), capable of determining the bone's trabeculae distribution.

OUTLOOK

For validation purposes additional set of specimens of young males and females should be used. If the findings can be approved within this introduced approach only one single material model could be used for different age groups. The reference material model probably can be implemented in a Finite Element program and bone properties can be adjusted in terms of requirements. Within this first approach BMD was used for scaling the loading curves. However, bone height and width was measured and results should be proved with moment of inertia (MOI) if similar outcome can be identified.

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