Analysing the Validity of a Skull Fracture Energy Criterion through Subject-specific Finite Element Modelling of Skull Impacts

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I. INTRODUCTION

Each year approximately 26 000 people are killed in road accidents in the European Union, 1.3 million are injured [1]. Head injuries are a common cause of mortality and disabilities among vulnerable road users [2]. The treatment and rehabilitation of patients with head injuries is often long and difficult, causing high socio-economic costs. These observations stimulate the need for research to determine the cause of injuries and to develop improved protective headgear.

Though numerous studies have investigated the mechanics and characteristics of skull fracture resulting from blunt head impacts [3], a criterion for skull fracture occurrence is still under discussion. [4] proposed that the strain energy absorbed by the skull could be a good predictor for skull fractures. Multiple authors have attempted to validate such an energy criterion using finite element head models and experiments. However, current generic finite element models are unable to accurately visualise bone fracture initiation and propagation, which complicates the investigation of skull fracture. This study aims to investigate the energy criterion using subject-specific head models, focusing on the inter-subjective geometrical and bone material differences.

Our research group previously investigated the existence of an energy failure criterion with a double pendulum set-up in a series of intact PMHS heads [5-6]. For the experimental conditions of this study, skulls fail at a level of 7-18 J for frontal impacts and 3-23 J for temporal impacts [5]. This study aims to critically investigate the energy criterion using 18 subject-specific head models (three frontal, five occipital and ten temporo-parietal) corresponding to the aforementioned experiment, focusing on the inter-subjective geometrical and bone material differences.

II. METHODS

High quality CT-scans (512x512 scanning matrix, slice thickness =1mm, slice increment =0.5mm, pixel size =0.449mm) were obtained using a Siemens SOMATOM Sensation-64 CT scanner. These scans were acquired before and after the impact experiments performed in [5], in order to evaluate pre-existing fractures and resulting fractures from the impacts. Each CT scan was imported in Mimics^{TM} (Materialise) and the skull was segmented manually, after which a 3D geometry was calculated and exported to 3-Matic^{TM} (Materialise). There, an initial mesh was calculated which was then further improved in ANSA^{TM} (BETA CAE Systems). The mesh consists of one million quadratic tetrahedral elements, a number resulting from a convergence study.

For each skull model two different materials were implemented: a homogeneous isotropic linear material and a subject specific isotropic material based on Hounsfield units. The homogeneous model uses a Young's modulus of $E = 8$ GPa, a Poisson's ratio of $\nu = 0.22$ and a density chosen such that the mass corresponds to the physical head. The subject-specific material is based on the relationship between Hounsfield units and Young's modulus as described by [7]. These values show good similarity to the material properties found in the head model of [8]. Similar to the method described by [9], the scalp is located on the impactor instead of the skull, where the average thickness of the impact region is used as the scalp thickness. Impact speed and location are established as documented in the experimental data. The experimental degrees of freedom of impactor and skull are respected as well as the mass of the impactor.

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III. INITIAL FINDINGS

The peak forces, skull strains and absorbed strain energy up to the point of fracture initiation (including the energy in the scalp layer) of each impact are calculated. The peak forces for frontal and occipital, associated with skull fracture, show reasonable accuracy (26% and 28% difference between modelled and experimental values, respectively). The frontal total strain energies range from 7.7 to 13.0 J, 5.0 to 20.7 J for the occipital area and 1.1 to 13.9 J for the temporal area. The correlation between the experimental and simulated values for both material models is however low (RMSE = 7.3 J, 7.8 J and 12.8 J for frontal, occipital and temporal respectively). Further investigations show that the results are highly sensitive to the geometry of the impact site and impactor orientation, especially in the occipital and temporal area.

Fig. 1. Comparison between the two material models, showing the simulated fracture lines imposed on a picture of the skull post-impact with the experimental fracture lines (dotted). The subject-specific material model is able to capture the fracture lines more accurately for all frontal impacts.

The fracture lines corresponding to the elements exceeding the bone tensile strength were also simulated. The subject-specific material parameters allowed for more accurate localisation of these fracture lines compared to the homogeneous material (Fig. 1).

IV. DISCUSSION

The correlation between the experimental and simulated absorbed strain energy is generally low, especially in the temporal and occipital area. This can be due to the geometrical sensitivity due to the lower smoothness and higher inter-subject variability for these areas compared to the frontal area. Small changes in the impactor positioning can result in large changes in the resulting peak force and strain energy. These findings were exposed to the high geometrical fidelity of our meshes and challenge the use of an energy fracture criterion for subject specific fracture investigations, as generic head models are unable to accurately take into account the geometrical differences between subjects.

The subject-specific material model and fine mesh enable the mapping of fracture lines with an, to the authors' knowledge, unprecedented accuracy. The influence of the local bone properties significantly determines the initiation and propagation of the skull fracture and is not captured when using homogeneous material parameters. Further experimental calibration of the curve used for conversion from Hounsfield units to skull bone material parameters is required to obtain more accurate results.

V. REFERENCES

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