Rib Fractures in Infants: Retrospective Survey of Fractures and Biomechanical Study.

By

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Abstract

Literature suggests that rib fractures are highly associated with abuse and the present understanding is that antero-posterior compression associated with the ‘shaken baby syndrome’ is their cause. However, this mechanism rests on a number of assumptions with little experimental data to support them. Recent work using a porcine model of fractures suggests that, in the case of lateral fractures this may be highly unlikely. This work shows a feasible alternate mechanism, that of blunt force trauma (BFT), for the cause of these lateral fractures. A piglet model is used and shows the ease with which ribs fracture as a result of BFT, compared to the difficulty of fracture seen previously in compressive injury. The initial development of a computational simulation of these ribs for use in injury scenarios is also outlined here.

Secondly, skeletal surveys from New Zealand’s largest children’s care facility, Starship Hospital, were examined to give a picture of non-accidental injury (NAI) and how its patterns compare with accidental injury in New Zealand. It has been found that, as in foreign studies, there are a number of lesions highly associated with abuse and these include rib fractures, which are highly specific (97%) for NAI. Unusually high frequencies of lateral-type rib fractures (46.4%) were found and half the cases were found to be unilateral. This is not wholly in line with the currently accepted idea that rib fracture is due to antero-posterior compression, in which bilateral, posterior fractures are said to be most common.

Overall, this work brings into question the traditional mechanism of rib fractures, provides a highly useful snapshot of abusive injury in NZ and also sets a strong foundation for future work.
Acknowledgements

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1 Introduction

“THE CURRENT SITUATION IN NEW ZEALAND:

- Child abuse and domestic violence are two of New Zealand’s most pressing problems. In fact we have unacceptably high rates of both child abuse and domestic violence.
- NZ has the fifth highest rate of child abuse in the OECD
- A child dies of abuse every five weeks
- 150,757 notifications of suspected child abuse were made to the Child Youth and Family Service over the year ending June 2011”
- The Glenn Inquiry

1.1 Child Abuse – an Endemic problem

Child abuse is a major, endemic problem within New Zealand, with rates comparing unfavourably within the spectrum of OECD countries (UNICEF, 2003). High profile child abuse and murder cases are occurring frequently, with approximately 10 child deaths per year (period 2007-2010 inclusive) and significantly more hospitalisations as a result of assault (New Zealand Family Violence Clearinghouse, 2012). These often enter our national consciousness through reporting by news media – for example: the murders of the Kahui Twins in 2006 and J.J. Lawrence in 2011. Child abuse remains an issue within this country with the rates of infant abuse showing no sign of abating in the past 2 decades. In fact, rates of older child abuse have increased (Gilbert et al., 2012). This study also found stable rates of abuse in most of the other countries surveyed, showing this is not only a problem within our own country. Further, these data show the limited/non-significant impact of the intervention methods that governments have put in place up to this point.

The number of reports to Child, Youth and Family Services (CYFS), both those requiring action and those that did not, increased steeply over the past 5 year period included in the most recent statistical report. The overall number of reports of concern increased from 89,646 to 152,800 and the reports requiring action increased from 40,739 to 61,074. Within the subset of notifications that required further action, the number of cases of substantiated abuse remained relatively constant (mean = 20,125) (Child Youth and Family Services, 2013a). CYFS also provides valuable descriptive
data on the forms of abuse that are found within New Zealand; of the substantiated abuse claims, 15% (3249 cases) were cases of physical abuse. Emotional abuse is the most common form found (56%), neglect also being more common than physical abuse (22%), lastly, sexual abuse made up the remaining 6% of cases (Child Youth and Family Services, 2013b).

Finally, child abuse leads to significant immediate and downstream economic costs, as well as the obvious social and personal costs. A study commissioned by Every Child Counts, suggests that, between the direct costs of injury and welfare, on-going health and social costs, and indirect costs of lost productivity, child abuse and neglect costs are near to 1% of the GDP of NZ ($2b) (Infometrics Ltd, 2010). Clearly, this is a major cost to New Zealand in both the short-term and long-term, and therefore, working to understand and reduce the impact of child abuse is a valuable and significant goal.

1.2 Rib Fractures in Abuse

Rib fractures are a rare occurrence in children and infants owing largely to the flexibility of the juvenile thorax (Crameri and Ferguson, 2009). In a study of 2,080 children admitted for traumatic injury, rib fractures were found in only 1.6% of cases; these fractures were a marker of severe trauma, with the majority of fractures in children under 3 due to abuse (Garcia et al., 1990). However, despite this rarity in the general population, their frequency is much greater in cases of abuse, with rib fractures occurring in between 5-27% of the populations surveyed (Bilo et al., 2010c).

These fractures are reported to be highly specific for physical abuse (Barsness et al., 2003). In other words, the presence of rib fractures indicates that it is highly likely that abuse has occurred, suggesting other processes, such as accidents or falls are unlikely, especially in the absence of a history of some major trauma and in children aged less than 3. It is therefore important that we understand the processes that lead to the formation of these fractures, as they are both frequent in the abused population and are highly associated with abuse. Further, while there have been a significant number of studies detailing the clinical and pathological picture of rib fractures in abuse (Bulloch et al., 2000, Garcia et al., 1990, Kemp et al., 2008, Kleinman, 2000, Kleinman et al., 1995, Worn and Jones, 2007), there is a scarce number of papers detailing the biomechanical view of this important problem – notably Kleinman and
Schlesinger (1997) examine a mechanical model in rabbits, but I suggest there were methodological limitations within this study (discussed in Chapter 2.3).

It is currently believed that the majority of rib fractures in infants are caused by compressive damage to the ribs in the form of a squeezing and shaking motion to the child (Bilo et al., 2010c). This suggests that, under increasing compressive stresses, the rib will begin to fail at several points: posteriorly, where the rib head articulates with the vertebral body and where the transverse process of the vertebrae articulates with the rib; along the arc of the rib, anteriorly, laterally and posteriorly, where the rib levers against itself, leading to tension on the outer surface and compression on the inner; and anteriorly, where the rib meets the costal cartilage (Worn and Jones, 2007). The distribution of these fractures has varied between studies, but generally posterior fractures are considered to be the most common, followed by fractures of the rib arc and anterior fractures being shown to be the least common (Barsness et al., 2003, Bulloch et al., 2000, Cadzow and Armstrong, 2000, Kleinman, 2000, Wootton-Gorges et al., 2008).

In contrast to the above, recent work within the University of Otago has shown the immense flexibility of juvenile ribs and the effects of storage upon them that may have confounded previous results. Utilising a piglet model, this research showed fresh ribs subjected to bending forces could bend beyond 90° before fracturing (Bradley, 2012). It was also shown that ribs that were preserved by freeze-thawing had an increased propensity for fracture, which may have played a role in some previous laboratory studies. Clearly this work challenges the assumption that rib fractures may be frequently attributable to thoracic compression by adult hands.

1.3 My Project

This project aims firstly to add to the body of work in understanding the frequency, distribution and cause of rib fractures within the New Zealand and, secondly, to expand on previous work into the biomechanics of rib fractures within the context of child abuse.

In order to quantify the frequency and nature of rib fractures within New Zealand, I undertook a retrospective analysis of skeletal surveys in the past 4 years. Two sites were used in this study. Dunedin was first assessed as a pilot study to determine the most efficient and thorough way to gather and analyse these data, but there was a
limited number of surveys available with an even lower rate of positive surveys. Auckland’s Starship Children’s Hospital was, therefore, selected as the primary site for data analysis as it is the largest paediatric healthcare centre in New Zealand and also deals with the most serious cases referred from other centres. Data from Starship were analysed to give a picture of the skeletal injuries, including rib fractures, which are seen in abuse within New Zealand and how these patterns compare to those seen in accidental injury. I hope that these data can work to resolve some disagreement and variability within fracture patterns in the literature. Demographic information has also been gathered to provide a social view of this population.

I have also developed apparatus and a model to examine the effects of blunt force trauma (BFT) on infant ribs using piglets. I aim to characterise the lateral rib fractures due to BFT in these piglets, both in terms of gross, microscopic and radiological appearance and in the biomechanical factors that lead to these. Piglets were selected due to their similarity to human infants and their previous use within forensic and biomechanical research (Baumer et al., 2009, Audigé et al., 2004, Duhaime, 2006). With this information, I hope to be able to show that BFT may be a more biomechanically feasible mechanism of fracture than previously considered.

Lastly, I will begin the development of a finite element analysis (FEA) model for the piglet and infant thorax to be continued by a future student and in collaboration with the University of Aveiro’s Mechanical Engineering Department. First, we will validate the material properties of the rib via comparison of 4-point bending data gathered in Bradley (2012) and undertake mesh convergence studies to verify our mesh. We then aim to develop a blunt force impact simulation using a 3-rib pair and vertebrae set, using data gathered from CT scanning and compare this to information gathered from the biomechanical tests. This will also allow for future work developing more detailed FEA modelling of compressive trauma to the ribs – following the work of Tsai et al. (2012). This will take the form of a pilot study.

1.3.1 Aims and Objectives

- Retrospectively analysis patterns of bony injury in a New Zealand population of skeletal surveys, using Dunedin as a pilot site and Auckland as the main data site.
- From this, gather specific information about the nature and cause of rib fractures within this population
- Develop correlations between injury pattern and cause
- Gather information on soft-tissue injury and assimilate this into the analysis
- Lastly, gather age and demographic information on this population.

- Develop apparatus to test the effects of different levels of BFT to piglet ribs and investigate any resulting fractures.
  - Investigate these fractures radiologically, gross anatomically, and microscopically
  - Determine, from a biomechanical perspective, the forces required to lead to the presence of these fractures and other factors that may be involved.

- Begin development of a FEA model of the pig rib and thorax structures
  - Scan and create a mesh of both an individual piglet rib and a set of ribs and vertebrae and validate the properties of the rib, utilising previously gathered 4-point bending data and new compressive testing.
  - Complete mesh convergence studies on the individual rib under 4-point bending
  - Begin simulation of BFT to a set of piglet ribs, attempting to replicate a simplified model of the parameters found within the biomechanical testing.
2 Literature Review

2.1 Shaken Baby Syndrome (SBS)

"The plural of anecdote is not data, and the sum of "vast clinical experience" is not science." (Plunkett, 1999)

A triad of symptoms has classically defined Shaken Baby Syndrome: subdural haematoma (SDH – macroscopic bleeding beneath the Dura of the brain), retinal haemorrhage (RH- bleeding within the retinal surface) and the presence of cerebral oedema (fluid within the brain tissue), especially when there is a lack of evidence of other external injury. This is said to be due to repetitive shaking of an infant (Caffey, 1974, Guthkelch, 1971). However, since the origin of this theory, there has been a great deal of controversy surrounding this syndrome, especially following early papers by Duhaime et al. (1987) and Plunkett (1999).

Duhaime et al's 1987 paper outlined and implemented a biomechanical model for testing forces generated by shaking. They found that, without impact, the accelerations/decelerations generated by shaking were not sufficient to generate concussion and insufficient to cause the aforementioned triad. The author also found that if shaking was followed by a sudden impact onto a soft or hard surface, the decelerations were approximately 50 times higher and above the threshold for cerebral injury. In a subsequent paper, Duhaime et al. (1998) suggested the term 'Shaken-impact syndrome' was a more apt description of the cause of these injuries. These observations were supported by a more recent paper by Wolfson et al. (2005), in which they replicated the Duhaime study and then modified a number of biomechanical parameters in order to assess the effect these have on the forces generated (as the exact biomechanics of the infant neck were unknown). Their study showed that as long as there was no impact, their results mirrored those of the Duhaime paper, from which they concluded that there were inadequate forces and decelerations to cause SDH or diffuse axonal injury (DAI). They also found that in the models in which the head was allowed to impact the thorax, significantly higher forces were noted. However, they suggested that if this occurred in cases of SBS, bruising would be more frequently noted on the chin/chest/occiput/back due to the impact forces, which is not the case.
Following the trial of Louise Woodward for the murder of a child in her care, Plunkett (1999) published a paper addressing the body of literature investigating SBS, and expressed his strong concerns with its reliability. This evidence has been described as an 'inverted pyramid' with limited scientific evidence supporting a large body of divergent clinical opinions (Donohoe, 2003). Plunkett noted that the papers that were the genesis of this theory, Caffey (1974) and Guthkelch (1971), had in fact provided neither experimental evidence to support their suggestions, nor any witnesses to the shaking. Hence, shaking could not be shown to be the mode of injury. Nevertheless, this theory has entered into the scientific consciousness as fact. Plunkett also points out that the signs 'specific' to child abuse keep shifting, he provides the example of retinal haemorrhages: "The pathognomonic sign has evolved from "retinal hemorrhage" to "flame-shaped retinal hemorrhage" to "multilayered flame-shaped retinal hemorrhage" to, most recently, "multilayered flame-shaped retinal hemorrhage with macular folds", with no data to support this progression other than the argument that the head injury must have been caused by shaking."

Donohoe (2003) provided a systematic review of the literature prior to 1999. He approached the literature using the framework of evidence based medicine (EBM), which attempts to evaluate evidence based on quality and sets a hierarchy of evidence, with randomised controlled trials at its peak (Guyatt et al., 2002). Donohoe found that a large body of the prior evidence suffered major methodological issues; the nature of these studies was largely retrospective and they bore the problem of circularity bias. Primarily, the studies reviewed were retrospective and lacked the appropriate control groups that form the hallmarks of good evidence. Secondarily, the authors fall into a trap of circular logic; they define their case group (those who have the condition - in this case SBS) often using the criteria that they are attempting to determine an association with. This naturally leads to a strong, but potentially fallacious, correlation being found with their criteria, which they then declare pathognomic of SBS. This underlines the poor scientific quality of the historical work underlying SBS and the need for continued research.

Rib fractures have also been linked with child abuse and the shaken baby syndrome (Lancon et al., 1998) and it has been suggested that they share a aetiological mechanism. The rib fractures are said to occur as a result of the antero-posterior compression that takes place as the child is shaken (Kleinman and Schlesinger, 1997)
and this is further discussed below. As it is suggested above that the injury mechanisms underlying SDH and RH may be flawed, we must also examine the mechanism underlying rib fractures in the same manner.

2.2 Epidemiology of Child Abuse and Rib Fractures

Child abuse is an endemic problem in New Zealand with a significant impact on our society. New Zealand is rated 24th worst out of 27 OECD countries for child abuse mortality with a rate of 1.2 deaths per 100,000 (UNICEF, 2003). The Ministry of Health reports that 4-8% of children experience some form of physical abuse; 8% experience some form of physical punishment and 4% being severely physically maltreated. 80% of these children suffer an injury as a result of this treatment (Ministry of Health, 2010).

Rib fractures have long been considered to be highly specific for abuse, meaning that in cases in which these are found, the cause is likely to be non-accidental injury or child abuse. Barsness et al. (2003) calculated the positive predictive value, a measure of the probability that a positive finding indicates a cause or condition, and found a value of 95% amongst children under 3. This value rose to 100% after exclusion of known accidental trauma or disease process. This showed that in the absence of alternative explanations for rib fractures, it is almost certain that they were the result of non-accidental injury.

It was, however, also noted by Barsness et al. (2003) that rib fractures were a rare occurrence. In a population of 3,700 children assessed for trauma in the study period, only 78 children were identified as having rib fractures (2%). Conversely, amongst those infants who were victims of abuse, rib fractures were quite frequent. In a study of 1794 abused children, rib fractures were identified in 180 (10%), and when the age group was restricted to those under the age of 1 year, this number rose to 18.1% (159 fractures in 875 infants) (Loder and Feinberg, 2007). Merten et al. (1983) showed that amongst 161 fractures found in a sample of 494 abused infants, 31 were rib fractures (19%), with 61% occurring in children less than 1 year of age. More recent work suggested rib fractures make up between 5 and 27% of all fractures sustained in child abuse, with 90% of these occurring in children under the age of 2 (Bilo et al., 2010c). Further, in an autopsy study of 31 abused infants, rib fractures were the most common extra-cranial skeletal injury present, with 84 fractures (51% of total fractures) found.
in these infants (Kleinman et al., 1995). Lastly a study including 141 fractures in 28 infants (<18 months of age) found rib fractures to be the most frequent type (58%) (Worlock et al., 1986). The author also noted that rib fractures did not occur in isolation in any of the cases, and, that of the 826 children with fractures not resulting from abuse, only 1 rib fracture was found (this was the result of major chest trauma from a car accident) (Worlock et al., 1986). These papers have shown clearly the strong relationship between fractures and abuse.

The number and distribution of the position of fractures along the rib also has been suggested to change between cases of accidental trauma and abuse. A number of studies have previously reported on the distribution of rib fractures in abuse and their findings are reported in Table 2.1. While the data from Barsness et al. (2003) suggests there are fewer posterior fractures in cases of accidental trauma compared to those found in abuse, this data was not supported by that found in Cadzow and Armstrong (2000) or Bulloch et al. (2000). This also casts a degree of doubt onto the compressive mechanism of rib fractures, as this mechanism would imply a higher rate of posterior fractures. This data additionally shows that a significant proportion of rib fractures found in child abuse are found in the lateral region. As there is current disagreement within the literature, more data will aid in determining the true relationship of rib fracture position and the intent of the injury.

A study conducted within New Zealand by Kelly and Farrant (2008) gathered significant information about 48 infants with SDH due to abuse, 6 of whom died. Amongst this group, the median age was 33.3 weeks (range 5.4-113.4) and Maori were significantly over-represented (27 of 48 cases). 20% of these cases presented with bruising away from the head, while being only 0.2 times as likely to present with bruising to the head compared to those who suffered accidental SDH. 89% of those with abusive SDH were given skeletal surveys and these found rib fractures in 5.4%, metaphyseal fractures in 10.8% and other long bone fractures in 10.8%. However no further information was available on the number of rib fractures found in these infants or their position.
Table 2.1. Distribution of rib fractures in child abuse as defined in each paper (Barsness et al., 2003; Bulloch et al., 2000; Cadzow and Armstrong, 2000; Kleinman, 2000; Wootton-Gorges et al., 2008). Note on Wootton-Gorges et al. (2008), only data gathered from X-ray is shown here, CT data is excluded as not all 12 subject received scans.

<table>
<thead>
<tr>
<th>Abuse fractures</th>
<th>No of Patients</th>
<th>Posterior</th>
<th>Posterolateral</th>
<th>Lateral</th>
<th>Anterolateral</th>
<th>Anterior</th>
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<td>-</td>
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<tr>
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<tr>
<td>Wootton-Gorges et al., 2008</td>
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2.3 Introduction to Biomechanics and Trauma Biomechanics

Biomechanics is the science “devoted to the analysis measurement and modelling of the effects which are observed under the various mechanical loading situations, primarily in humans” and, specifically, injury biomechanics uses the principles of mechanics to study how the body or tissue responds at extreme loading conditions and its tolerance to these forces (Schmitt, 2010).

Important concepts in biomechanics include stress, strain, strength, toughness, viscoelasticity, Young’s modulus, Poisson’s ratio and isotropy. These will be discussed below.

Firstly, stress is a measure of force acting over a defined area, and is given the symbol sigma, $\sigma$ ($\sigma=F/A$). There are, generally speaking, 3 different forms of stress: tensile stress, in which the forces act to extend the object they act upon; compressive stress, which acts to shorten or compress the object; and lastly, shear stress which gives a twisting or shearing moment of force. The first 2 of these stresses are considered to be ‘normal’ stresses – acting perpendicular to the surface - and shear stress has a parallel or tangential moment of force (Kieser et al., 2012a).

Strain is a measure of deformation or change of shape and is dimensionless. It is a relative measure of the change of a dimension as a result of an external force. It is given the symbol epsilon, $\varepsilon$, and calculated by dividing the change in dimension by the dimension at rest ($\varepsilon=\Delta L/L_o$) (Kieser et al., 2012a). A further measure with a relationship to strain is the Poisson’s Ratio, a measure of the change of the dimensions tangential or perpendicular to the stress compared to the strain in the axial direction ($\nu=\varepsilon_t/\varepsilon_a$) (Kieser et al., 2012a). Stress and strain have a unique relationship that defines the behaviour of the material. When plotted on a graph (Fig. 2.1) they can tell us a significant amount of information about a material or object.
Figure 2.1 An example of a Stress-Strain graph, showing the linear (elastic) and non-linear (plastic) regions. Taken from Currey (2002).

From the origin of the graph, we see a linear elastic region, in which stress and strain are proportional to one another. In this region the slope of the graph is known as the Young’s Modulus (E), and defines the ‘stiffness’ of the material or its ability to resist deformation and is a property inherent in the material (Beer et al., 2011). In the non-linear region, the material or object is undergoing plastic deformation and at this point changes in length are irreversible and energy put into the system is irrecoverable. The stress at which the material begins to deform plastically is known as its Yield Strength, and the point at which the material comes to complete failure/fracture is known as the Ultimate Strength (Kieser et al., 2012a).

The ‘toughness’ of the material is the amount of post-yield deformation that a material will undergo before ultimate failure. Materials with very low toughness are described as brittle, whereas materials with a high degree of toughness are said to be ductile (Currey, 2002).

Viscoelasticity is a property often found in biological materials and known to be present in bone (Currey, 2002). A viscoelastic material exhibits a number of properties related to this: the modulus of the material changes with the strain rate at which it is loaded; when held at specific stress or strain value that material will experience creep or relaxation, respectively; it will also experience a loss of energy in the loading/unloading cycles (Kieser et al., 2012a, Kieser et al., 2012b).

Finally, some materials exhibit different reactions depending on the direction they are stressed in and have differing moduli in each direction. This property is known as
anisotropy, and materials that exhibit it are anisotropic. Bone is an excellent example of this, as in the longitudinal direction (e.g. down the shaft of a long bone) the modulus of bone is considerably higher than in the transverse direction (perpendicular to the shaft) (Currey, 2002).

These properties, along with the structure of the bone itself, determine when the bone will fracture and how it behaves when it fractures. The properties of bone also change significantly with age. As age increases, the mineralisation of bone increases and as it does bone becomes stiffer and stronger, however, immature bone is capable of absorbing more energy before fracturing (Currey and Butler, 1975, Vinz, 1975). These changes become apparent when we observe the fracture patterns found in children and infants compared to adults. The most obvious is the presence of partial “greenstick” fractures found in children, but only very rarely in adults (Blount et al., 1942).

2.4 Finite Element Analysis

Finite element analysis (FEA) is a mathematical and computational technique that allows complex objects and simulations (separated into domains) to be broken down into smaller subdomains, known as elements, and utilising a computer to solve the vast number of equations produced to create an approximate solution to the complex problem (Love et al., 2013). It is often used to describe behaviour of materials under various stresses and strains, and has been used in a wide range of applications, such as materials engineering (Hobbs et al., 1999), dental technology (Rosner, 2006), crash simulations (Szumilas, 2010a), and biomechanics (Szumilas, 2010b).

FEA creates a numerical model, using algebraic equations calculated at every vertex of each element within the mesh, the resultant values of which are then interpolated to create an approximation over the domain. The interpolation function takes the form of a piecewise polynomial function of a specified degree. First, values are interpolated across each element to give field quantities for each element, then between all the elements with a domain to give a numerical approximation of the physical reality. The precision of this approximation is determined by 2 factors: the number of elements used (larger numbers of smaller elements are more precise) and the polynomial degree of the interpolation function (Kleinman et al., 1996).
In order to create these simulations, an ordered process of steps must be completed. Initially, the geometry of the objects to be simulated must be constructed. There are several ways to do this; if the geometry is simple, it may be most practical to use a computer-aided design (CAD) program to create a digital model of this geometry. In many biological applications, however, the geometry is significantly too complex to create in this manner. Therefore, a form of 3D laser or contact scanning may be used. These operate by either using a laser or thin needle to probe the surface dimensions of the object, creating a point cloud, which can be converted to a smooth object surface. The shortcoming of these 3D scanning methods is that, while good data on the surface of these objects may be gathered, they provide no data on the internal structures of the object. In situations where the internal structure of the object is important for the simulation or the geometry of the object must be extracted from within other structure (as in the case with bone *in vivo*), a more traditional imaging modality may be used such as CT, MRI or micro-CT.

Following capturing of the geometry of the object, it must be discretised or converted from a smooth surface into one made up of elements and the form of the interpolation function must be specified. The discretisation is conducted by software, with the user specifying the element density and properties. The elements may be constructed in such a way as to create either a shell, with only the surface represented (thickness of the object is later applied as a result of the material properties), or 3D elements may be used in order to represent the complete structure. The shape of the element may also be specified, most commonly as either a triangular or quadrilateral shape (Love et al., 2013).

The material properties of each element may then be specified following meshing. One or more material properties may be applied to an individual element depending on its type. These properties will affect the result of the calculations, and therefore, that of the simulation. As any set of material properties will produce data and a result at the end of the simulation, it is therefore important to validate these properties in a real world scenario or approximate them from previously known data to ensure data produced is valid and useful.

In the last step before solving the simulation, boundary conditions must be applied to allow the simulation to have a determinate solution. If these are not correctly applied
the simulation will fail to reach equilibrium and so produce no solution. These may take the form of restrictions on the displacement or rotation of objects in a specified dimension for example (Love et al., 2013).

Finally, the simulation must be solved to find equilibrium values and a final solution for the simulation. This produces data for each element at each time point throughout the simulation, and can also give approximations for objects as a whole. This data may be represented graphically as a spectrum of colour indicating levels of a given output at each element, superimposed over the object. The length of time a simulation takes is proportional to the number of elements involved, the time increment of each step, and the polynomial degree of the interpolation, along with the computational power of the machine being used.

Due to the inherent processes of FEA, a set of results will be produced, regardless of the accuracy of the material properties. Conclusions cannot be drawn based on the results of FEA, unless we know the simulation properties are appropriate. Therefore, 2 important considerations must be taken, firstly, that the coarseness of the mesh is not leading to significant changes in the results of the simulation. So a mesh convergence study must first be done. This is a process where the detail of the mesh is gradually increased, until the solution does not change with further increase in mesh detail (Loder and Bookout, 1991). This is done in order to find a balance between computational efficiency and mesh convergence. Secondly, it is important to have physical, experimental data to provide the material properties for the objects in the simulation as otherwise the results are essentially meaningless.

Software packages have been produced by a number of companies, which allows easier construction of simulations and specification of material properties. Some examples of these packages are LS-DYNA (Livermore Software Technology Corporation), Abaqus (Dassault Systemes) and ANSYS (ANSYS Inc.), each with its own pros and cons.

2.5 Biomechanics of Rib Fractures

It has long been considered that static loading and compressive injury (Fig. 2.2) are the main cause of rib fractures in the abused infant (Bilo et al., 2010c). It is suggested that force is applied in the anterior-posterior direction and this causes deformation of the ribs. This is said to cause fractures in a number of locations. Alternatively,
dynamic impacts, either intentional or unintentional, are considered a rare means of fracture. (Bilo et al., 2010c)

Posterior fractures are commonly discussed in abuse and are thought to be due to very high mechanical stress at the points of fixation of the rib to other structures (Merten and Carpenter, 1990). These points are found: in the rib head, as the bone levers against the supporting ligaments; the costovertebral area, as the rib levers across the transverse process of the adjacent vertebrae (Worn and Jones, 2007). These fractures are said to be very infrequent in non-abuse cases, and not likely to occur due to major trauma or resuscitative efforts. A recent study of CPR in infants found that of 19 rib fractures due to CPR, none were found in the posterior region (Reyes et al., 2011).

Anterior fractures are also considered to be the result of compression rather than impact, as a result of depression of the anterior rib and bowing of the rib in the anterior arc (leading to a similar situation as described for lateral fractures below). (Gendron and Parker, 2009).

Theoretically, lateral compressive fractures occur due to excessive bending of the rib at its most convex point, leading to high tensile stress on its outer surface and high compressive stress on the inner surface leading to periosteal damage and fracture (Gendron and Parker, 2009). However, work by Bradley (2012), using a porcine model of the infant thorax, showed that, upon compressive loading (both in 3- and 4-point bending tests), fresh piglet ribs bent to the point where they were touching the
loading span before breaking, and fractures only occurred when manually bent passed 90 degrees (Fig. 2.3).

Figure 2.3. Manual bending of piglet ribs to the point of fracture. (Adapted from Bradley (2012))

This sheds some doubt on the idea that simple compressive bending would produce fractures in the lateral arc, as the current hypothesis would suggest.

It is considered that the minority of cases are the result of direct impact. Upon impact, fractures occur at either the point of impact or at a point of high stress away from the direct site of impact (Bilo et al., 2010c). It is considered that these direct impact fractures are more common in older children, while compressive fractures are most frequent in those under 1 year of age (Kleinman, 1987).

The issue with these hypotheses is that there is a great deal of difficulty in showing that the process suggested would indeed cause the related injuries, as, up to this point, little experimental work on modelling infant rib fractures has been done, the only experimental study on abusive fracture was done by Kleinman and Schlesinger (1997) using rabbits. This study found that, upon anterior-posterior compression, a number of posterior rib fractures were found. However, this study used rabbits at 90 days of age, and with rabbits reaching maturity between 4 to 7 months of age (Gendron and Parker, 2009) it is possible that these rabbits’ skeletons were more mature than those found in infants and so may exhibit different behaviours upon trauma.
The lack of mechanical data on the infant ribs is also a major issue. Only a single unpublished study has been conducted on the biomechanical properties of the infant rib (Pfefferle et al., 2007) and this was subject to methodological faults such as inconsistent span length and poor application of beam theory (Kent et al., 2013). There has also been some work on the behaviour of the infant thorax in non-failure loading. Sandoz et al. (2011) examined the behaviour of the infant and toddler thorax under compression as part of respiratory physiotherapy. This study reported the effective stiffness of the thorax in the infants (mean = 6615Nm$^{-1}$) and showed the behaviour of the thorax at low speed impacts (0.11ms$^{-1}$). Little other experimental work has been done on infant ribs, however pigs have been used to model behaviour of the paediatric thorax, and this will be discussed in the following section.

A finite element analysis study of the stress profile of the infant rib system was recently completed by Tsai et al. (2012) who investigated the locations of peak stresses within the ribs as well as the effect of the modification of material properties on the distribution of stress. Points of highest stress were located in the anterolateral segments of the ribs and in the posterior section of the rib, as it levered over the transverse process, in line with the hypothesis of compressive fractures (Worn and Jones, 2007). Their work found that modification of the Young’s Modulus of the bone caused significant changes in the average stress found in the anterior and lateral segments of the ribs, with less of an effect on the posterior areas. Variation of Poisson’s Ratio had no effect. Specified cartilage modulus also had a significant effect on stress distribution; at a low value almost no stress occurred in the ribs, however at a high value there was a disproportionate increase in stress in the posterior segments compared to the baseline modulus. It was also noted that asymmetry in the ribs led to slightly different stresses in each rib.

### 2.6 Porcine Bone as a Model

Domestic pigs (*Sus scrofa*) have previously been utilised in biomechanical and forensic research. In a number of cases, porcine bone has been used to model adult human bony injury and fracture. Most recently, Kieser et al. (2013) investigated rib fracture patterns using adult pig ribs under low-velocity compressive strain. Lynn and Fairgrieve (2009) provided a second example of pig bones used in low velocity trauma in their research into the microscopic indicators of axe/hatchet wounding. Pigs have also been used to model human bony trauma at ballistic velocities; Kieser et al.
(2011) utilised pig ribs in their investigation of the effects of close range impacts from a .22 calibre rifle. Lei et al. (2012) also used porcine mandibles in validation of their blast force finite element model. These studies show that there has been significant development of porcine bone as a model for human injury in trauma and forensic research.

Piglets have also been frequently employed in crash biomechanics, child abuse research and in the study of the shaken baby syndrome. Young piglets have been used in the development of a paediatric model for the thorax and the abdomen for use in crash simulations (Kent et al., 2006). Kent et al. (2013) details a number of studies which cumulatively have shown piglets are acceptably similar in terms of the physical properties of their lungs and costal cartilage (Oyen et al., 2006). However data on the behaviour of both paediatric human and porcine ribs is sparse at present and further work on this in order to validate the porcine model is required.

While ribs are not well characterised, other bony structures of the piglet and infant have been investigated and characterised, especially in the context of child abuse. Porcine parietal bone has been shown to have similar flexural rigidity to that of infants, with 1 day of porcine life being approximately equivalent to 1 month of human life (Baumer et al., 2009). These findings are echoed in an older study, which similarly shows the elastic modulus, rupture modulus and energy absorbed to failure were approximately equivalent to between 2-3 day old piglets and neonates (Margulies and Thibault, 2000). While this information does not allow a direct correlation with the behaviour of ribs, it does give evidence for similarities between human infant and piglet bone, which may also hold true for ribs.

Lastly, it is worth noting that a piglet model has been used a number of times in testing the effects of shaking and impacts on the brain, in order to model the shaken-baby and shaken-impact syndrome. Duhaime (2006) detailed and reviewed these studies, mentioning particularly the maturational similarity between the piglet and the human infant in terms of neurological development.

2.7 Radiology of Rib Fractures

The ease of visualisation of rib fractures varies significantly over the course of their healing. Immediately after their occurrence, they are considered incredibly difficult to visualise on standard plain film X-ray. As time progresses and the soft callus forms
around the fracture (the first stage of bone healing), a mass becomes visible around the fracture and this is significantly more easy to identify (Hobbs et al., 1999). This major discrepancy in the detectability of these fractures means there is a great need for follow-up skeletal surveys in cases of suspected child abuse, and the value of these has been shown by Kleinman et al. (1996).

Following the soft callus stage of healing, a hard callus begins to form. This is also subtler than the soft callus phase and after approximately 1 month, only slight cortical thickening is present to distinguish fractures (Hobbs et al., 1999). After this, remodelling occurs and the fracture becomes indistinguishable.

Figure 2.4. Chest X-ray of an abused in showing numerous bilateral rib fractures. The blue arrow indicates an example of posterolateral fracture; lateral fractures are indicated by the orange arrow. Adapted from Bilo et al. (2010c).

An occult finding is one that is not initially visible on a plain film X-ray or suspected by clinical presentation. As previously mentioned, rib injury has been shown to be difficult to detect and is often an occult finding on a skeletal survey, 1 study showed that over 80% of fractures were unsuspected on the basis of presentation (Merten et al., 1983). A more recent study showed that, in a sample of children with suspected abuse, 26% had occult fractures on skeletal survey; ribs were the most common occult fracture by a factor of 3 (42%) (Belfer et al., 2001).
While there is a great deal of information on the classification of the position and type of fractures found in long bones (Audigé et al., 2004), little work has taken place to create a similar schema for rib fractures. Recently, Love et al. (2013) developed a classification system, dividing fractures by both the location and type of fracture. This study divides the location into 3 groups: posterior, posterolateral and, anterolateral and anterior. They then further separated the fractures by the type of fracture that occurred, namely: buckle, transverse, oblique and sternal end plate.

2.8 Imaging Techniques

2.8.1 Plain Film X-ray
Plain film radiography is a frequently used modality in medical imaging. It is able to separate objects by density and provides good imaging of bone. X-ray imaging uses radiation produced by an X-ray tube (at a specified energy level), which is then passed through the object of interest or patient and captured, either digitally or using photographic film. X-rays are able to pass through objects of low density, such as skin and soft tissue/viscera, but are absorbed by bone, therefore obstructing their access to the photographic film. This leaves a pattern where bone shows up brightly on the film and soft tissue appears darker as the X-rays expose the film, turning it black upon development. Plain film X-ray provides good differentiation of bone and soft tissue, but can only provide a limited amount of soft tissue detail and the images that appear are in 2D, so some structures may be hard to resolve due to shadowing of other structures in front of or behind them.

2.8.2 CT Scanning
Computed Tomography (CT) scanning is a more complex imaging modality, also based on the use of X-rays. In this method, many 2D slices are captured which allows both visualisation of 2D in the $x$, $y$ and $z$ planes and also 3D reconstructions such as surface and volume rendering of structures. Like plain film radiography, X-rays are emitted from an X-ray tube, passed through the object/patient, and then detected. In plain film X-ray, detection is done using a piece of photographic film, but in CT scanning the detectors are most frequently an array of scintillation detectors that detect the presence of the X-rays that have not been absorbed by the intervening structures. Both the emitter and the detector array are rotated around to give multiple angles through each slice, and then shifted to scan further slices across a given range
of space. Scintillation values for each point (known as a voxel) and from each angle are mathematically processed, using tomographic reconstruction, to give a pixel intensity value that can then be visualised and interpreted. This method has significant advantages over plain film X-rays as it allows viewing of slices in all dimensions and creation of 3D reconstructions of the objects, defined by pixel intensity as to isolate either bone or soft tissue. Further, greater detail of soft tissue is also visible on CT scanning, when compared to plain film X-ray. The major shortcoming of CT scanning is cost and the significant radiation dose that the patient will be exposed to in the course of data gathering.

2.8.3 Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) is a technique, infrequently used in a medical or clinical context, but very useful in high magnification and detail imaging in a research context. SEM operates by using a focused beam of electrons passed through a series of magnetic coils that act as lenses and then onto the sample. The samples are coated, before scanning with a thin layer of a conductive material, often gold or another precious metal that grounds the specimen and prevents charge build-up that may lead to artefacts. The electron beam, on contact with the sample is scattered and this pattern of scattering is detected by a detector array. This beam scans across the surface of the object with great detail, giving pixel intensity and position values at each point. This allows a 2D image, with depth of field, of the surface of the specimen to be formed and viewed. A variety of image magnifications may be produced by the SEM method.
3 Methods

3.1 Radiological study

For this part of the project, ethical consultation was undertaken with several research bodies in order to ensure ethical compliance throughout this work. Gaining full ethical approval was particularly important here as confidential information about children was being gathered and analysed. Therefore, Category A ethics approval was sought through the University of Otago and this acted as general ethical approval for the study. Secondary local clinical ethical approval was then obtained separately from both Health Research South, for the Dunedin study, and the ADHB Research Office, for the Auckland study. The statements of confirmation of ethical approval from these 3 institutions are found in appendices 1 to 3, respectively. Maori consultation was also undertaken and approval was gained from Ngai Tahu for both this radiological study and the biomechanical work.

3.1.1 Dunedin survey

A preliminary study was conducted in Dunedin first, in order to refine the method before the larger study to be conducted in Auckland. I accessed information for all patients who had a skeletal survey for the investigation of non-accidental injury in the period between 2008 and the present, as this was the period in which the PACS radiological server has been in use. Data were collected from the radiologists’ reports within these files, and reviewed by a radiologist at the time of collection. Data were then anonymised by assignment of a case number and removal of personal information. One additional case was found, as it was mentioned in the clinical data of another report. Further information was then gathered from the case files found in the Dunedin Hospital’s iSoft clinical database and this was added to the radiological data. This and the Auckland survey were separated due to the possibility of differing local protocols for skeletal survey and do ensure the data was as contiguous as possible.

3.1.2 Auckland survey

The primary study was completed in the Radiology Department of Starship Children’s Hospital, Auckland. The skeletal surveys were accessed from the hospital’s PACS radiological server, and all those for the period from 2009 to present were retrieved
from the digital archives. These radiographs were also accompanied by radiologists’ reports, from which the skeletal injury information in the study was drawn. Further information on patients, such as soft tissue injury, reason for survey, ethnicity and conclusions on the cause of any injuries found was drawn from the hospital’s Concerto Clinical Database under supervision of Dr. Russell Metcalfe. All cases were then anonymised by assigning of a case number and saved in a secure password-protected spreadsheet.

### 3.1.3 Statistical and data analysis

Following consultation with a biostatistician, I selected the open-source statistical package R 3.01 (http://cran.r-project.org/bin/windows/base/old/3.0.1/) for use. This was augmented, for ease of use, with the Java GUI-for-R package (http://rforge.net/JGR/), Deducer (http://www.deducer.org/) and a custom package prepared by Dr. Athens, a biostatistician within the University of Otago.

For consistency across all data and due to the scarcity of data in the Dunedin population, only cases from Auckland were included in the statistical analysis. The data from Auckland were coded into a format that allowed analysis in R. All information was divided into variables and formatted as either integers or factors, and data were checked and modified to ensure consistency.

Mean incidence rates were calculated as follows:

\[
Incidence = \frac{\text{No.of Cases}}{\text{Population (Total NZ or Ethnic)}} \quad (\text{Eqn. 3.1})
\]

Incidence rate ratios (IRR) were calculated as a simple ratio of the 2 appropriate incidence rates, and their confidence intervals were calculated using Eqn. 3.2 (taken from Rosner (2006)), where \(a_1\) and \(a_2\) are the number of events in groups 1 and 2, respectively.

\[
95\% CI = \exp\left(\log[IRR]\right) \pm \sqrt{\frac{1}{a_1} + \frac{1}{a_2}} \quad (\text{Eqn. 3.2})
\]

When determining odds ratios, for categorical variables, such as the presence of fractures or soft tissue injury, standard calculations to determine odds ratio (OR) were used. However where variables were discrete integers, for example the number of
fractures found, OR was determined using the exponential function of the regression coefficient determined by logistic regression (Szumilas, 2010a)

3.2 Biomechanical testing of blunt force trauma in piglets

For this part of the project, ethical approval was not required as all animal samples were acquired already deceased (due to natural causes or still births). All appropriate care was taken, however, in storage and disposal of any biohazardous or animal materials used here. As mentioned above, Maori consultation was also undertaken for this part of the project and approval was gained from Ngai Tahu.

3.2.1 Design of fist apparatus

A mould of a human forearm and fist was constructed using alginate to create an initial imprint. This imprint was then filled with Plaster of Paris and subsequently used to form a final permanent negative, poured from a 2-part silicon solution (Shera Duosil H).

The modulus of elasticity I selected for the fist and arm system was based on an estimate of a 3-part system of skin, bone and cartilage using the following equation:

\[
\frac{L_{total}}{E_{eff}} = \left( \frac{L_{bone}}{E_{bone}} + \frac{L_{cartilage}}{E_{cartilage}} + \frac{L_{skin}}{E_{skin}} \right)
\]

(Eqn. 3.3)

where L was the length of the component in millimetres, E was the Young’s Modulus of the component and E_{eff} was the effective Young’s Modulus of the system as a whole. The total length of the system was taken as the knuckle-to-elbow distance of the subject from which the fist was cast, and equalled 370mm. The length of bone was empirically determined as 364mm and the system was assumed to contain approximately 5mm of cartilage and 1mm of skin tissue. The modulus values were taken to be 15GPa for bone (Reilly and Burstein, 1975) and 83.3MPa for skin (Ní Annaidh et al., 2012). Cartilage is considered to be a highly viscoelastic material and therefore, its modulus varies proportionately to the loading rate (Martin et al., 1998). Because of the high impact rates involved, I selected the upper end value for the elastic modulus of cartilage, 500MPa (Martin et al., 1998). The resultant calculation using these values gave a modulus of 9.226GPa for the system.
Because type 4 dental stone was suggested as an appropriate material, I undertook 4-point bending testing of bars of dimensions 80mm/5mm/5mm using an Instron 3369 machine with Bluehill Software to capture stress/strain data (Fig. 3.1.). Bars were then cast in a silicon mould from GC Fujirock EP (GC Europe) mixed to the manufacturer’s specifications and then dried at 50°C for 72 hours. These samples were then subjected to a four-point bending test in the Instron machine. The support diameters were 15mm, internally, and 25mm, externally. Samples were preloaded to 30N to ensure that the linear portion of the stress/strain graph was captured, and were then loaded at a rate of 2mm/min, until failure. The Bluehill Software automatically captured stress/strain data and calculated the modulus of elasticity. Thirty-seven samples were tested and the resultant calculated elastic modulus (excluding two outliers) was 8898.16MPa (s.d. = 1599.58MPa). This empirically derived value was thought to be close enough to the calculated modulus for the system and hence this material was selected for use in this model. A forearm and fist were then cast from this material and dried at 50°C for 72 hours.

3.2.2 Force calibration

In order to determine the force of a blunt force impact, such as a blow from a fist, I elected to use a modified indentation test. Firstly, I determined the hardness of a block
of plasticine via application of a known force and digital determination of area of impact, using the following formula to determine the hardness:

\[ H = \frac{F}{A} \]

(Eqn. 3.4)

To determine the hardness of the plasticine, a 42mm diameter glass sphere was indented at a rate of 10mm/min into a 90mm thick stack of plasticine blocks. (Figure 3.2). These blocks were loaded to a peak force between 150-225N which was then relaxed to 0N. The blocks were then removed and the diameter of the indentation was measured at 2 different angles (at approximately 90° degrees to each other). As the force and area of indentation were now known, the hardness, or resistance to deformation, of the material could then be calculated, giving us a mean value from 13 trials of 0.3255N/mm².

Sufficient knowledge of the material properties of this type of plasticine allowed me to set-up an apparatus to test the force of a punch impact, a schematic of this is shown in Figure 3.3. It consisted of 67.5mm of stacked layers of plasticine, 45mm of which (2 blocks thick) was considered backing plaster and experienced minimal deformation, and 22.5mm (1 block thick) of impact plasticine to which the punch was delivered.

This was then placed hard against 40mm of wood backing to provide support and then positioned against a solid wall. The apparatus was set up on a shelf at approximately chest height for the subject delivering the impacts. After 2 practice impacts, the subject impacted the plaster at maximal force for 5 trials.

After each trial the area of indentation was outlined and photographed with a scale bar (Fig. 3.4.). These were analysed using ImageJ software to calculate the area of the impact. After each test the impacted plasticine was replaced and any deformation to the backing plaster was reshaped. From the 5 trials a mean area of 5315.2mm² was found and a resultant mean force of 1730.34N (s.d. = 150.52N) was calculated. These values were close to those found by Smith et al. (2000) in novice boxers (although slightly lower).
Figure 3.2. Indentation testing of plasticine blocks with spherical indenter using an Instron 3369 machine.
Figure 3.3. Schematic of punch force testing apparatus.
Figure 3.4. Outlined indentation from fist impact into plasticine.

Figure 3.5. Preliminary fist impact apparatus.
I then created a simple pendulum apparatus, with the fist attached, to determine the height and weight that the fist would require to generate the equivalent levels of force (Fig. 3.5.). A 1.9m aluminium bar was drilled to allow it to be bolted to a G-clamp (also drilled) and then affixed to a doorframe. The fist was then lashed using plastic cable to the opposite end of the pendulum bar. The impacting set up was the same as previously described (22.5mm of impact plasticine, 45mm of backing plasticine, 40mm of wood) except that, in place of the wall, a large heavy iron T-shaped plate was used as the base and weighted with an anvil to minimise movement on impact.

Pendulum height was 1.9m and the fist was impacted from a height of 1.5m. The fist (poured from the Type IV dental stone – weighing 2kg) was then released from a height of 1.5m and allowed to impact the plaster, the area of indentation was outlined and again digitally measured using ImageJ. With no additional weight added, the 1.5m impacts generated a mean area of 4493.6mm$^2$ from 5 trials and a calculated mean force of 1532.5N (s.d. = 170.9N). A weight was then added to the back of the fist with hardened putty, weighing an additional 3kg in total, and again the fist was impacted from 1.5m. From 2 trials, a mean area of 6187.4mm$^2$ was calculated and the mean force was determined to be 2014.3N (s.d. = 359.32). It was therefore determined that the addition of 3kg to the fist (now weighing a total of 5kg) was more than sufficient to deliver the forces equivalent to those found from the actual punch.

Finally, I commissioned a custom designed apparatus, which consisted of a large metal A-frame, a pendulum with a ratchet to prevent the fist from bouncing back and causing repeat impacts, appropriate weighting at the rear of the fist, and the digital accelerometer and piezometer for data capture purposes (Fig. 3.6)

Force calibration then occurred using the putty system as previously described. An adjustable spirit level (Stanley FatMax Xtreme® Magnetic Torpedo Level) was attached to the pendulum and the angle from this was used to calculate the height of release (an angle of 49.62° was found to be equal to 0.5m). Acceleration data were captured from a Model 64C Accelerometer (Measurement Specialties) via a PowerLab 8SP and Octal Bridge (AD Instruments) and using LabChart software (AD Instruments), with a sampling rate of 20 KHz and a low pass filter of 100Hz. The putty was impacted from 0.5m twice and 0.3m, and a mean force of 1501.09N (s.d. = 24.90N) and 1103.11N (s.d. =37.65N0 and a mean acceleration of 212.48ms$^{-2}$
and 151.56 ms$^{-2}$, respectively were found. This indicated the effective mass of collision was 7.135 kg and this value was used for future force calculations.

Figure 3.6. Customised impact apparatus, designed by EmTech, with fist and forearm attached.
3.2.3 Piglet impact testing

For the initial testing, the height of 0.5m was used. A stillborn piglet was acquired from Bloem Pig farms in Dunedin, and stored at 4°C, and placed into the apparatus within a plastic bag as shown in Fig. 3.7. This piglet was then impacted from the specified height and then frozen at -20°C.

It, along with an un-impacted frozen piglet as a control, was then sectioned in the mid-line and the thorax was removed from the rest of the body using a butcher’s band saw. These were then imaged via X-ray in a Schonander Skull Unit containing a Toshiba X-ray tube. A Lanex Medium Intensifying Control Screen and Kodak TMaTG RA Film were used to capture the image. A variety of exposure and voltage settings were used until it was found that the best image results were gained using 20mA of current, 50kVp of energy and an exposure of 0.105 seconds.

Figure 3.7. Position of first piglet in testing apparatus; side view (left) and front (right)
As significant fractures were seen in the test piglet, I elected to use a half interval search strategy to find the force at which fractures begin to occur in these ribs. As such, 2 fresh piglets were received, placed in plastic bags and impacted at 0.25m (34.52°) – halfway between the point at which fractures were known to occur, 0.5m, and 0. The acceleration of the impact was recorded as in the putty experiment above. The piglets were weighed and then frozen at -20°C, finally they were sectioned; first through the midline in the sagittal plane and then through the neck, caudally, and below the base of the rib cage, rostrally, to leave only the thorax in 2 halves and X-rayed as described above. This process was completed using a butcher's band-saw by the Outram Butchers.

Piglets were periodically collected and further impacts were completed at a number of heights; 0.15, 0.20, 0.25 and 0.35. In these cases the piglets were again stored at -20°C until completely frozen and soon after this, sectioned and X-rayed as described above.

### 3.2.4 Scanning electron microscopy

Three impacted piglet hemi-thoraxes (0.25-2, 0.20-2 and 0.20-4(2)) were defrosted overnight at room temperature and viscera were removed. A number of complete (3) and partial/greenstick (4) fractures were identified visually and dissected from the thoracic wall. These bones were then sectioned with a scalpel in order for them to fit on an appropriate 25mm mount for electron microscopy. One of the partial fractures was also decalcified, in order to view collagen structure, in a solution of 10% EDTA for 14 hours at 37°C in a KOS microwave (Milestone Medical SRL), and then washed in water. The specimens, a total of 3 complete fractures and 4 partial fractures, were mounted on 3 aluminium stub mounts using double-sided carbon tape and a conductive carbon paste. These were then coated with approximately 15nm of gold palladium using an Emitech K575x peltier cooled sputter coater (EM Technologies Ltd).

Samples were then visualised in a Cambridge Stereoscan S360 scanning electron microscope (Cambridge Instruments) fitted with a Dinidima Image Slave frame grabber (Dinidima Group Pty Ltd). Samples were viewed at an accelerating voltage of 8kV, probe current was 50pA and working distance was approximately 15mm.
### 3.3 Finite element analysis (FEA) study

#### 3.3.1 3D data capture

A CT scan of a stillborn piglet was captured using a Siemens Emotion 16 CT scanner. Images (Siemens AG) were taken in the axial, sagittal and coronal planes and a virtual 3D surface reconstruction of the bones of the thorax was completed using OsiriX software package. This reconstruction was exported in the STL format, and cropped using Solidworks (Dassault Systemes SA) to give 2 models; one with only a single 5\textsuperscript{th} rib, and the second with 3 rib-pairs (4\textsuperscript{th}, 5\textsuperscript{th} and 6\textsuperscript{th}) and the associated vertebra. This was converted to a surface file using the ScanTo3D function in SolidWorks. These were saved in the IGES format for import into the FEA software package, Abaqus (Dassault Systemes SA).

The first impactor from the biomechanical apparatus experiments was scanned using a Roland PICZA Laser Scanner (Roland Corporation) and data were acquired with the Dr. PICZA 3 Software (Roland Corporation). This scan was taken in 4 planes, with a height-/width-direction pitch of 0.8mm. The point cloud gathered by the scanner was converted into a surface using the aforementioned software, and this was imported into Abaqus for FEA analysis.

#### 3.3.2 Meshing and mesh convergence analysis

Within Abaqus, a four point bending simulation was created with appropriate boundary conditions and the rib model was placed within this. This simulation is graphically represented in figure 4.8. A mesh was then created for the surface model using the processes inherent in Abaqus.

A mesh convergence analysis was carried out beginning with a global seed size of 1 with a gradual stepped decrease to 0.12. Between 0.25 and 0.12, the mesh converged with no further change in the output results from this increase in complexity of the mesh, therefore a 0.25 seed size was decided upon for the mesh. A quad-dominated mesh was used for this model.

A number of errors were found within this mesh and refinement is on-going at time of writing. Similarly the 3 rib-pair model had significant errors and a great deal of refinement is still required before it is usable for simulation purposes.
3.3.3 Four-point bending simulation and material property determination

Despite errors within the mesh, 4-point bending simulations were carried out in order to begin quantification of material properties of the rib. The elements in the mesh were assigned as continuum shell elements, which allowed assigning of multiple material properties to each element, as this was suggested to provide an appropriate model. Two sets of material properties were assigned to each element, 1 for cortical bone and 1 for trabecular bone.

This simulation (as seen in Figure 3.8) was then run with a multitude of material properties and these were compared to the 4-point testing data found in the thesis by Bradley (2012) in order to assess their accuracy.

![Four-point bending simulation containing single pig rib mesh (0.25 global seed size).](image)

3.3.4 Compressive testing and simulation

In order to further clarify behaviour of the ribs, a small sample of ribs were dissected from non-impacted piglets and subjected to compressive testing in Intron 3369 machine with Bluehill Software. These ribs were held in place using small cups moulded from Ivolen-SR acrylic polymer (Ivoclar Vivodent) positioned such that they would not contact the rib as they became compressed, shown in Figure 3.9.
The ribs were then subjected to the following procedure: preloading to 0.5N; loading to compression of 10mm at a rate of 10mm/minute; held at this point for 2 minutes; unloaded at a rate of 10mm/minute until load was 0.05N; reloaded 10mm at a rate of 10mm/minute; held for 1 minute; unloaded at the same rate. This was done to assist in giving an idea of the viscoelastic and viscoplastic properties of the rib.

Four rib pairs from two piglets were tested, 2 left and right 5th and 6th ribs were used and data on force and displacement were captured from the apparatus.

A compressive simulation was then created within Abaqus using the single rib model with appropriate boundary conditions, and the materials properties were also varied here in order to determine those that most closely match with data obtained from the experiments.
4 Results

4.1 Radiological study

4.1.1 Dunedin survey

In the Dunedin population, in the period from 2008 to present, only 23 skeletal surveys for suspected abuse were carried out. In this group of patients, the median age was 9 months. Nine skeletal surveys were positive for some kind of skeletal injury, and of these 6 were considered to be cases of abuse (one further patient with a negative survey was found to be abused based on soft tissue injuries present). In the remaining positive three surveys, fractures were explained by either falls or of unknown cause (possibly abusive). The fractures that were accidental were exclusively parietal skull fractures due to short falls. Fractures that were found due to abuse (or possible abuse) are presented in Table 4.1 below.

Table 4.1. Fractures due to abuse/suspected abuse in the Dunedin population obtained from skeletal survey data

<table>
<thead>
<tr>
<th>Fracture Location</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Skull</strong></td>
<td></td>
</tr>
<tr>
<td>Parietal</td>
<td>2</td>
</tr>
<tr>
<td><strong>Ribs</strong></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>3</td>
</tr>
<tr>
<td>Lateral</td>
<td>5</td>
</tr>
<tr>
<td>Posterolateral</td>
<td>1</td>
</tr>
<tr>
<td>Posterior</td>
<td>4</td>
</tr>
<tr>
<td><strong>Upper Limb</strong></td>
<td></td>
</tr>
<tr>
<td>Ulna</td>
<td>2</td>
</tr>
<tr>
<td>Radius - CML</td>
<td>2</td>
</tr>
<tr>
<td><strong>Lower Limb</strong></td>
<td></td>
</tr>
<tr>
<td>Tibia - CML</td>
<td>7</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
</tr>
<tr>
<td>Vertebra</td>
<td>1</td>
</tr>
</tbody>
</table>

In this group, the mean number of fractures in the abused group was 3.85, compared to 1 in the accidental group. It is worth noting the high frequency of both rib fractures in various positions and classic metaphyseal lesions (CML) in the abuse group.

Ethnicity data were also gathered, and these are presented below, with the number of abuse cases in each group presented in parentheses (Table 4.2). Of those who were
determined to be victims of abuse (or possible abuse), 5 were of Maori descent and two were of NZ European descent. Maori are over-represented in both the survey and abuse groups, making up 50% of those surveyed and 71% of those abused, compared to 13.8% in the Otago Population aged 0-4 taken from the 2006 census (Statistics New Zealand, 2007).

Table 4.2. Ethnicity count of those surveyed, numbers of cases of abuse/possible abuse are shown in brackets. The percentage of each ethnicity aged 0-4 in the Otago population taken from the 2006 NZ Census.

<table>
<thead>
<tr>
<th>Ethnicity</th>
<th>No.</th>
<th>% Ethnicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>European</td>
<td>10(2)</td>
<td>93.0</td>
</tr>
<tr>
<td>Maori</td>
<td>11(5)</td>
<td>13.8</td>
</tr>
<tr>
<td>Pacific</td>
<td>1</td>
<td>3.9</td>
</tr>
</tbody>
</table>

4.1.2 Auckland survey

In the Auckland population, a larger group of surveys were found. Between 2009 and the time of study (2013), 305 patients had skeletal surveys were carried out on them. The median age in this group was 8 months. More positive skeletal surveys were found here, with 125 patients showing skeletal injury (at least one fracture). Of those with skeletal injuries, 51 cases were found to be due to accidental (or probable accidental) causes, 50 were found to be due to NAI (or probable NAI), and 24 were due to unknown or medical causes. A number of additional patients with non-skeletal injuries due to accident or NAI were also found, 11 and 56 patients respectively, were identified in each of these groups. 64.15% of cases of NAI were found in children under 1, the remaining 35.85% were seen in those older than 1. A very similar distribution was seen in accidental cases with 66.13% of accidental injury occurring in those less than 1, and 33.87% in those older than 1. Fractures found in the aforementioned groups are shown before in Table 4.3, and in cases where there was a significant difference (p<0.05) between the accident and NAI group on one-way analysis of variance (ANOVA) the larger group is indicated by an asterisk(*). The mean number of fractures found differed significantly between individuals with NAI, accidental fractures or fractures of unknown origin (both p<0.001, Welch t-test, t=-3.78 and -3.54, respectively). The mean number of fractures in the 3 groups (NAI, Accidental and Fracture of Unknown origin) were 4.40, 1.29 and 1.46, respectively. The effect of age (divided into 2 groups: less and greater than 1-year-old) and its
interaction with cause of injury on the mean number of fractures was then examined using a Poisson regression. This found a significant (p<0.0001) effect for cause of injury, reflecting the results above, and also for the interaction between cause and age (p=0.002). This interaction is presented in figure 4.1, along with the group means. This shows the discrepancy between the numbers of fractures due to accident versus abuse is significantly greater in the less than 1-year-old group, and this difference is non-significant in the older group. As well as a significant interaction, this figure also shows a significant difference (p<0.05) in the mean number of fractures in the abuse group, stratified by age.

Figure 4.1. Interaction on Poisson regression between cause of skeletal injury and age (less and greater than 1-year-old) in Auckland population. Cell means and error bars representing 95%CI are also shown.
Table 4.3. Number of fractures at each location found in Auckland population, stratified by cause. (CML= classic metaphyseal lesion).

<table>
<thead>
<tr>
<th>Fracture Location</th>
<th>Accident</th>
<th>NAI</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skull</td>
<td>34*</td>
<td>16</td>
<td>9</td>
</tr>
<tr>
<td>Parietal</td>
<td>28*</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>Occipital</td>
<td>4</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Frontal</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Ribs</td>
<td>1</td>
<td>119*</td>
<td>5</td>
</tr>
<tr>
<td>Anterior</td>
<td>0</td>
<td>25*</td>
<td>1</td>
</tr>
<tr>
<td>Anterolateral</td>
<td>0</td>
<td>31*</td>
<td>1</td>
</tr>
<tr>
<td>Lateral</td>
<td>0</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Posterolateral</td>
<td>1</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>Posterior</td>
<td>0</td>
<td>41*</td>
<td>0</td>
</tr>
<tr>
<td>Upper Limb</td>
<td>22</td>
<td>37</td>
<td>12</td>
</tr>
<tr>
<td>Scapula</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Clavicle</td>
<td>6</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Humerus-Shaft</td>
<td>3</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Humerus-CML</td>
<td>1</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Radius-Shaft</td>
<td>5</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Ulna-Shaft</td>
<td>7</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Metacarpal</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Phalanx</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Lower Limb</td>
<td>10</td>
<td>47*</td>
<td>5</td>
</tr>
<tr>
<td>Pelvis</td>
<td>0</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Femur-Shaft</td>
<td>5</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Femur-CML</td>
<td>0</td>
<td>9*</td>
<td>2</td>
</tr>
<tr>
<td>Tibia-Shaft</td>
<td>2</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Tibia-CML</td>
<td>0</td>
<td>14*</td>
<td>0</td>
</tr>
<tr>
<td>Fibula-Shaft</td>
<td>0</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Fibula-CML</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Tarsal</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Metatarsal</td>
<td>3</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>67</strong></td>
<td><strong>219</strong></td>
<td><strong>31</strong></td>
</tr>
</tbody>
</table>

In total there were 21 cases of patients with rib fractures within this population. Of these, there were 16 cases of NAI containing a total of 119 rib fractures. 13 cases had unilateral rib fractures and 8 of these cases were determined to be due to NAI. The remaining 8 cases had bilateral fractures and were exclusively due to NAI. There was a significant (p=0.0108) difference in the mean number of rib fractures between those who had bilateral (mean = 12.38) and unilateral fractures (mean = 2.00) on student’s
Further, 95% of patients who were found to have rib fractures were aged less than 1 year old and there was a significantly difference in the mean numbers of rib fractures between the less than and greater than 1 year old group (means =0.58, 0.06 respectively, Welch t-test p=0.012). Distribution of rib fractures around the rib arc was as follows: Anterior = 20.8%, Anterolateral= 25.6%, Lateral = 10.4%, Posterolateral = 10.4%, Posteromedial/Posterior = 32.8%.

A number of soft tissue injuries were also seen, the most frequent of which were bruising, brain haemorrhages (e.g. SDH, EDH, and SAH) and diffuse axonal injury (DAI) These more frequent soft tissue findings are presented in the table 4.4 below. Again, in cases where there is a significant difference (p<0.05) between the accidental and NAI groups on one-way ANOVA, an asterisk indicates the larger group.

Table 4.4. Frequent soft tissue injuries in the Auckland population, stratified by cause. (SDH = Subdural Haematoma, DAI = Diffuse Axonal Injury, RH = Retinal Haemorrhage, EDH = Extradural haematoma, SAH = Sub-arachnoid haemorrhage).

<table>
<thead>
<tr>
<th>Soft Tissue Injury</th>
<th>Accident</th>
<th>NAI</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bruising</td>
<td>15</td>
<td>53*</td>
<td>11</td>
</tr>
<tr>
<td>SDH</td>
<td>4</td>
<td>39*</td>
<td>17</td>
</tr>
<tr>
<td>DAI</td>
<td>0</td>
<td>12*</td>
<td>2</td>
</tr>
<tr>
<td>RH</td>
<td>0</td>
<td>24*</td>
<td>5</td>
</tr>
<tr>
<td>EDH</td>
<td>4</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>SAH</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Dyspnoea</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Intra-abdominal Injury</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Laceration</td>
<td>0</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Burn</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Ethnicities of the cases surveyed were also determined and these are shown in table 4.5. This table is also stratified by the number of cases of both abusive and accidental injury in this group (cases of injury with unknown cause are excluded here).
Table 4.5. Ethnicities of cases surveyed in Auckland population, with number of cases of abuse and accidental injury. Percentages are shown in brackets. Percentage of children of each ethnicity aged 0-4 in the Auckland population taken from the 2006 NZ Census also shown (Statistics New Zealand, 2007)

<table>
<thead>
<tr>
<th>Ethnicity</th>
<th>Total Surveyed</th>
<th>Accident</th>
<th>NAI</th>
<th>% Ethnicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asian</td>
<td>10(3.2%)</td>
<td>3(4.8%)</td>
<td>2(1.9%)</td>
<td>17.7%</td>
</tr>
<tr>
<td>European</td>
<td>68(22.3%)</td>
<td>13(21.0%)</td>
<td>24(22.6%)</td>
<td>59.1%</td>
</tr>
<tr>
<td>Indian</td>
<td>12(3.9%)</td>
<td>2(3.2%)</td>
<td>4(3.8%)</td>
<td>N/A</td>
</tr>
<tr>
<td>Maori</td>
<td>130(42.6%)</td>
<td>19(30.6%)</td>
<td>52(49.0%)</td>
<td>19.2%</td>
</tr>
<tr>
<td>Pacific</td>
<td>79(25.9%)</td>
<td>23(37.0%)</td>
<td>22(20.8%)</td>
<td>26.0%</td>
</tr>
<tr>
<td>Other</td>
<td>6(1.9%)</td>
<td>2(3.2%)</td>
<td>2(1.9%)</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Within ethnic groups there appear to be disparities, both in the number of cases surveyed and those who were victims of abuse compared to the frequency of these ethnic groups in the general population. This is further discussed in the following section.

The reasons for the skeletal survey being carried out was also collected and these are presented in table 4.6. Note that in a number of cases there were multiple reasons leading to survey and this is reflected in the table with some cases belonging to more than 1 group. A suspicious history was one that a clinician considered to be either inconsistent with the injury present or suggested abusive processes such as shaking; this is compared with a history of abuse, where abusive injury was explicitly suggested. Those cases in the ‘incidental fracture’ group were indicated for skeletal survey when an unexplained fracture was found over the course of an unrelated medical or radiological examination.

Table 4.6. Reasons for skeletal survey being carried out within Auckland population.

<table>
<thead>
<tr>
<th>Reason for Survey</th>
<th>Number of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bruising</td>
<td>41</td>
</tr>
<tr>
<td>Known Fracture</td>
<td>72</td>
</tr>
<tr>
<td>Incidental fracture</td>
<td>12</td>
</tr>
<tr>
<td>Head Injury</td>
<td>66</td>
</tr>
<tr>
<td>Other Soft Tissue Injury</td>
<td>11</td>
</tr>
<tr>
<td>History of Abuse</td>
<td>38</td>
</tr>
<tr>
<td>History of Family Violence</td>
<td>22</td>
</tr>
<tr>
<td>Suspicious history</td>
<td>5</td>
</tr>
<tr>
<td>Post-mortem</td>
<td>5</td>
</tr>
<tr>
<td>Sibling with NAI</td>
<td>28</td>
</tr>
<tr>
<td>Other</td>
<td>2</td>
</tr>
<tr>
<td>Unknown</td>
<td>9</td>
</tr>
</tbody>
</table>
It is worth noting that of the cases with rib fractures, 8 of 20 patients presented with these as an incidental finding during an alternate radiological examination, and 10 of the remaining cases were surveyed due to the presence of unexplained bruising or other injuries and rib fractures were then seen as an occult or unexpected fracture on these surveys. The final 2 cases were seen during the course of a NAI survey, 1 due to a history of abuse, and 1 on post-mortem, in these cases rib fractures also appeared to be clinically unsuspected.

Within this population, 9 fatal cases were present. 8 of these were the result of NAI, and of these 5 were due to DAI, 1 was due to intra-abdominal injury, 1 was the result of SDH, and 1 was due to laceration/stab injuries. The one case that was determined to be due to accidental causes was due to sudden unexplained death of an infant syndrome (SUDI).

4.1.3 Statistical analysis

As stated in the methods section (3.13), only the Auckland population has been included in the following analyses. This was done to ensure consistency between data and give these analyses the greatest amount of meaning and relevance.

Where significant differences in the mean frequency of an injury were found, an odds ratio (OR) for NAI over accidental injury was also calculated. Along with this, measures of diagnostic usefulness of each injury type, i.e. sensitivity and specificity to NAI or accidental injury (whichever group in which the frequency was highest), were determined. ORs and 95% confidence intervals for these, along with specificity and sensitivity values for these injuries, within the total cohort are presented in table 4.8.

In a number of cases, a ratio could not be found as there were no injuries of this type in the one group and therefore the ratio calculated was infinite. The large CIs seen in a number of cases are due to the infrequency of the injury in one group, most often accidental injury. The cohort was then limited to include only those between the age of 0 and 1 but no significant (p<0.05) difference was found in ORs or diagnosticity in these cases.
Table 4.7. Odds Ratios and diagnostic measures for injuries with statistically significantly different means between groups within the Auckland population.

<table>
<thead>
<tr>
<th>Injury Type</th>
<th>OR</th>
<th>95% CI</th>
<th>Sensitivity</th>
<th>Specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parietal*</td>
<td>0.183</td>
<td>0.085, 0.394</td>
<td>44%</td>
<td>92%</td>
</tr>
<tr>
<td>Femur CML*</td>
<td>NA</td>
<td>NA</td>
<td>6%</td>
<td>99%</td>
</tr>
<tr>
<td>Tibia CML*</td>
<td>NA</td>
<td>NA</td>
<td>9%</td>
<td>99%</td>
</tr>
<tr>
<td>Rib Fractures #</td>
<td>10.84</td>
<td>1.4, 83.92</td>
<td>15%</td>
<td>97%</td>
</tr>
<tr>
<td>Bruising #</td>
<td>3.13</td>
<td>1.56, 6.28</td>
<td>50%</td>
<td>87%</td>
</tr>
<tr>
<td>SDH #</td>
<td>8.44</td>
<td>2.85, 25.04</td>
<td>37%</td>
<td>89%</td>
</tr>
<tr>
<td>DAI #</td>
<td>NA</td>
<td>NA</td>
<td>11%</td>
<td>99%</td>
</tr>
<tr>
<td>RH #</td>
<td>NA</td>
<td>NA</td>
<td>23%</td>
<td>97%</td>
</tr>
</tbody>
</table>

* numerical variable
# categorical variable

1 For Accidental Population
2 For NAI Population

Odds ratios were also assessed for the reason for survey, comparing those that, following the skeletal survey were identified as being cases of NAI or accidental injury. The odds ratios that were determined to be significant (p<0.05) are presented in table 4.9 below, along with the 95% CIs.

Table 4.8. Odds ratios for reason for survey and determined cause of injury.

<table>
<thead>
<tr>
<th>Reason for Survey</th>
<th>OR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bruising</td>
<td>11.84</td>
<td>2.72, 51.55</td>
</tr>
<tr>
<td>Known Fracture</td>
<td>0.05</td>
<td>0.02, 0.12</td>
</tr>
<tr>
<td>Head Injury</td>
<td>3.86</td>
<td>1.72, 8.66</td>
</tr>
</tbody>
</table>
4.2 Biomechanical study

4.2.1 Pig impact testing

In this study, a total of 20 stillborn piglets were impacted at various heights, ranging from 0.15m to 0.35m. Of this group, 16 piglets have been included for fracture analysis purposes as, of the remaining 4, 3 were sectioned too small to view all ribs and 1 was considered to be an outlier due to a complete absence of fractures coupled with a force that would have expected to produce significant fracturing. The information gathered from the piglet impacts is presented in table 4.9, this includes piglet weight, force of impact, acceleration, the number of fractures seen and ribs these were seen in.

Firstly, there is a statistically significant (p<0.05) correlation between the force of impact and the number of fractures found. The Pearson’s correlation coefficient for this was shown to be 0.543 (95% CI, 0.052, 0.814), and a linear regression was carried out to further quantify this relationship. The regression equation found is stated below:

\[ \text{No. of Fractures} = -0.377 + 0.005607 \times \text{Force} \]  
\[ \text{(Eqn. 4.1)} \]

This regression was significant (p=0.033) and indicated that the minimum force for one or more fracture is 245N or more, based on extrapolation of the above equation. A graph representing this equation with 95% CI is presented in Figure 4.2.
Table 4.9. Information gathered from the piglet impacts. Only analysed piglet data is included here, 4 impacted samples were excluded.

<table>
<thead>
<tr>
<th>Piglet ID</th>
<th>Weight</th>
<th>Height</th>
<th>Angle</th>
<th>Accel (m/s²)</th>
<th>Force (N)</th>
<th>Fracture number</th>
<th>Ribs Fractured</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15-1</td>
<td>1001</td>
<td>0.15</td>
<td>26.57</td>
<td>97.41</td>
<td>695.04</td>
<td>2</td>
<td>3,5</td>
</tr>
<tr>
<td>0.15-2</td>
<td>1364</td>
<td>0.15</td>
<td>26.57</td>
<td>86.33</td>
<td>615.95</td>
<td>2</td>
<td>7,8</td>
</tr>
<tr>
<td>0.15-3</td>
<td>1175</td>
<td>0.15</td>
<td>26.57</td>
<td>108.60</td>
<td>774.84</td>
<td>2</td>
<td>6,7</td>
</tr>
<tr>
<td>0.15-4</td>
<td>1134</td>
<td>0.15</td>
<td>26.57</td>
<td>92.12</td>
<td>657.25</td>
<td>4</td>
<td>5,6,7,8</td>
</tr>
<tr>
<td>0.15-5</td>
<td>881</td>
<td>0.15</td>
<td>26.57</td>
<td>109.19</td>
<td>779.04</td>
<td>3</td>
<td>7,8,9</td>
</tr>
<tr>
<td>0.20-1</td>
<td>1611</td>
<td>0.2</td>
<td>30.77</td>
<td>82.89</td>
<td>591.45</td>
<td>3</td>
<td>7,8,9</td>
</tr>
<tr>
<td>0.20-2</td>
<td>1718</td>
<td>0.2</td>
<td>30.77</td>
<td>105.46</td>
<td>752.44</td>
<td>5</td>
<td>5,6,7,8,9</td>
</tr>
<tr>
<td>0.20-3</td>
<td>1112</td>
<td>0.2</td>
<td>30.77</td>
<td>161.87</td>
<td>1154.91</td>
<td>5</td>
<td>5,6,9,10,11</td>
</tr>
<tr>
<td>0.20-4</td>
<td>1628</td>
<td>0.2</td>
<td>30.77</td>
<td>113.31</td>
<td>808.43</td>
<td>4</td>
<td>5,6,7,8</td>
</tr>
<tr>
<td>0.20-5(2)</td>
<td>1384</td>
<td>0.2</td>
<td>30.77</td>
<td>109.87</td>
<td>783.94</td>
<td>3</td>
<td>8,9,10</td>
</tr>
<tr>
<td>0.20-6(2)</td>
<td>878</td>
<td>0.2</td>
<td>30.77</td>
<td>120.17</td>
<td>857.43</td>
<td>5</td>
<td>9,10,11,12</td>
</tr>
<tr>
<td>0.25-2</td>
<td>1509</td>
<td>0.25</td>
<td>34.52</td>
<td>112.82</td>
<td>804.94</td>
<td>8</td>
<td>3,4,5,6,7,8,9,10,11</td>
</tr>
<tr>
<td>0.25-3</td>
<td>1537</td>
<td>0.25</td>
<td>34.52</td>
<td>127.53</td>
<td>909.93</td>
<td>5</td>
<td>3,4,5,6,7</td>
</tr>
<tr>
<td>0.25-4(2)</td>
<td>1108</td>
<td>0.25</td>
<td>34.52</td>
<td>136.46</td>
<td>973.62</td>
<td>6</td>
<td>8,9,10,11,12,13</td>
</tr>
<tr>
<td>0.35-1</td>
<td>1912</td>
<td>0.35</td>
<td>41.1</td>
<td>130.28</td>
<td>929.52</td>
<td>6</td>
<td>3,4,5,6,7,8,9</td>
</tr>
<tr>
<td>0.35-2</td>
<td>1421</td>
<td>0.35</td>
<td>41.1</td>
<td>156.47</td>
<td>1116.41</td>
<td>5</td>
<td>3,4,5,6,7,8,8</td>
</tr>
</tbody>
</table>
Figure 4.2. Regression line of force of piglet impact against number of fractures identified on X-ray. 95% CI is indicated by red dashed lines.

Also of note is the strong relationship between the weight of the piglets and the peak force, when adjusted for the height of impact (p<0.001). This relationship is shown in figure 4.3, and is quantified by a Pearson’s correlation coefficient of -0.784 (95% CI, -0.9075, -0.4021).

Figure 4.3. Regression line of piglet weight plotted against impact force adjusted for height. 95% CI indicated by red dashed lines.
The fractures found were determined via radiology, as would be the most likely case clinically. These fractures were usually subtle and seen as small hairline shadowing on the rib line. More noticeably displaced fractures were also seen in some cases, but it is possible these would have been held in alignment by muscle tension in a live piglet or infant. Both these types of fractures are seen in figure 4.4.

Three piglets were also dissected to obtain fractured bone for SEM. Within these 3 animals, 20 fractures were visualized and 6 were taken for microscopy. Of the fractures seen, 15 were complete fractures through the bone and a number of them piercing through the parietal pleura of the thoracic wall (seen in figure 4 - 4), with the remaining 5 observed to be greenstick fractures with a butterfly patterning.

Figure 4.4. Piglet hemithorax with a number of complete fractures visible. A fracture can be seen piercing the parietal pleura, and this indicated by the arrow

4.2.2 Scanning electron microscopy

A number of ribs were analysed by SEM and these can be divided into two main groups: those with complete, and those with greenstick lateral fractures. Of the first group (complete fractures) three were scanned and both ends of each of the fractures were visualised. These complete fractures appear as straight fractures perpendicular to the rib arc (Figure 4.5). These fractures appear as brittle type fractures with minimal fibre pull
out indicating the high strain rate. In figure 4.6, an excellent example of sacrificial bonding is present, in which crack termination occurs due to the sacrificial rupture of collagen fibres running transverse to the direction of crack propagation. Further, there were scarce micro-cracks present in these samples, again indicating the high strain rate present (Zioupos et al., 2008).

![Image of fracture end](image)

Figure 4.5. Exemplary complete fracture as a result of blunt force impact, showing straight fracture end (Magnification = 25x).

Four of the greenstick fractures were analysed using SEM, 1 of which was decalcified. Fractures in this group began as straight fractures at the side of impact then, as fracture energy dissipated, the fractures changed direction to form oblique fractures and then terminate, this is demonstrated in figure 4.7. Again, few micro-cracks were seen and fibre pull out was absent or rare (one of these unusual cases is seen in figure 4.8). Sharp tears were seen within the lamellae and this is shown in figure 4.8. Little additional information was gained from decalcified bone and scans from this bone are not presented here.
Figure 4.6. Complete bone fracture exhibiting sacrificial bonding of collagen fibres across a fracture adjacent to a nutrient foramina.

Figure 4.7 Exemplary greenstick fracture showing straight fracture pattern at the point of impact and oblique fracturing as the fracture dissipates (Magnification = 35x)
Figure 4.8 Incomplete fracture showing lamellar tearing (right images), and line of sharp fracture with a singular pull-out fibre (left images)
4.3 Finite element analysis

As a result of software and scanning errors, meshing of the 3-rib pair was unable to be completed by the time of writing and work is on-going in order to complete meshing and blunt force trauma simulation.

4.3.1 Four-point bending simulation

The first FEA simulation completed was a 4-point bending test to compare with experimental results gained from Bradley (2012). The material properties of the rib were modified in order to get the greatest degree of agreement between the 2 data sets. Unfortunately, due to either: a) errors within the mesh, b) limitations of the elements and materials used, or c) errors in the geometry of the simulation, the degree of matching was limited. A graph showing 4 experimental data curves, along with simulation that had the closest match to this data is presented in Figure 4.9, with a log scale and again in Figure 4.10 with linear scale. This closest match was obtained with an elastic model of the bone with material properties of: for cortical bone, an elastic modulus of 12Gpa and Poisson’s ratio of 0.3; and for the trabecular bone, an elastic modulus of 5Mpa and Poisson’s ratio of 0.45. For the purpose of comparison, a simulation was also run using the baseline material properties from Tsai et al. (2012), with the shell model converted to a solid and assigned the following properties: elastic modulus of 38Mpa and Poisson’s ratio of 0.379. The results of this simulation are similarly shown in figure 4.9; in this figure, a log scale is used to enable appreciation of the similarity of shape of the Tsai curve with the others, despite a large difference in the resultant force.
Figure 4.9. Comparison of simulation and experimental data from Bradley (2012) in 4-point bending, including curve using material properties from Tsai et al. (2012). Logarithmic scale is used here.

Figure 4.10. Comparison of simulation and experimental data from Bradley (2012) in 4-point bending using a linear scale.
4.3.2 Compressive testing and simulation

The results taken from the compressive testing of the 4 rib pairs, exported from the Bluehill software are shown, first collectively in Figure 4.12, then each data from each pair are shown in Figures 4.13 to 4.16. Each pair exhibited quite similar, however due to differences in geometry or size, there was some difference between the pairs and this can be seen in Figure 4.12. These curves show viscoelastic and viscoplastic behaviour; viscoelastic behaviour is seen as viscoelastic creep following loading and viscoplastic behaviour as the loss of energy between cycles.

The model from the four point bending test was also utilised in this simulation to compare the degree of matching in these two scenarios. The same material properties as described above were used and the simulation was run to compare these with the first phase of this compressive testing (10mm loading at 10mm/min). The material properties match to an extent but due to the importance of the viscoelastic effects this matching is quite limited.

Work is continuing to characterise the viscoelastic and viscoplastic characteristics of the ribs seen in the later phases of the experimental testing.

![Figure 4.11](image)

*Figure 4.11. Graph showing the first loading phase of the compressive experimental curves, along with the numerical simulation using the material properties from the 4-point bending simulation.*
Figure 4.12. Compressive extension versus Load graph, with all 4 rib pairs shown and an additional thicker line indicate their mean.

Figure 4.13. Compressive extension versus Load graph showing first 5th rib pair and an additional thicker line indicating their mean.
Figure 4.14. Compressive extension versus Load graph showing second 5\textsuperscript{th} rib pair and an additional thicker line indicating their mean.

Figure 4.15. Compressive extension versus Load graph showing first 6\textsuperscript{th} rib pair and an additional thicker line indicating their mean.
Figure 4.16. Compressive extension versus Load graph showing second 6th rib pair and an additional thicker line indicating their mean.
5 Discussion

The current work aimed to provide a snapshot of skeletal injury in abuse in New Zealand and to contrast this with what is seen in accidental cases, especially with regards to rib fractures. Secondary to this, information on soft tissue injury has also been gathered in order to give a more complete picture of what may be found.

A biomechanical and computational assessment of blunt-force trauma (BFT) to a model of piglet rib was also carried out. An apparatus was assembled and stillborn piglets were impacted in order to define patterns and morphology of fractures in order to compare and contrast these with fractures that are found in which compressive trauma is suggested. Finite element analysis (FEA) was also attempted, however due to issues with meshing and material property assignment this work is presently ongoing, but the results found at time of writing are discussed below.

5.1 Radiological survey

The results of the radiological study, namely the data from within the larger Auckland population, are largely in line with previously published literature of patterns of injury seen in non-accidental injury (NAI). The first result, showing a significant (p<0.05) difference in fracture frequency in NAI and accidental injury, amongst those who had skeletal injury (4.40 vs. 1.29), was similar to the finding reported by Worlock et al. (1986) who observed a significantly higher proportion of multiple fractures in the abused group, although specific group means were not provided. The population seen in this study also observed a higher mean number of fractures in the NAI group than seen in Loder and Bookout (1991), which showed a mean of 2.00 fractures per case in their study of 75 abused children. A highly significant interaction was noted between age and the number of fractures seen in the groups. No statistically significant different mean was seen between groups in those older than 1 year; however the inter-group discrepancy was much greater in those younger than this. Those in the NAI group, who were younger than 1 year, were highly significantly more likely to have multiple fractures compared to any other group, including those with NAI older than 1 year. This difference can be largely attributed to the increased frequency of rib fractures, often occurring as multiple fractures, in children less than 1 year (95% of rib fractures are found in this group and within these patients, the mean number of rib fractures was 9.5 in those with NAI). This high mean
number of rib fractures in patients with NAI, has been also documented previously (Barsness et al., 2003), as has the increased frequency of rib fractures in those less than 1 year old (Loder and Feinberg, 2007, Merten and Carpenter, 1990). These findings suggest, firstly, that multiple fractures in children are highly suspicious for abuse, especially in those less than 1 year of age, and secondly, rib fractures may account for this difference due to being more frequent in those less than 1 year.

The current work also identified a number of fractures that were more likely to be due to, or suggestive of abuse than an accidental injury process, such as falls etc. Those that were found to have significant differences between the abuse and accidental groups were parietal fractures, lower limb classic metaphyseal lesions (CMLs), and rib fractures. All of those identified, except parietal fractures were significantly more probable in NAI than accidental injury (p<0.05). Bilo et al. (2010a) noted that CMLs fall into the category of high specificity for abuse, along with rib fractures and these findings were replicated here. Bilo et al. (2010) also suggests scapular, spinous process and sternal fractures were highly specific but here they were not present in this study in any great number, as with CMLs of the upper limb (83.33% of humerus CMLs were found in abuse, but the total number was not high enough to gain statistical significance). Parietal fractures were identified as being more specific and more common for accidental injury than NAI in this work, and this is reflected in previous literature (Bilo et al., 2010b). The majority of both all-cause parietal fractures and parietal fractures due to NAI were found in children aged less than 1 year old. This is also echoed in the literature, with infants in this age group 6 times more likely to sustain a skull fracture (Kleinman et al., 1995, Merten and Carpenter, 1990). These fractures were also more likely to be due to abuse; in a study of children (0-13 years), only 3% of skull fractures were due to abuse (Johnstone et al., 1996), but in populations limited to those less than 1-2 years this number increased drastically to 27-33% (Hobbs, 1984, Kleinman, 1987).

Bruising, while often a normal pattern in child development, has also previously been found to be a significant marker of abuse. Roberton et al. (1982) found that, despite lower limb bruising as a frequent injury in normal infants, this and all other forms of bruising were more common in infants as a result of abuse. This effect was further pronounced as the age groups were limited to younger children. These findings were again echoed in Ingham et al. (2011), which showed that bruising in autopsied children was frequently associated with other injuries, with a great deal of specificity (97%), and was found in a
majority of cases where homicide/NAI was the cause of death. This work showed bruising was significantly more likely where NAI was the cause of injury compared to accidental causes (OR = 3.13), and further that bruising was highly specific for abuse (87%). This specificity must be appreciated in the context that this population was under investigation for abuse so the presence of bruising was much more likely in abuse than accident; however in the general population bruising will occur less specifically for abuse. In conjunction with this, bruising was also found to be the most sensitive injury (50%) for abuse, although this value was still not especially high.

Other soft tissue injuries with significant associations included intra-cranial injuries, namely subdural haemorrhage (SDH), retinal haemorrhage (RH) and diffuse axonal injury (DAI). These 3 injuries, when found in young children, have long had a high association and predictive value for abuse, usually in the context of the shaken baby syndrome (as has been discussed in chapter 2). There is a wealth of literature detailing these, especially that of SDH and abuse (Feldman et al., 2001). This association is clearly shown within this study. SDH was found occur 8.14 times more frequently due to NAI compared to accidental injury (OR = 8.14, 95% CI = 2.85, 20.54). Further, the specificity of SDH to NAI was 89%, indicating a strong association between SDH and NAI and showing if SDH is seen it is highly unlikely to be due to any other cause.

Retinal haemorrhages have also been found to have a high association with abusive injury (Gilliland et al., 1994) (often in conjunction with SDH and/or rib fractures – forming the triad of shaken baby syndrome (Caffey, 1974, Guthkelch, 1971)). Again this finding was echoed in the Auckland population, as there were no cases of RH found as a result of accidental trauma. As such, it was not possible to calculate an odds ratio (OR) and a specificity of 99% was found. Retinal haemorrhages continue to be a strong marker of abuse in this and other populations. DAI was found to be similar in this group also, all cases of DAI were found in the abuse group, leading to an unspecified OR and 99% specificity. These patients with DAI made up 55.5% of fatalities in this population and 62.5% of those dying due to NAI.

Rib fractures are highly associated with abuse (Barsness et al., 2003) and again this was echoed within this study. A high OR was seen in this study for abusive causes over accidental (10.84) and a specificity of 97%. This indicates, in concordance with previous work, that rib fractures are almost exclusively found in cases of abuse. Again, it was
shown that rib fractures were often an occult finding in this population, unrelated to the reason for presentation to the clinician - 40% with rib fractures were found secondary to unrelated investigations, and the remaining 60% were found unexpectedly during investigation of abuse. This is similar to what was shown in (Merten et al., 1983), in which 80% of rib fractures were seen unexpectedly during the course of a survey or investigation. The distribution of fractures along the rib arc in this work was in line with what has previously been seen in studies of rib fracture in NAI (see table 2 – 1), 32.8% of fractures were seen in the posterior region, compared with a range of 32-43% in previous studies, and 20.8% in the anterior region, compared with a range of 6-45%. A predominance of lateral fractures was seen in this work, with a total of 46.4% of fractures occurring in either the anterolateral, lateral or posterolateral regions, and this value was higher than what was seen in all but one (Wootton-Gorges et al., 2008) of the studies in table 2 – 1. Also, in a notable proportion of the cases with NAI and rib fractures (50%), these fractures were found unilaterally. This is noteworthy as the mechanism most frequently proposed for these fractures – anteroposterior compression – is said to usually result in bilateral fractures, and that these fractures will most commonly be found in the posterior rib region (Bilo et al., 2010c). This study, therefore, suggests alternate mechanisms may be occurring in a number of cases leading to both the higher frequency of lateral fractures, and large proportion of unilateral fractures in this population, and this may be attributed to lateral impacts.

Lastly, the present study shows the diverse range of clinical decisions that lead to a NAI skeletal survey being performed. Protocols state that skeletal surveys should be carried out on all children less than 2 years of age who presented with concern for possible NAI. Reasons for concern may be a presenting injury or any history of abuse (of either the patient or of another child living in the same household). The younger the patient the more trivial the presenting injury needs to be to indicate a skeletal survey (Personal communication, Kelly, 2013). In this study surveys were mostly frequently carried out as after clinical presentation for a fracture, a head injury or after a more trivial injury (bruising, for example). Those who had a survey following a known fracture, tended to be found to be cases of accidental injury (OR = 0.05), while those who were referred following a head injury or unusual bruising were more likely to be found to be victims of abuse (ORs = 3.86 and 11.84, respectively).
While this study has produced valuable and interesting data, it also has limitations. Firstly, it was retrospective, meaning there was little control over how the population was collected and what information was gathered for each patient. Further, clinical judgements at the time have been relied on for classification into the NAI or accidental groups, and this decision would have been made based largely on the injuries analysed here, so circularity bias may be an issue within this study. This means those injuries previously associated with abuse in the literature would have led to a child being classified as abused, so these same associations were seen here. Only one site was used in this study, which may be somewhat limiting however, the site selected in the analysis phase is the largest single children care facility in NZ. Starship Children’s hospital services several district health boards and a large population base, as well as taking the most severe cases from outside this area, making it a useful site.

This work primarily provides a snapshot of the relative frequencies and types of injuries seen within a population of abused children in a major children’s hospital in New Zealand. The injuries most frequently seen in abuse and those that were found more in cases of abuse than accidental injury aligned well with what has been found in past literature. This study also reinforces the strong associations certain injuries have historically had in cases of abuse; namely CMLs, SDH, RH, DAI and rib fractures. This study supports the diagnosticity for abuse of these injuries and also suggests the importance of noting bruising in detecting and evaluating the risk of NAI in children and infants. The data gathered about rib fractures is also of note, as it appears to have some discrepancies with what is normally described with these in NAI. While the association of rib fractures with NAI was still the highest for any injury, the high proportion of lateral-type fractures and the frequency of unilateral fractures in this population are unusual and do not wholly fit with previous understanding of anteroposterior compression. However, from the results of the study determining the mechanism of injury is purely speculative.

5.2 Biomechanical study and SEM

This experiment set out to describe the biomechanics of blunt force trauma (BFT) and the fractography of the resultant fractures using a piglet model of the infant thorax. It was shown that force, predictably, determines the number of fractures seen at a statistically significant level ($p<0.05$) and linear regression suggests that the minimum force required for fracture is approximately 245N. The forces required for fracture were low compared
to the forces that were delivered from impacts to plasticine carried out in my preliminary study and those seen in Smith et al. (2000). It is suggested that the reason for the low force requirement for impact fracture is due to the short time of impact and therefore high impulse and strain rate generated in the rib – a suggestion supported by the lack of microcracks seen microscopically (Zioupos et al., 2008). We hope to be able to quantify the stress and strain rates using FEA in future in order to characterise the failure behaviour of the ribs more precisely.

It was also found that for a given height of impact, weight of the piglets played a significant role in determining the force of impact. As the weight of the piglet increased, the resultant force decreased and this is likely due to increased damping and force absorption by the additional mass of the piglet. This, as well as the increased development and strength of the bone over time, may explain the increased frequency of fractures, especially those of the rib, seen in children under 1 year of age as seen both in this study and historically (Loder and Feinberg, 2007, Merten and Carpenter, 1990).

The fractures seen in this study were seen exclusively on the lateral aspects (anterolateral, lateral and posterolateral) of the rib and this work only suggests blunt force trauma as a mechanism for this group of fractures, rather than posterior fractures etc. However, lateral fractures make up a significant proportion of rib fractures, which was seen both in this study and in the literature (see table 2 – 1). The mechanism of antero-posterior compression is suggested to explain these fractures, but little experimental work has been shown to determine the biomechanical feasibility of this, only a single study of 3 rabbits by Kleinman and Schlesinger (1997) which may have not, in fact, been appropriate. More recent work by Bradley (2012) has shown that simple compression appears to be an unlikely mechanism for these fractures using a piglet model (as used in this study). We therefore suggest that blunt force trauma from single or multiple impacts may be a more likely reason for such fractures. We show here that these BFT impacts require relatively small forces before fractures begin and that these forces are well within the range that might be expected from a blow from an adult.

These fractures also differ morphologically on both the gross and microscopic level to those as a result of compression/bending. On the gross level, fractures due to compressive appear as exclusively incomplete green stick fractures, with straight fractures on the tensile surface and no oblique fracturing seen on the compressive side (Bradley, 2012).
Conversely, this study showed that most of the fractures visualised in BFT were complete, straight fractures and the minority that were seen as incomplete fractures exhibited both straight and oblique type fracturing. However, few greenstick fractures were seen so in future, more should be found and visualised in order to be more certain of the patterning seen here. Microscopically major differences were also seen between the compressive and BFT groups. Bradley (2012) found that compressive type fractures in fresh bone were the same as those in the frozen-then-thawed bone and showed little pull out but had numerous microcracks in the subsurface region of the fracture site (Figure 5.1). Delamination was not noted here.

![Figure 5.1 SEM of compressive fracture in frozen-then-thawed bone, showing a number of subsurface microcracks (indicated by arrows) in the highest magnification. (Adapted from Bradley (2012))](image)

In BFT fractures, microcracks were not seen frequently and this is the most significant difference microscopically. Fibre pull-out was also rarely seen here, in both the greenstick and complete fractures. Delamination and laminar tearing were also noted in a number of cases (Figure 4.8) and these were not considered in the case of compressive damage. These features may enable differentiation of BFT and compressive fractures at
both the gross and microscopic level. The archetypal compressive fracture appears as an incomplete greenstick fracture containing little fibre pull-out or delamination and many microcracks; this is compared to the most common form of BFT fracture, which is likely to be complete showing, again, little fibre pull-out but much fewer microcracks and with the presence of delamination. In future, more work may be carried out to further develop this schema and determine its accuracy in real-life cases.

In this work, a few issues may be identified. Due a limited supply of piglets, the sample size was smaller than preferred and repetition of trials would be useful to provide more information and verify what has been seen in this work. As a large animal model was being used, issues arise in control of variable in terms of development and health. The piglets used were stillborn or died soon after birth so these may not represent normal bone development or may exhibit increased skeletal fragility. These were used primarily out of ethical consideration, but in future ethical approval may be sought in order to euthanise healthy animals and further verify the results seen here.

Overall, these results provide a feasible, alternate mechanism to the previously proposed option of antero-posterior compression, instead suggesting a BFT process may be responsible for more fractures than previously thought. An initial schema is also provided to enable the differentiation of compressive type lateral fractures from those seen as a result of a rapid BFT impact.

5.3 Finite Element Analysis (FEA)

Ultimately, the results of the FEA in this thesis serve as preliminary and guiding results for what is to be completed in future. Firstly, this work attempted to determine a model that would accurately capture the properties of the rib on 4-point bending and compressive testing. From the results of the compression experiment, it has been shown that juvenile piglet ribs exhibit significant viscoelastic and viscoplastic behaviour. The viscoplastic activity of the bone is visualised as the force creep as the bone is held static. The viscoplastic behaviour is seen as the loss of energy between the first and second compressive cycles and the remaining displacement of the bone as it returns to rest (both these features are seen in Figures 4.12 to 4.16). These behaviour types are highly complex to model computationally, and as such we began with more simple models in order to assess whether these would capture physical behaviour to a degree that would be acceptable for use in simulations.
A basic elastic model was used at first for 2 reasons; it is the most simple to model and assess the effects of changing variables, and a similar model had previously been used by Tsai et al. (2012). Our results show that, while some of the ribs behaviour can be captured elastically, inclusion of viscoelastic/viscoplastic properties will eventually be necessary to model this system. It was also shown that the baseline material properties used by Tsai et al. (2012) were far lower than what was seen to be near accurate in this study. This suggests the distribution of stresses seen in an actual rib, is more likely to follow what was seen in their ‘high value’ condition (as opposed to the baseline condition). This ‘high value’ showed significantly higher stresses in the anterolateral components compared to the posterior component – whereas in the baseline condition these stresses were approximately equal. It is therefore reasonable to say, if the limited stresses in the posterior rib were adequate to cause the fractures seen in anteroposterior compression then, certainly, the much higher stresses in the anterolateral rib would also produce fractures. This is against the previous understanding of anteroposterior compression, where posterior fractures are said to be more numerous and more common. It is also worth noting that in the course of this work, it was seen that the variation of the Poisson’s ratio had little effect on the results of the simulation, a finding also seen in Tsai et al. (2012).

Similarly, simulation of the compressive experiment using an elastic model also gave results that did not entire map to what was seen experimentally, regardless of variation in the elastic modulus or Poisson’s ratio. Work is therefore continuing (at time of writing) to use the results of these experiments to quantify the non-elastic behaviours of the rib in order to gain greater fidelity and validity in these simulations.

There were issues in meshing and processing the larger objects (namely the 3 rib set) due to issues in scanning and as such the simulation was highly computationally inefficient. In future, the mesh will be manually refined in order to decrease the number of small or deformed elements allowing the simulation to progress smoothly following determination of a correctly set of material properties. There were also some errors in the single rib mesh, which may be leading to errors in the results of the simulation, however as this work is preliminary, these results are still sufficient to draw the conclusions made here and stimulate future work.
5.4 Conclusions

This work provides several useful points of information and also acts as a robust point of departure for future research. The first part of this work gives both a snapshot of abuse in New Zealand and also provides information on the injurious patterns seen in abuse or accidental injury to supplement what exists in the international literature. A point of particular note is the higher than previously seen proportion of the lateral type rib fractures, which, in supplement to the biomechanical analysis completed here, begins to suggest an alternate injury mechanism to compression, which is said to lead primarily to posterior type fractures.

The biomechanical analysis suggests that BFT may offer a more credible explanation for lateral rib fractures in infants. We show that relatively small forces were required to induce these lateral fractures in our piglet model and force induced due to impact was related to the weight of the animal. The role of weight, as well as normal bone development, may go some way to explaining the increased frequency of fractures in the younger age group, and a prospective analysis of future NAI cases may be useful in order to determine if this relationship is found in injuries in a real world situation. A means to microscopically differentiate between BFT and compressive fractures was also provided here and it is hoped this may be further developed and its functionality determined in future work.

Lastly, due to a number of issues in the FEA analysis work continues to materially characterise the infant bone and simulate compression and BFT injury in a validated model of bone, in order to determine the biomechanical features of these situations in more detail. Preliminary results found here, when compared to the analysis previously completed by Tsai et al. (2012), suggest that in compression strains may be greater in the anterolateral segments compared to those in the posterior region. This finding in conjunction with the experimental work on compression by Bradley (2012), showing the resistance of bone to anterior/lateral compressive fracture further bring into question this mechanism.
References


PFEFFERLE, K., LITSKY, A. & DONNELLY, B. Biomechanical properties of the excised pediatric human rib. 35th international workshop on injury biomechanical research, 2007 Washington, DC. NHTSA.


6 Appendices

6.1 Appendix 1 – Statement of Category A Ethical approval from University of Otago

Dear Professor Kieser,

I am writing to let you know that, at its recent meeting, the Ethics Committee considered your proposal entitled ‘Retrospective analysis of rib injury patterns and frequency in cases of non-accidental injury’.

As a result of that consideration, the current status of your proposal is:- Approved

For your future reference, the Ethics Committee’s reference code for this project is:- 13/043.

The comments and views expressed by the Ethics Committee concerning your proposal are as follows:-

While approving the application, the Committee would be grateful if you would respond to the following:

The Committee accepts your reasoning for not seeking consent from participants for this study. Given the possible importance of this research, the Committee would be grateful if some safeguards could be put in place to review the findings of the student researcher. The Committee suggests that two radiologists should review the xrays to confirm accuracy of the information.

Please note that the legal requirement for Health Information is that data must be kept for a minimum of ten years.

Please provide the Committee with copies of the updated documents, if changes have been necessary.

Approval is for up to three years from the date of this letter. If this project has not been completed within three years from the date of this letter, re-approval must be requested. If the nature, consent, location, procedures or personnel of your approved application change, please advise me in writing.
Yours sincerely,

[Signature]

Mr Gary Witte
Manager, Academic Committees
Tel: 479 6256
Email: gary.witte@otago.ac.nz

c.c. Sir John Walsh Research Institute
6.2 Appendix 2 – Statement of clinical ethical approval from Health Research South

Health Research South

18/03/2013 Project ID 00887

Prof. Jean-Claude Theis
Orthopaedic Surgery, DSM

Dear Jean-Claude

REF: Retrospective analysis of rib injury patterns and frequency in cases of non-accidental injury

I am writing on behalf of Health Research South to confirm that the project mentioned above has been granted approval to proceed.

According to our records:

This project is due to commence on: 18/03/2013
It is due to be completed by: 30/04/2013

If you have any questions with regards to this process, please contact me quoting the project ID shown above.

Yours sincerely

Ruth Sharpe
Clinical Research Advisor

CC: Prof. Jules Kieser, Sir John Walsh Research Institute, William Blackburne, Lynley Chinside, Southern DHB

Health Research South
University of Otago, Dunedin School of Medicine and Southern District Health Board
PO Box 913, Dunedin 9054
Ruth Sharpe, Clinical Research Advisor, Ph 03 470 9032 (Hosp 9033); Ruth.Sharpe@otago.ac.nz

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6.3 Appendix 3 – Statement of clinical ethical approval from the ADHB Research Office

4 March 2013

Jules Kieser
Sir John Walsh Research Institute
Dept. Oral Diagnostic and Surgical Sciences
Faculty of Dentistry
University of Otago
Dunedin

Dear Jules

RE: Research Project ADHB 5806  Ethics: UoO D13/025
Study title: Retrospective Analysis of Rib Injury Patterns and Frequency in cases of Non-accidental Injury

The Auckland DHB Research Review Committee (ADHB-RRC) would like to thank you for the opportunity to review your study and has given approval for your research project.

Your Institutional approval is dependant on the Research Office having up-to-date information and documentation relating to your research and being kept informed of any changes to your study. It is your responsibility to ensure you have kept Ethics and the Research Office up to date and have the appropriate approvals. ADHB approval may be withdrawn for your study if you do not keep the Research Office informed of the following:

- Any communication from Ethics Committees, including confirmation of annual ethics renewal
- Any amendment to study documentation
- Study completion, suspension or cancellation

More detailed information is included on the following page. If you have any questions please do not hesitate to contact the Research Office.

Yours sincerely

On behalf of the ADHB Research Review Committee
Dr Mary-Anne Woodnorth
Manager, Research
ADHB

cc. William Blackburne, Russell Metcalf, Sally Vogel, Zubin Dalal, Raewyn Curin, Jean-Claude Theis

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