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A comparison between rib fracture patterns in peri- and post-mortem compressive injury in a piglet model

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ABSTRACT

Objectives: Forensic biomechanics is increasingly being used to explain how observed injuries occur. We studied infant rib fractures from a biomechanical and morphological perspective using a porcine model.

Methods: We used 24, 6th ribs of one day old domestic pigs *Sus scrofa*, divided into three groups, desiccated (representing post-mortem trauma), fresh ribs with intact periosteum (representing peri-mortem trauma) and those stored at -20 °C. Two experiments were designed to study their biomechanical behaviour fracture morphology: ribs were axially compressed and subjected to four-point bending in an Instron 3339 fitted with custom jigs. Morphoscopic analysis of resultant fractures consisted of standard optical methods, micro-CT (μCT) and Scanning Electron Microscopy (SEM).

Results: During axial compression fresh ribs did not fracture because of energy absorption capabilities of their soft and fluidic components. In flexure tests, dry ribs showed typical elastic–brittle behaviour with long linear load-extension curves, followed by short non-linear elastic (hyperelastic) behaviour and brittle fracture. Fresh ribs showed initial linear-elastic behaviour, followed by strain softening and visco-plastic responses. During the course of loading, dry bone showed minimal observable damage prior to the onset of unstable fracture. Frozen then thawed bone showed similar patterns to fresh bone. Morphologically, fresh ribs showed extensive periosteal damage to the tensile surface with areas of collagen fibre pull-out along the tensile surface. While all dry ribs fractured precipitously, with associated fibre pull-out, the latter feature was absent in thawed ribs.

Conclusions: Our study highlights the fact that under controlled loading, fresh piglet ribs (representing perimortem trauma) did not fracture through bone, but was associated with periosteal tearing. These results suggest firstly, that complete lateral rib fracture in infants may in fact not result from pure compression as has been previously assumed; and secondly, that freezing of bone during storage may affect its fracture behaviour.

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1. Introduction

Rib fractures in infants are uncommon, but when diagnosed, are often associated with child abuse (Bulloch et al., 2000; Worn and Jones, 2007). In fact, Cosway et al. (2011) have recently argued that occult rib fractures in infancy have the highest positive predictive value for physical child abuse of all fractures. While manual antero-posterior compression of the chest such as occurs in the shaken baby syndrome is thought to be the primary mode of such injuries (Betz and Liebhardt, 1994), some studies have called this into question (Wolfson et al., 2005; Findley et al., 2012). Additionally, there has been a recent increase in the number of infants presenting at autopsy with rib fractures associated with cardiopulmonary resuscitation (Reyes et al., 2011). Moreover, there is evidence for rib fractures in archaeological settings, with such fractures possibly attributable to infant swaddling (Lewis, 2009). The question thus arises, how can fractures of immature ribs be better understood?

Non-accidental fractures and injuries in children are often associated with child harm. One of the earliest studies on child abuse was undertaken in 1946 by Caffey who used the term *whiplash shaken-baby syndrome* as a collective representation of the multitude of injuries found on battered children. This term was then changed to *battered child syndrome* and denoted the collection of metaphyseal lesions, rib fractures and subdural haemorrhaging found on abused infants (Kempe et al., 1962). A number of studies have shown that such injuries are most common in children under the age of 2 yr (Thomas,1977; Feldman and Brewer, 1984). Rib fractures in particular are quite rare given the high malleability of infant chests, thus the finding of rib fractures raises the suspicion of child abuse given that the forces applied to the ribs must have exceeded a certain point in order to cause fracture (Bilo et al., 2010). The mechanism of rib fracture and the force limit at which this fracture occurs are not well understood, as to date there have been no experimental studies to determine the maximum compressive limit of infant ribs. Current literature suggests that there are two means of producing rib fractures in infants: static compressive loading and dynamic impact loading.

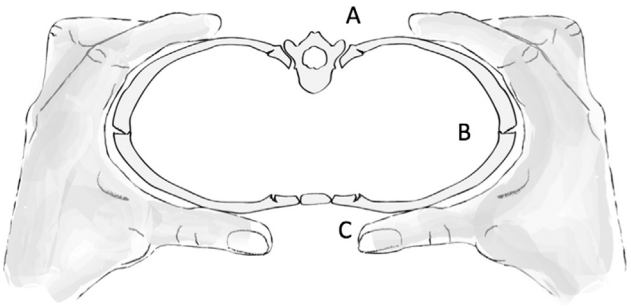

Fig. 1 – Infant rib fracture under manual compression may hypothetically lead to failure in three regions; over the transverse vertebral process (A), along the lateral arc (B) and at the sternal head (C). Failure will be initiated in the tensile pulmonary surfaces of (A) and (C), and the outer surface of (B).

Compression fractures occur when the chest deforms through encircling the rib cage with both hands and squeezing or compressing (Cadzow and Armstrong, 2000; Barsness et al., 2003; Bilo et al., 2010), with the fractures located where the most mechanical force and leverage are applied, see Fig. 1. Hence, excess force may lead to failure in three main regions; over the transverse-vertebral process (Fig. 1a), along the lateral arc (Fig. 1b) and at the sternal end (Fig. 1c) (Worn and Jones, 2007). While failure will be initiated in the tensile pulmonary surface of 1a and 1c, fracture will commence on the tensile outer surface in 1b. The prevalence of lateral arc fractures in infants is highly variable and is reported to range from 16% to 41% (Feldman and Brewer, 1984; Cadzow and Armstrong, 2000; Barsness et al., 2003). However, Worn and Jones (2007) note that these figures tend to be lower than those reported in older children, leading them to hypothesise that there were possible links between lateral rib fractures and the material properties of infant ribs.

The present study was primarily designed to study the differences between peri- and post-mortem rib fractures in a piglet model. The secondary objectives were to apply our observations of failure dynamics and morphoscopy to the issue the forensic biomechanics of rib fractures in infants, and also to determine the effect of freezing as a storage method on experimentally fractured infant ribs.

2. Materials and method

Twenty-four piglets, all approximately new born or one day old, were used in two different protocols. Domestic pigs, *Sus*

Fig. 2 – A piglet rib fitted into a custom made four-point bending jig.