Investigation of a Local Absorption Energy Criterion for Skull Impacts through Subject-specific Finite Element Head Modelling

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I. INTRODUCTION

Head injury is recognised as the leading cause of mortality and morbidity in children and young adults [1-2]. Among children aged between 1 and 15 years, 15% of deaths are caused by head injuries [3]. It is the most frequent cause of death in the paediatric population, accounting for up to 80% of all trauma-related deaths each year [4]. These surveys stimulate the need for research to determine the cause and to develop improved protective headgear.

Over the past decades, the mechanics and characteristics of skull fracture have been studied [5-7]. An efficient tool to study subject-specific variations and the mechanisms of skull fracture is computational modelling of head impacts. Yoganandan *et al.* postulate that the energy absorbed by the skull before it fractures likely represents the best predictor for skull fracture, by incorporating impact as well as structural characteristics [5]. Sahoo *et al.* used the strain energy of the skull bone to predict skull fracture [8].

By encompassing impact information as well as structural characteristics, the energy criterion has the potential to accurately predict skull fracture [9]. Previous results at our research group investigated the existence of an energy failure criterion with a double pendulum set-up in a series of intact cadaver heads [9-10]. The average age of the subjects is 78.3 ± 12.7 years. For frontal impacts, an energy failure level of 22–24 Joule (J) is suggested [10], for temporal dynamic loading conditions 5–15 J [9]. Monea *et al.* concluded that the energy criteria for impacts are location dependent [9]. The energy absorbed by the skull depends on the impacted mass as well as the local bone characteristics expressed by bone density. The interest of this study is to gain insight into the local absorbed energy of an impact by the skull using the finite element method.

II. METHODS

CT-scans of each subject are obtained before and after the impact experiment with a 512x512 scanning matrix, slice thickness of 1 mm, slice increment of 0.5 mm and pixel size of 0.449 mm (using a Siemens SOMATOM Sensation-64 CT scanner).The high quality CT-scans are segmented in Mimics^{TM} (Materialise) to create a mask of the skull. A 3D object is calculated from the mask and exported to 3-Matic^{TM} (Materialise), where the mean thickness of the impact site is measured. To calculate the local bone density, Hounsfield Units of each subject are callibrated based on the CT-scan of the European Spine Phantom with known bone mineral densities.

In a second step the 3D object calculated in Mimics^{TM} is exported to ANSA (BETA CAE Systems), this software environment creates a tetrahedral mesh that conforms with the quality criteria of Abaqus (SIMULIA). In Abaqus, an explicit dynamic method is used to develop a simplified model of the experiments, consisting of a rigid impactor with a geometry identical to the one used in the experiments [9] and a subject-specific skull. For the skull, an isotropic linear material model is used with a Young's modulus of E = 15 GPa, a poisson's ratio of $\nu = 0.21$ and a density of $\rho = 1800$ kg/m^3. As boundary conditions, the skull base is fixed in three translational directions. The impactor has 1 degree of freedom (DOF) and the displacement of the impactor is identical to the measured deformation of the skull.

A sensitivity analysis is performed on one subject-specific skull. Five meshes with density ranging from 50,000 to 1,400,000 elements are constructed. A static simulation of the impact is performed in Abaqus.

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III. INITIAL FINDINGS

The sensitivity analysis showed a convergence of the results for a mesh density of 550,000 elements, looking at the Von Mises stress at the location of impact and the normal contact force.

The experimentally measured total absorbed energy at the impact site amounts to 21.11 J. When the internal energy of the finite element model (FEM) reaches the experimentally measured absorbed energy, the maximum principal strain at impact site is 0.69% (fig. 1) and the maximum principal stress is 105 MPa. Both values are in the range of bone failure criteria and predict fracture at the impact site. The locations of failure strains and fractures on the skull, identified by physicians after examination of the impact experiments, show a good correspondence; both displayed at the sphenoid and zygomatic bone.

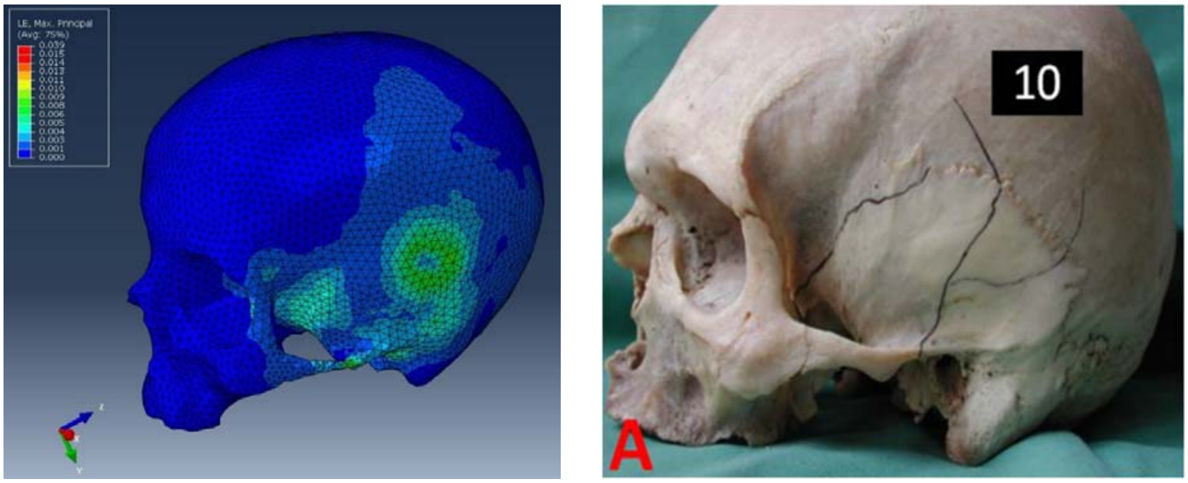

Fig. 1. Comparison between the results of the FEM and the corresponding experiment. The FEM shows a Maximum Principal Strain > 0.4% at the site of impact, the lateral side of the skull and on the sphenoid and zygomatic bone. The skull shows a corresponding fracture pattern on the lateral side, sphenoid and zygomatic bone.

IV. DISCUSSION

This subject-specific finite head model is a useful tool to investigate the influence of the subject-specific geometry of the skull, with emphasis on the thickness and curvature of the skull at lateral side. Results of the FE head model confirm the dependence of the absorbed energy on local geometrical features. Future work will include the development of multiple subject-specific FE models of the experimental set-up in Abaqus in order to investigate the influence of the local geometrical characteristics on the energy criterion. Experimental results will be compared to the outcome of the FE head model of the subject, ultimately leading to a fracture criterion based on strain energy density.

V. REFERENCES

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