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Research Paper

The effect of age on the structural properties of human ribs

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ABSTRACT

Traumatic injury from motor vehicle crashes is a major cause of morbidity and mortality in the United States. The thorax is particularly at risk in motor vehicle crashes and is studied extensively by the injury biomechanics community. Unfortunately, most samples used in such research generally do not include children or the very elderly, despite the common occurrence of thorax injuries at both ends of the age spectrum. Rib fractures in particular, are one of the most common injuries, especially in the elderly, and can greatly affect morbidity, mortality, and quality of life. As the proportion of older adults in the population increases, such age-related fragility fractures will continually grow as a worldwide problem. Additionally, the risk of rib fracture significantly increases with age with confounding deleterious effects. Studies on elderly ribs are not uncommon, however very few studies exist which explore the mechanical properties and behavior of immature human bone, especially of ribs. Previous research identifying rib properties has provided useful information for numerous applications. However, no study has included a comprehensive sample of all ages (pediatric through elderly) in which ribs are tested in the same repeatable set-up. The goal of this study is to characterize differences in rib structural response across the age spectrum. One-hundred forty excised ribs from 70 individuals were experimentally tested in a custom-built pendulum fixture simulating a dynamic frontal impact. The sample includes individuals of ages ranging from six to 99 years old and includes 58 males and 12 females. Reported data include fracture location, displacement in the X and Y directions at fracture (δ_X, δ_Y), force at fracture (F_X), and linear structural stiffness (K). δ_X and K exhibit a statistically significant linear decrease with age ($p<0.0001$). F_X reveals a trend in which a peak is reached in the young adult years (25–40). Detailed

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mechanical property data, as provided here, will prove useful for application in computational modeling efforts, which are vital to help prevent injury and to understand injury mechanisms from childhood through old age.

1. Introduction

The thoracic skeleton is an important anatomical area to defend from injury because of its role in protection of vital organs (Bliss and Silen, 2002; Pattimore et al., 1992). Unfortunately, it is also one of the most commonly injured regions during a motor vehicle crash (MVC). Specifically, the thorax is the second most often injured body segment in *children* during MVCs (Brown et al., 2006). Kent et al. (2005a) examined crash experiences in older (65+ years) and younger (16–33 years) drivers between 1992 and 2002. In frontal crashes, 19% of injuries for drivers 65 and older were to the chest, while this number dropped to 9.8% for drivers 16–33. Fatal injuries to the chest occurred in 47% of older drivers, nearly double the number for the younger drivers.

Rib fractures, in particular, are prevalent in those of all ages in MVC's and can affect morbidity and mortality. The elderly are at high risk of rib fractures from MVC's and have an associated increased mortality due to those rib fractures (Bulger et al., 2000; Hanna and Hershman, 2009; Holcomb et al., 2003; Kent et al., 2008; Sirmali et al., 2003). Garcia et al. (1990) studied rib fractures in children, and concluded that the number of rib fractures a child obtained is correlated to the severity of injury and increased mortality rate. Of the study groups examined, motor vehicle occupants had the highest mortality rate, which increased with increasing number of rib fractures.

Thoracic injury criteria are usually related to chest compression, as measured at the sternum. Several studies have measured chest compression from dynamic and quasi-static tests for various loading patterns, many of which are summarized by Kent and Patrie (2005) (e.g., Cesari and Bouquet, 1994, 1990; Crandall et al., 1999; Kemper et al., 2011; Kent et al., 2003, 2001; Shaw et al., 2000). Rib cage geometry can influence thoracic injury tolerance, and has been characterized primarily through the use of chest CT scans to show age-related changes (Sandoz et al., 2013). Openshaw et al. (1984) noted that the most dramatic geometric changes occur during the first two years of life. The overall size of the rib cage stops changing around age 20–30 years, and a few studies have observed notable but inconsistent changes in rib angles throughout adulthood that could result in different thoracic geometry (Kent et al., 2005b; Weaver et al., 2014). Other studies have characterized the local geometry of the rib outside of the context of the thoracic region to determine overall change in curvature along the rib and other global geometric and cross-sectional properties (e.g., Mohr et al., 2007; Roberts and Chen, 1972).

Age-associated trends in injury tolerance could possibly be related to geometric or mechanical properties. A decrease in thoracic injury tolerance with increasing age has been noted (Kent and Patrie, 2005; Zhou et al., 1996). Specific properties of the thoracic skeleton can help elucidate the mechanisms behind such changes in injury thresholds. Several research studies have examined changes in bone material properties with age. Material tests by Evans (1973) revealed that ultimate tensile strength, tensile strain, and elastic modulus all decrease as adult age increases. Zioupos and Currey (1998) also found that ultimate strength, elastic modulus, fracture toughness, and energy to fracture decreased from age 35 to 92. Carter and Spengler (1978) hypothesized that the general degradation of material properties of bone occur due to the continuous remodeling of bone throughout life, and summarized several previous studies on material and compositional changes. Vinz (1975) noted that tensile strength and elastic modulus were lower for pediatric bone, peaked around age 40, and then decreased again in later middle and old age. Pediatric bone was also found to absorb greater energy to failure and deform more than adult bone specimens (Currey and Butler, 1975; Özkaya et al., 2012). A significant positive relationship between age and microcrack damage accumulation has also been demonstrated, and may contribute to bone quality degradation (Schaffler et al., 1995).

Several studies in the past have looked at rib material and structural properties. Stitzel et al. (2003) and Kemper et al. (2005) tested cortical bone specimens from anterior, lateral, and posterior aspects of several rib levels in 3-point bending and tension coupons, respectively. Results from the two studies pertaining to material and structural differences did not agree. Kemper et al. (2005) did find age to be a significant factor in determining material properties; however only one of the six subjects was considered adolescent (18 years old) and differences disappeared when this subject was removed. A later study by Kemper et al. (2007) examined anterior and lateral regions of ribs 4–7 in tension and 3-point bending specimens. Six male subjects (ages 42–81 years) were examined and only geometric property differences were observed between rib level and location. Cormier et al. (2005) tested whole bone specimens from four elderly cadavers (ages 61–71 years) and observed differences in strain at peak force and geometry based on rib level and location. None of these studies tested the entire rib structure, but rather used the straight section cut from the rib bones. The complex internal and external geometry of the rib as a whole could therefore not be assessed. Two previous studies by Charpail et al. (2005) and Kindig et al. (2011) have performed structural testing of whole ribs using a similar method to the current study. However, both studies only included a few adult subjects of similar ages, and were therefore unable to establish a relationship between age and whole rib properties.

Few studies have focused on experimental testing of subjects on the extremes of the normal age distribution