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Research Paper

Biomechanical investigation of impact induced rib fractures of a porcine infant surrogate model

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ABSTRACT

This study investigated the structural, biomechanical and fractographic features of rib fractures in a piglet model, to test the hypothesis that fist impact, apart from thoracic squeezing, may result in lateral costal fractures as observed in abused infants. A mechanical fist with an accelerometer was constructed and fixed to a custom jig. Twenty stillborn piglets in the supine position were impacted on the thoracic cage. The resultant force versus time curves from the accelerometer data showed a number of steps indicative of rib fracture. The correlation between impact force and number of fractures was statistically significant (Pearson's $r=0.528$). Of the fractures visualized, 15 completely pierced the parietal pleura of the thoracic wall, and 5 had butterfly fracture patterning. Scanning electron microscopy showed complete bone fractures, at the zone of impact, were normal to the axis of the ribs. Incomplete vertical fractures, with bifurcation, occurred on the periphery of the contact zone. This work suggests the mechanism of rib failure during a fist impact is typical of the transverse fracture pattern in the anterolateral region associated with cases of non-accidental rib injury. The impact events investigated have a velocity of ~2–3 m/s, approximately 2×10^4 times faster than previous quasi-static axial and bending tests. While squeezing the infantile may induce buckle fractures in the anterior as well as posterior region of the highly flexible bones, a fist punch impact event may result in anterolateral transverse fractures. Hence, these findings suggest that the presence of anterolateral rib fractures may result from impact rather than manual compression.

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1. Introduction

Rib fracture in infants is frequently, but not exclusively, associated with child abuse (Cadzow and Armstrong, 2000; Worn and Jones, 2007; Bulloch et al., 2000). Because manual antero-posterior compression of the chest, typically seen in the so-called shaken baby syndrome, is thought to impose enough force on the ribs to result in fracture, these injuries have become pathognomonic of physical abuse in otherwise healthy children (Cosway et al., 2011; 2013; Sheets et al., 2013). An overarching question in studies of child trauma and abuse is the biomechanical mechanism of such injury (Betz and Liebhardt, 1994) reflecting a long running inquiry in the general area of bony fracture in infants.

Biomechanical analysis has gained popularity within the medical and forensic literature as a means of quantifying and visualizing bony fracture patterns in a variety of situations. Most of this research has focused on orthopedic fracture of long bones in adults and the related subject of skeletal fragility due to osteoporosis [see (Al Nazer et al., 2012; Basso et al., 2012; Kieser et al., 2012) for reviews]. Recently, various mechanical application approaches and fractographic analysis have been used in order to explore the biomechanics of rib fracture in an adult pig model as a surrogate for human material (Kieser et al., 2013; Bradley et al., 2014). The first of these studies focused on compressive rib fractures in adult pigs and on the ability to differentiate between perimortem and postmortem injuries of legal significance, especially in cases of rib fracture related to cardiopulmonary resuscitation (CPR). The results pointed to significant differences in fracture behavior between fresh and dry rib bones, with the former showing initial linear-elastic behavior followed by strain softening and visco-plastic mechanical response. Morphologically, fresh porcine bone showed buckling on the compressive surface with cracking on the tensile surface, with the periosteum playing a significant role in crack bridging. The results of the latter study, carried out using pigs (Bradley et al., 2014), showed that axial compression of fresh juvenile porcine ribs did not result in fracture, given the considerable energy-absorption capability of soft and fluidic components within the infantile bone. The above raises the question as to the bio-fidelity of the piglet model to simulate human infants. Various studies (Kent et al., 2013; Oyen et al., 2006; Baumer et al., 2006) have used young piglets to simulate a variety of pediatric conditions including crash simulation of the thorax and abdomen as well as child abuse. In addition an older study (Margulies and Thibault, 2000) showed that elastic modulus, rupture modulus and energy absorbed to failure of 2–3 day old piglets was approximately equivalent to neonates.

Similar behavior to that found for the porcine rib fracture (Kieser et al., 2013; Bradley et al., 2014) was also reported by Agnew et al. (2013) in their recent comprehensive study of flexural responses in human infant ribs. This raises the critical question; if fresh infantile ribs could not be broken under axial loading, considered comparable to thoracic squeezing, what would cause classical lateral rib fractures observed in abused infants? In addition, the presence of skin, muscles and internal pressure within the lungs would potentially further resist the onset of fracture. Another factor that previous research has failed to explore is the rate at which the loading force is applied. With most laboratory studies (Kieser et al., 2013; Bradley et al., 2014; Agnew et al., 2013), the loading rates have been relatively low, typically less than 0.16 mm s^{-1}. These loading rates may not necessarily accord with those found in forensic cases of infant rib fracture.

Recent studies of rib fracture of infants by Love et al. (2013) have focused on a classification of rib fractures based upon post-mortem examination of all infant deaths over a one year period by the Harris County Institute of Forensic Sciences (Texas USA). These authors, on the basis of their examinations, were able to assign fractures to one or more of four regions of the ribs of children and also define the nature of the fracture. The majority of the fractures were present in the anterior (51.2%) followed by anterolateral (26.0%), posterior (19.0%) and posterolateral (3.8%) regions. The form of the factures was very mixed in the anterior with almost equal occurrence of sterna end, buckle and transverse fracture, a higher incidence of transverse fracture in the anterolateral region and only transverse fracture in the posterior. These authors suggest that the presence of anterior and posterior cracking, on the basis of observations on near mature rabbits and associated analysis by Kleinman and Schlesinger (1997), was indicative of thoracic squeezing. Also, a very recent study by Pavier et al. (2016) investigated rib fracture following impact with low velocity “rubber tipped” bullets used in riot control. They investigated the impact of an adult pig thorax which had been strain gauged and also with high speed cameras to determine the impact mechanics.

This article focuses on an alternative to manual squeezing induced compression of the thoracic cage as the causation of rib fractures in children. The main goal is to investigate if an impact and associated higher loading rate, rather than compression induced bending, of juvenile ribs can result in fractures. It is often claimed in court cases that squeezing between the thumb and fingers of an infantile thorax or compression induced bending can result in rib fractures (Bulloch et al., 2000; Williams, 2002; Bilo et al., 2010). In particular, this paper explores the hypothesis that while manual compression acts to distribute pressure evenly across highly flexible bones, and may cause fracture with very high magnitude forces, it is however impact events, such as the blow of an adult fist, that are also possible origins of such fractures, especially in the anterolateral region. The study then attempts to quantify the magnitude of fist induced impact forces required to cause such fracture of juvenile piglet ribs.

2. Materials and methods

2.1. Materials

Stillborn piglets, associated with a normal litter delivery, were commercially acquired (Bloem's Piggery, Highcliff Rd, Dunedin, NZ) and stored at 4 °C. These were typically retrieved less than 12 h after the piglet litter was born. The