Development and Validation of a Detailed Finite Element Model of Human Eye for Predicting Ocular Trauma

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INTRODUCTION

Approximately 2.5 million traumatic eye injuries occur each year in the United States. Eye injuries can be caused by blunt, penetrating and blast trauma to the eyeball, orbit or through the face. Eye trauma in sports is most frequently resulted from ball sport and contact sport. In car crashes, there were increased incident of eye injuries sustained by occupant due to an airbag deployment. The most ocular injuries sustained by causalities in the recent combat were related to explosive blast. Eye injuries often involve orbital, facial bone fracture and brain damage. Finite element (FE) models of eye were developed to study biomechanical response of the traumatic globe rupture and orbital fracture [1,2]. None of the published models incorporate eye within the orbit of an anatomically accurate head model.

The current communication reports the development and validation of a detailed FE eye model integrated with an anatomically inspired human head model that can be used to improve our understanding of the mechanism of ocular, orbital, maxillo-facial injuries in blunt trauma.

METHODS

FE Human Eye Model

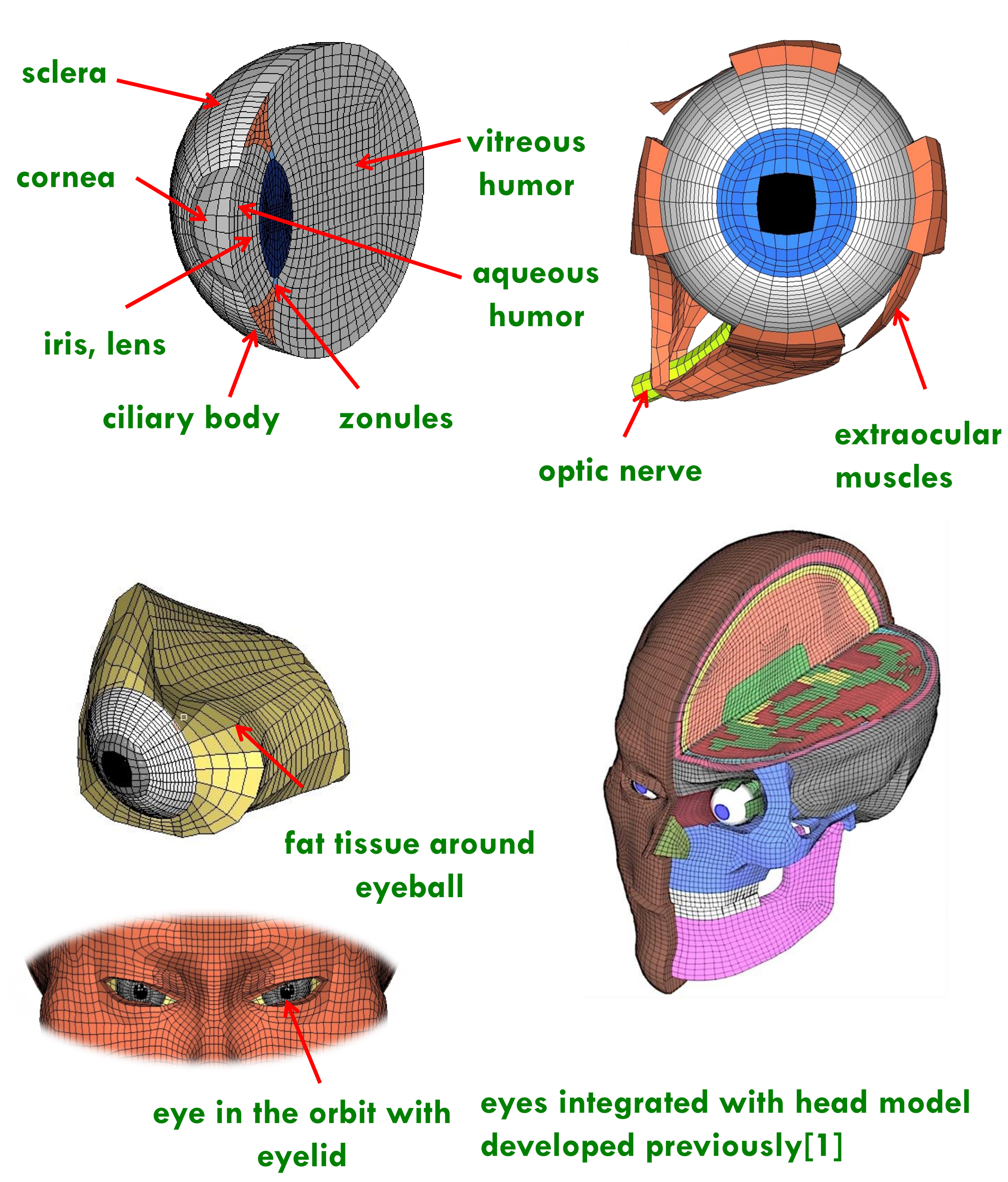
The geometry of the FE human eye was developed using literature data [3].

Mesh of anatomical structures included:

- Eyeball: Intraocular components (see Figure)
- Six extraocular muscles
- Optic nerve
- Fat tissue

Over 28,000 elements, 95% hexahedral
Average element resolution: 0.6 mm

Material properties:
Five different material models to simulate mechanical behaviors of the intraocular structures, muscles, optic nerve and fat tissue with their material properties based on the literature.



Mesh tools:

Hypermesh by Altair (Troy, MI), ANSA by BETA (Greece), Meshwork by DEP (Troy, MI)

FE solver:

LS-DYNA 971 (LSTC, CA)

Integration of Eye with Head Model

- Wayne State University Head Model [4,5]: 350,000 elements at ~2 mm resolution, validated against existing cadaveric impact and blast tests
- Refined bone thickness and shape of the orbital cavity: ethmoid, lacrimal, maxillary, zygomatic, and sphenoid bones
- Improved mesh at the orbital roof, wall and floor in order to accurately represent the geometry and anatomy of the orbit
- The ocular fat and orbit were merged via the common nodes to avoid the use of a contact interface

Model Validation

Mechanical responses predicted by the model were validated against experimental measurements from cadaveric eye impact tests from different projectile types and impact velocities [2].

Projectile	BB pellets		Baseball		Foam			
Diameter (mm)	4.50		76.10		6.35			
Mass (g)	0.375		146.5		0.077			
Velocity (m/s)	55.8	91.7	34.4	41.2	10.6	14.3	28.6	31
Globe rupture	No	Yes	Yes	Yes	No	No	No	No

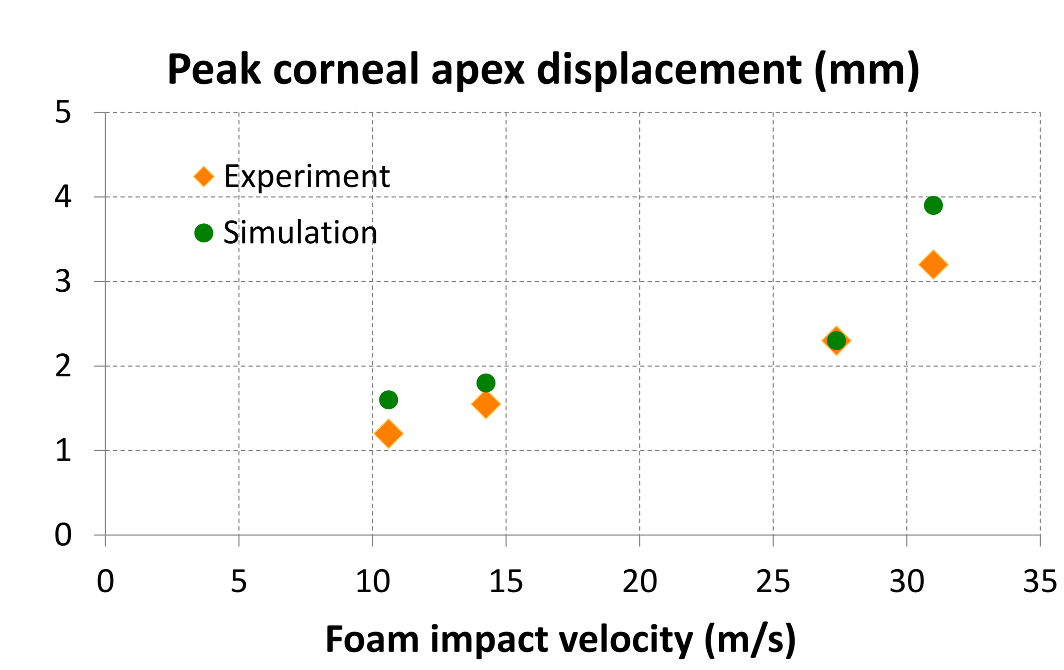
Tissue Level Responses

Various biomechanical response parameters in the eye were analyzed: Ocular pressure, localized stress and strain for cases with and without globe rupture

RESULTS

Corneal Displacement Validation

- Corneal displacement of the frontal aspect of the eye was compared with experimental data (Figure)
- Good correlation with difference <15%



Intraocular Pressure Responses

- BB impact: the high pressure localized at the impact site affecting the aqueous humor, lens and anterior portion of the vitreous
- Foam impact: the high pressure affected the aqueous humor but not the lens
- Baseball impact: the intraocular pressure affected the eye globally

Ocular Maximum Principal Strain Responses

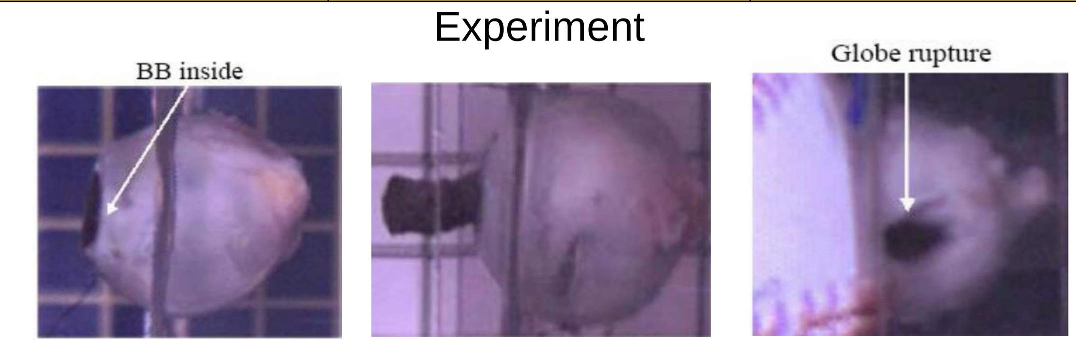
- Strain of 0.46-0.68 from BB impact, 0.3-0.38 from baseball impact, and < 0.11 from foam impact
- The maximum strain was found in the apex of cornea for BB impact, near the limbus for foam impact, and on the equator for baseball impact.

Deformation Pattern Comparison

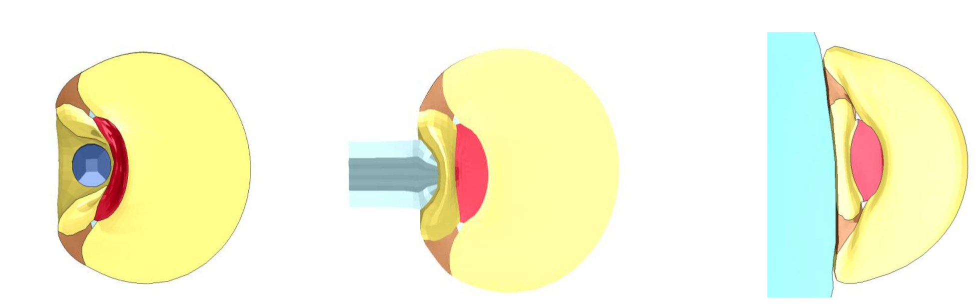
- Images below compares the deformation patterns simulated by the model to the experimentally observed deformation on eye specimens
- The model predictions matched quite well to experimental results for all three projectiles

Maximum globe deformation from various projectiles		
BB impact 91.7 m/s	Foam impact 30 m/s	Baseball 41.2 m/s

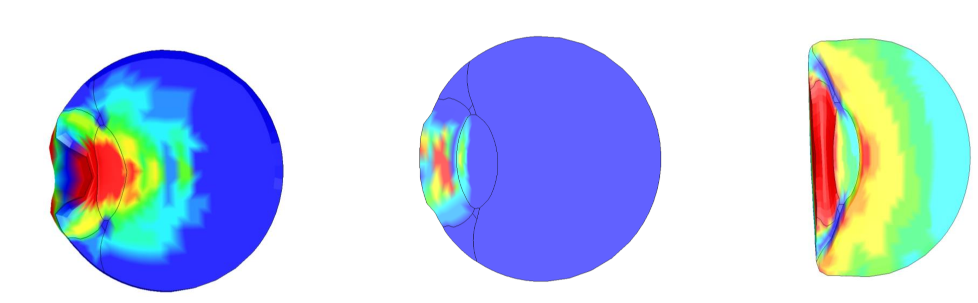
Experiment



Model Prediction



Model Prediction: Intraocular Pressure



DISCUSSION / CONCLUSIONS

- An anatomically detailed FE eye model with essential extraocular tissues was developed and validated against corneal displacement in eye impact tests with globe rupture.
- The model has been integrated with a human head model, making it the first sophisticated human head model with detailed eye, face, brain and skull anatomy.
- FE model simulation can provide ocular pressure, stress and strain information which are relevant mechanical measures for tissue level injury.
- Simulations revealed that the pressure in the aqueous humor and lens were constantly higher in the case with globe rupture than that without globe rupture.
- The model results suggested that the localized ocular pressure might be a relevant injury predictor for ocular trauma induced globe rupture.
- The estimated globe rupture pressure in the anterior aspect of the eyeball was 2.5 MPa which was insistent with the 0.4-1.5 MPa reported [6].
- More cases will be simulated to establish the injury predictor and threshold for ocular trauma.

Acknowledgement

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