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3 **Head impact biomechanics simulations: A forensic tool for**  
4 **reconstructing head injury?**  
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19 **ABSTRACT**  
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22 This paper describes a computer simulation method, which is used widely in engineering design  
23 and accident investigation reconstructions, which could constitute a valuable forensic tool for  
24 investigating cases of head impact injury and skull fracture. This method, the finite element  
25 method, relies on knowing the physical properties and strength of biological materials, including  
26 cranial bone and neural tissue, and on having evidence of the extent of head injuries in order to  
27 deduce causative forces. This method could help forensic pathologists to infer causes of skull  
28 fracture and to determine whether probable causes of fracture were accidental or intentional.  
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32 **KEYWORDS**  
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34 Skull fracture; accident investigation; computer simulation; finite element modelling  
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## INTRODUCTION

Skull fractures are commonly observed on victims of falls, road traffic accidents (RTAs), murders and assaults. In Ireland, head injuries occur in approximately a quarter of all hospital fall admissions [1]. RTAs and falls generally lead to different types of skull trauma: RTAs tend to cause diffuse and multifocal injuries, whereas falls tend to lead to focal injuries. Biomechanics research serves to establish the development of injury, damage and fracture that can occur from various impacts to the head. This can be modelled using computational techniques, once accurate details are known for the geometry and anatomy of the head and the physical stress-strain response (i.e., constitutive properties) of the materials of the head. The objective of this present paper is to outline a procedure by which occurrences of skull fracture can be reconstructed using computational engineering techniques. While the same techniques can also be used to simulate occurrences of traumatic brain injury (TBI) lesions, the present paper shall focus solely on skull fracture, for the sake of simplicity.

## MATERIALS AND METHODS

The constitutive properties of both the skull and brain influence the system response to mechanical loads and these must be known if the physical response of the skull-brain system is to be predicted accurately. A dynamic force applied to the head induces a complex series of mechanical and physical reactions involving local bending of the skull, volume changes to the intracranial contents, shock wave propagation throughout the brain and inertial effects, all of which induce tissue strains and stresses which may give rise to damage of the scalp, cranium, blood vessels or brain matter [2-4].

Cranial bone is a complex material comprising a three-layered structure. The outer and inner layers consist of compact, high-density bone called cortical bone, while the central layer consists of a low-density, irregularly porous bone structure. In order to examine the mechanism of skull fracture it was necessary to carry out mechanical tests on specimens of cranial bone. Most mechanical tests to date of cranial bone have been carried out at quasi-static speeds. In this instance, we have attempted to investigate the mechanical properties of cranial bone under more realistic accident conditions and the current tests were carried out under three-point bending to destruction at dynamic speeds of 1m/s. Cranial bone specimens (6cm x 1cm) were extracted from 8 fresh frozen cadavers (F=4, M=4; 81±11 yrs old; max=97 yrs old; min=62 yrs old). 62 specimens were obtained from the parietal and frontal cranial bones. Prior to testing all specimens were scanned using a microCT scanner at a resolution of 56.9 µm. The moment of inertia for each specimen was calculated from the microCT scan sets using custom written Matlab code. From the measured force-displacement curves and the calculated moment of inertia values, it was possible to evaluate the Young's modulus for each of the bone specimens. Furthermore, it was possible to quantitatively describe the structural properties and their variation within the cranial bone specimens and to investigate the link between mechanical and structural property variation. The measured moment of inertia and stiffness modulus (Young's modulus) from these tests were  $2.39 \times 10^{-4} \text{ m}^4$  and 9.82 GPa.

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3 The geometry of two human cadavers was determined by CT, MRI and sliced colour  
4 photographs. The geometric data are available through the Visible Human Database (National  
5 Institute of Health, USA) with 0.3 mm incrementation in the coronal plane [5]. A three-  
6 dimensional finite element (3DFE) model was created using this CT data [6,7]. Such digitised  
7 data is made up of voxels, which can be considered to be three-dimensional pixels. The scans are  
8 stored in stacks which make a stepped volume sampled recording. Interpolation and thresholding  
9 schemes were used to identify voxels representing bone, for example, and interpolate through the  
10 voxel generating smooth triangulated surfaces closer to the shape of the actual scanned head. The  
11 CT data was used to create a polygonal model of the visible male skull using vtk-software. The  
12 resulting polygonal model was decimated and smoothed in order to make the model more  
13 portable. This then was converted into IGES format and imported into the commercially  
14 available software MSC/Patran and used in the ABAQUS simulation software.  
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18 The 3DFE model of the skull-brain complex includes scalp, a 3-layered skull (outer and inner  
19 tables, diploe), dura, CSF, pia, falx, tentorium, cerebral hemispheres, cerebellum and brain stem.  
20 This is shown in cutaway view in Fig. 4. Much emphasis was placed in the model on mesh  
21 quality and ease of meshing, without sacrificing anatomical accuracy. For example, the ridge of  
22 the sphenoid wing, or the cusp of the skull upon which the temporal lobe sits, does not have an  
23 element face traversing it, which would necessitate smoothing this ridge (for element quality).  
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## 27 **RESULTS**

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29 The use of this three-dimensional finite element head model is illustrated in Figure 2, in which a  
30 physical example of linear skull fracture was successfully modelled: the location of the fracture,  
31 and the general extent of the fracture, are both consistent with what was observed in a physical  
32 reconstruction of an impacted skull. This computational analysis was undertaken using  
33 ABAQUS 5.8. Further details of such reconstructions are provided elsewhere [8].  
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## 38 **DISCUSSION**

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40 This paper reports on the status of ongoing research efforts to simulate the effects of head  
41 impacts and to reconstruct the extent of damage and fracture to cranial bone under such impacts.  
42 This computational technique requires knowledge of the force-time history in order to estimate  
43 the full-field distribution of stress and strain within the cranium. It also requires reasonably  
44 accurate knowledge of the geometry of a specific head if predictions more accurate than generic  
45 simulations are required. It is suggested that this simulation technique could provide useful  
46 knowledge when attempting to infer the relative likelihood of particular scenarios having led to  
47 known patterns of injury and skull fracture.  
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## 22 **FIGURE LEGENDS**

23 **Figure 1:** Cutaway view (left) and surface view (right) of finite element head model.

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25 **Figure 2:** Example of skull fracture in physical specimen (left; red dot and dashed line indicates

26 extent of linear fracture) and as predicted by finite element model (right; high gradients of colour

27 indicate region of greatest stress and location of fracture).

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3 **ROLE OF FUNDING**  
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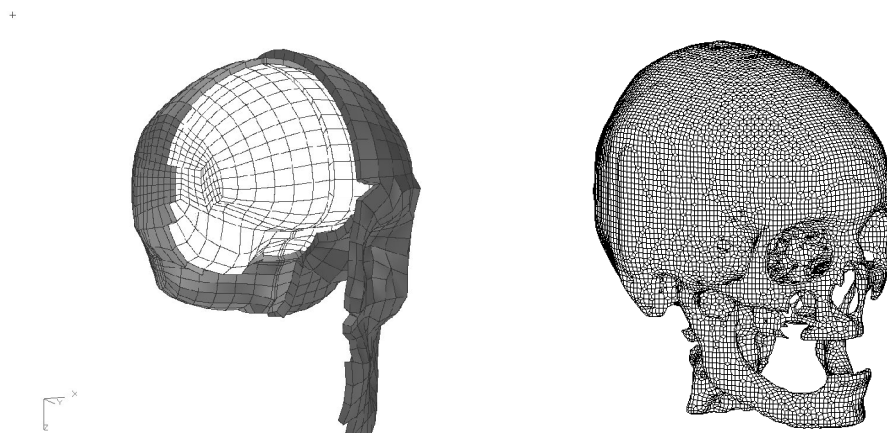
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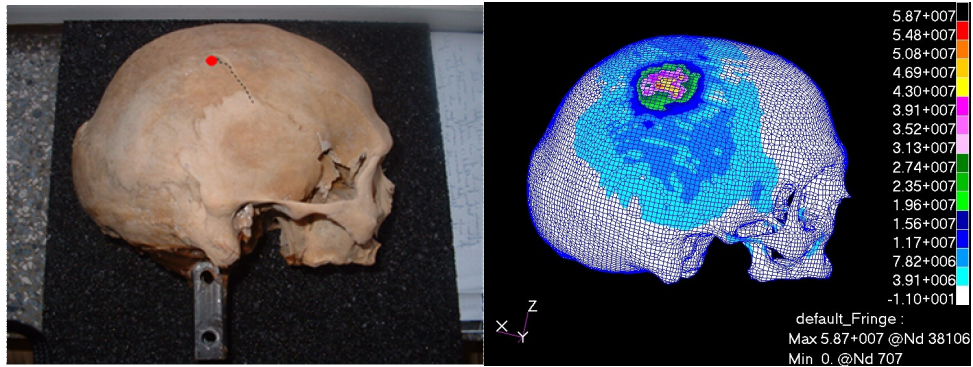
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17 **CONFLICT OF INTEREST STATEMENT**  
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19 None of the authors have any conflict of interest in this publication  
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*Figure 1: Cutaway view (left) and surface view (right) of finite element head model.*

**Figure 2**



**Figure 2:** Example of skull fracture in physical specimen (left; red dot and dashed line indicates extent of linear fracture) and as predicted by finite element model (right; high gradients of colour indicate region of greatest stress and location of fracture).