JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 51 (2015) 154–162

Available online at www.sciencedirect.com

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Research Paper

A novel ex vivo model of compressive immature rib fractures at pathophysiological rates of loading

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ARTICLE INFO

Article history:
Received 7 May 2015
Received in revised form
19 June 2015
Accepted 27 June 2015
Available online 16 July 2015

Keywords:
Rib fracture
Non-accidental injury
Forensic biomechanics
Loading rate
Axial compression

ABSTRACT

Introduction: Compressive rib fractures are considered to be indicative of non-accidental injury (NAI) in infants, which is a significant and growing issue worldwide. The diagnosis of NAI is often disputed in a legal setting, and as a consequence there is a need to model such injuries ex vivo in order to characterise the forces required to produce non-accidental rib fractures. However, current models are limited by type of sample, loading method and rate of loading. Here, we aimed to: i) develop a loading system for inducing compressive fractures in whole immature ribs that is more representative of the physiological conditions and mechanism of injury employed in NAI and ii) assess the influence of loading rate and rib geometry on the mechanical performance of the tissue.

Methods: Porcine ribs (5–6 weeks of age) from 12 animals ($n=8$ ribs/animal) were subjected to axial compressive load directed through the anterior–posterior rib axis at loading rates of 1, 30, 60 or 90 mm/s. Key mechanical parameters (including peak load, load and percentage deformation to failure and effective stiffness) were quantified from the load–displacement curves. Measurements of the rib length, thickness at midpoint, distance between anterior and posterior extremities, rib curvature and fracture location were determined from radiographs.

Results: This loading method typically produced incomplete fractures around the midpoint of the ribs, with 87% failing in this manner; higher loads and less deformation were required for ribs to completely fracture through both cortices. Loading rate, within the range of 1–90 mm/s, did not significantly affect any key mechanical parameters of the ribs. Load–displacement curves displaying characteristic and quantifiable features were produced for 90% of the ribs tested, and multiple regression analyses indicate that, in addition to the geometrical variables, there are other factors such as the micro- and nano-structure that influence the measured mechanical data.

Conclusions: A reproducible method of inducing fractures in a consistent location in immature porcine ribs has been successfully developed. Fracture appearance may be indicative of the amount of load and deformation that produced the fracture, which is an

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http://dx.doi.org/10.1016/j.jmbbm.2015.06.031
1751-6161/

important finding for NAI, where knowledge of the aetiology of fractures is vital. Characteristic rib behaviour independent of loading rate and, to an extent, rib geometry has been demonstrated, allowing further investigation into how the complex micro- and nano-structure of immature ribs influences the mechanical performance under compressive load. This research will ultimately enable improved characterisation of the loading pattern involved in non-accidental rib fractures.

1. Introduction

Non-accidental injury (NAI) in infants is a significant medico-legal issue worldwide and rib fractures, in the absence of major accidental trauma, are highly indicative of NAI in children of non-ambulatory status (typically under 18 months of age) (Cadzow and Armstrong, 2000; Worn and Jones, 2007). In court cases relating to suspected NAI, the level of force required to cause the rib fractures is often deliberated, however, there have been no convincing models replicating compressive force that would allow this question to be confidently addressed. It is therefore of great importance that research is undertaken to understand the mechanical performance of immature ribs under compressive load, and how tissue structure influences this, in order to determine the cause of clinically presenting fractures with a greater degree of certainty.

Non-accidental rib fractures are generally thought to be produced by anterior–posterior compression of the thorax, usually in combination with the shaking of the child (Chapman, 2004; Worn and Jones, 2007). As a result of this thoracic compression, fractures in infants can occur in any region of the rib; posterior rib fractures, which result from the levering of the rib over the transverse process of the vertebra, are considered to be characteristic of NAI, whereas lateral rib fractures are generally more common and less characteristic of NAI (Barsness et al., 2003; Kleinman et al., 1995). However, the prevalence and location of rib fractures reported in studies of this nature varies and it remains difficult to accurately diagnose NAI based on the location and number of rib fractures alone, hence the necessity for further research in to the fundamental structure and mechanical properties of immature ribs.

The structure of immature ribs in the first year of life, when there is the greatest rate of bone growth (Miller et al., 2014), is highly dynamic and variable. As described in detail in Agnew et al. (2013), developing ribs undergo a process known as cortical drift, which significantly alters the location of various types of primary (woven, lamellar and fibrolamellar) and secondary bone (lamellar bone with signs of remodelling) throughout the cortex of the rib, resulting in an uneven distribution of microstructural features. To our knowledge, an in depth study investigating the micro- and nano-structure of immature ribs (in humans or animals) and how this influences the mechanical performance of the whole bone under compressive load has never been undertaken.

As reviewed, numerous retrospective studies have reported the incidence and location of paediatric rib fractures that occur in NAI (Cadzow and Armstrong, 2000; Darling et al., 2014; Garcia et al., 1990), yet there are few studies that have investigated the structure and mechanical performance of immature ribs. Moreover, the application of existing studies of this nature to the context of non-accidental rib fractures is limited by the rate of load application, the method of applying the load and the source of the samples. One such study subjected 1 day old porcine ribs to 4-point loading at a rate of 10 mm/min (Bradley et al., 2014). In the study, fractures of fresh ribs could not be produced, and indeed previous unreported work by the authors here found that ribs axially compressed at 5 mm/min also failed to fracture. It is widely reported in the literature that bone is viscoelastic and will behave differently depending on the rate at which it is loaded (Agnew et al., 2013; Carter and Hayes, 1976; Kulin et al., 2011), suggesting that fresh immature ribs do not fracture under quasi-static loading conditions.

The utilisation of a 4-point bending method of loading (Bradley et al., 2014; Kieser et al., 2013) removes the capacity to investigate how the whole rib would respond to axial compression, which is perhaps more demonstrative of the type of loading to which the ribs would be subject in the context of NAI. Studies by Agnew et al. (2015) and Daegling et al. (2008) applied dynamic axial compression to whole ribs, however the youngest ribs tested in either of these studies were 6 years of age (Agnew et al, 2015), which is beyond the age range (up to around 18 months of age) of the individuals that present with non-accidental rib fractures (Worlock et al., 1986). Moreover, the human samples used in these two studies have the potential to be compromised by damage or disease.

Therefore, the aims of this study were to: i) develop a reproducible method of inducing compressive fractures in whole immature porcine ribs in a manner that is more representative of the loading involved in non-accidental rib fractures and ii) assess the influence of loading rate on the mechanical performance, which to our knowledge has never been addressed in immature ribs.

2. Materials and methods

2.1. *Biological samples*

There are clear ethical and practical issues related to the use of paediatric human ribs, hence a suitable animal model is required for this type of study. Compared to the bone of other species such as dogs and sheep, porcine bone has been