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INFLUENCE OF BRAIN ANISOTROPY ON PREDICTION OF TRAUMATIC INJURIES

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INTRODUCTION

Traumatic Brain Injury (TBI) results from a sudden and violent impact to the head, in which an external force produces damage to the brain and disrupts its normal function. Injury symptoms can include physical, cognitive and behavioral aspects, with effects that range from partial recovery to permanent disability or death.
Finite element (FE) head models are often used as tools to analyze TBIs and measures based on mechanical parameters, such as tissue principal strains or invariants of the strain tensor, are used as metric to predict the risk of injury.
However, while in vitro researches [1] show that the vulnerability to TBI is due to both viscoelastic properties and highly organized structure in white matter tracts, current FE models incorporate only isotropic homogenous features into injury analysis and do not consider the strain in the specific fiber direction. This approach may not be adequate to completely understand and capture the mechanism of axonal impairment.
In the current work, an attempt to enhance the injury prediction of FE head models is realized: the 3D spatial varying anisotropy of the brain is integrated into the constitutive framework [2] and the kinematics of concussive impacts is applied first to a FE model with isotropic properties and then to the same model considering anisotropic properties. A comparison between the principal and axonal strains of the two models is operated. The aim of the work is to investigate the influence of anisotropy on the mechanics of the head.

METHOD

In this study, KTH FE head model [3] is used and extended with the purpose to account for the anisotropy of the brain. Specifically, brain matter is considered as a hyper-viscoelastic fiber-reinforced anisotropic material, characterized by the following strain energy potential [4]:

$$\begin{aligned} W &= \frac{G}{2}(\tilde{I}_1 - 3) + K(\frac{J^2-1}{4} - \frac{1}{2}ln(J)) + \frac{k_1}{2k_2}(e^{k_2\langle\tilde{E_\alpha}\rangle^2} - 1) \\ \tilde{E_\alpha} &= k(\tilde{I_1} - 3) + (1-3k)(\tilde{I_{4\alpha}} - 1) \qquad \tilde{I_{4\alpha}} = \tilde{\mathbf{C}} : \mathbf{n_{0\alpha}} \otimes \mathbf{n_{0\alpha}} \end{aligned} \tag{1}$$

where G is the shear modulus, K defines the bulk modulus and k_1, k_2 and k are parameters related to the fiber contribution to the material.

Figure 1: Axial cross-section of the redefined brain at Zpos of -3.3mm in the FE model geometry. Redefinition is based on FA.

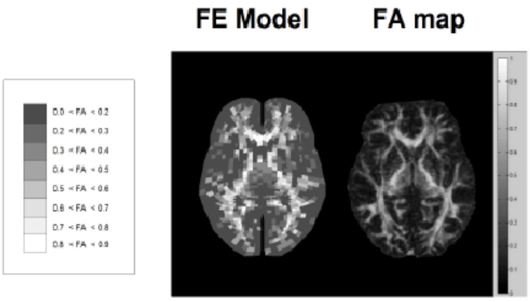

Table 1: Correlation between fractional anistropy (FA) and mechanical anisotropy (k) for FE simulations. Taken from Giordano and Kleiven, 2013.

FA range	k value
0.0 - 0.2	0.3333
0.2 - 0.3	0.2732
0.3 - 0.4	0.2500
0.4 - 0.5	0.2273
0.5 - 0.6	0.2000
0.6 - 0.7	0.1667
0.7 - 0.8	0.1282
0.8 - 0.9	0.0769
0.9 - 1.0	0.0000

A direct relationship between the fiber dispersion parameter (k) and fractional anisotropy (FA) from diffusion tensor images (DTI) is utilized (Table 1), which allows to incorporate a 3D spatially varying anisotropy in the brain material model [2]. In addition, the main diffusion direction from DTI is assumed to correspond to the axonal fiber orientation and used to calculate axonal strains. To map the diffusion information within the FE model, the brain mesh is voxelized and successively registered to the DTI brain: twelve parameters defining a spatial transformation which aligns the DTI scale to FE geometry are detected and diffusion information is resampled at FE resolution (Figure 1).
The FE head model is imposed the kinematics based on reconstructions of sport accidents that took place in the American National Football League (NFL) [5]. The cases are selected due to the high rotational accelerations, which are often related to traumatic brain injuries.

RESULTS

To study the influence of the anisotropy on the mechanical head response, principal strains and axonal strains are investigated for the isotropic and the anisotropic model for several concussive cases. To a large extent, a stiffer behavior of the brain in the principal direction of strain is found for isotropic features while considering the actual fiber local orientations and their heterogeneities leads to a general more extended deformation with white matter particularly involved into the process. The anisotropy of the brain affects also the orientation of the principal strains predicted by the FE model [2][6].
For the anisotropic areas of the brain, the FE prediction of maximum axonal strains is significantly lower than maximum principal strains in both models. It is therefore concluded that the principal strain is an over-prediction for the axonal strain in brain tissue. Observing the data from simulations, the amount of over-prediction seems to depend on the loading direction with respect to the principal orientation.

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