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Traumatic eye injuries as a result of blunt impact: computational issues

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Abstract. The detachment or tearing of the retina in the human eye as a result of a collision is a phenomenon that occurs very often. Reliable numerical simulations of eye impact can be very useful tools to understand the physical mechanisms responsible for traumatic eye injuries accompanying blunt impact. The complexity and variability of the physical and mechanical properties of the biological materials, the lack of agreement on their related experimental data as well as the unsuitability of specific numerical codes and models are only some of the difficulties when dealing with this matter. All these challenging issues must be solved to obtain accurate numerical analyses involving dynamic behavior of biological soft tissues. To this purpose, a numerical and experimental investigation of the dynamic response of the eye during an impact event was performed. Numerical simulations were performed with IMPETUS-AFEA, a new general non-linear finite element (FE) software which offers non uniform rational B-splines (NURBS) FE technology for the simulation of large deformation and fracture in materials. IMPETUS code was selected in order to solve hourglass and locking problems typical of nearly incompressible materials like eye tissues. Computational results were compared with the experimental results on fresh enucleated porcine eyes impacted with airsoft pellets.

1. Introduction

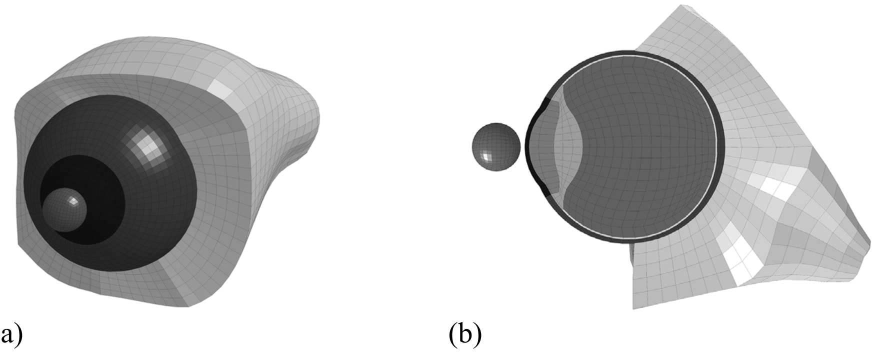
Ocular traumas are the second leading cause of visual impairment in the United States. Approximately 2.5 million new eye injuries occur in the United States each year. Blunt objects account for the largest percentage of eye injuries (30%), followed by sharp objects (18%), vehicle crashes (9%), gunshots, nails, BB guns (6% each) and fireworks and falls (4% each) [1]. Sports injuries account for about 100000 eye injuries per year and approximately 10% to 40% of all eye injuries. Many sports and occupational injuries could be prevented if appropriate, properly fitted, task-specific eye protection were worn [2].

The severity and type of injury depends on the size, speed and hardness of the object hitting the eye. High speed projectiles, such as airsoft pellets, may cause severe eye injuries [3]. Retinal detachments and globe ruptures are typical results of high speed blunt trauma. In the case of larger impacting objects the fracture of the bony orbit (commonly referred to as orbital blow-out fracture) is more frequent than the globe perforation. Understanding the mechanism of traumatic retinal detachment is helpful for ophthalmologists to make a more accurate diagnosis before the symptoms develop. Recently some clinical cases of retinal damage following blunt impact with a BB pellet or blast exposure were found at the Ophthalmic Hospital of Rome. In previous works a computational model and an alternative explanation of these injuries was proposed [4-6]. Numerically it was demonstrated that the shockwave-generated pressure could play a role in the ocular damage. In this work experimental impact tests on enucleated porcine eyes were performed and used to validate the computational eye model proposed by the authors. Pressure measurements acquired during impacts using an in situ pressure sensor, compared with the calculated time resolved pressure, provided insight on this matter.

2. Materials and methods

The injury potential of an air soft gun (ASG) bullet impact was selected as the subject matter of the research. For this purpose, a finite element model (FEM) of the eye with simple constitutive models was developed [4-6]. Esposito *et al.* [6] identified the model parameters by reverse engineering on available experimental data, using the multi-objective optimization software modeFRONTIER v4.3. Numerical simulations were performed with the FE code MSC/Dytran 2012 varying the material constants until the error between the calculated response and available experimental measures was minimized. A reduced integration scheme (i.e., one Gauss point per element) was used to prevent locking phenomena (occurring when dealing with nearly incompressible materials such as for the cornea, sclera, and retina), as well as to achieve a low computational cost. A single integration point at the center of the element makes the program very efficient since each element requires relatively little processing, but it also introduces the problem of hourglassing. With a single integration point, some deformation modes have no stiffness associated with them and are called the zero energy or hourglass modes [7]. In order to control these modes and improve the accuracy of the analysis, a stiffness form of hourglass control with a reduced control parameter was used. However it can cause overly stiff response (specially with soft materials) so it could invalidate the reliability of material models parameters. In order to overcome these problems, in the present paper, a new optimization procedure was run using IMPETUS-AFEA, a new software package for non-linear computational mechanics, primarily developed to predict large deformations of structures and components exposed to extreme loading conditions. It uses high order fully integrated isogeometric elements, which are free of hourglass and so they don't have any artificial stiffness.

In this computational study the eye was struck at the corneal apex with a 6 mm 0.2 g ASG bullet. In order to take into account the constraint effects of the eye containment the real condition of the eye inside the orbital cavity (figure 1) was considered.



(a) (b)

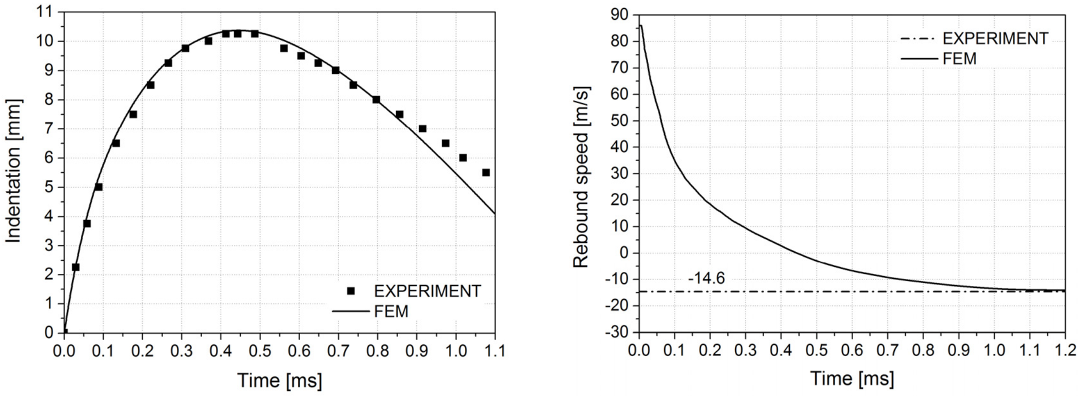
Figure 1. The computational model of the blunt eye impact in the investigated configuration: eye inside the orbital cavity. The FE mesh is shown in 3D view (a) and transverse section (b).

The orbit model was developed from computerized tomography (CT) scan data and its volume was assumed filled by fat tissue only. As demonstrated by Kennedy *et al.* [8], the six extraocular muscles do not significantly contribute to the mechanical response of the eye during an impact event, allowing a uniform medium to be used to simulate the orbital content. The fatty tissue surrounding the eye was modelled using a simple linear elastic model with Young's modulus value taken from literature [9], whereas the orbital bone was simulated as a rigid surface. The softair bullet was also modeled as a rigid sphere.

The fidelity and reliability of the computational model was obtained by tuning its parameters on experimental blunt impacts performed on fresh enucleated porcine eyes. The test setup consisted of a softair gun, a high-speed camera, and a circuit for the triggering of the camera. A miniature pressure transducer (Precision Measurement Company, Model 060, Ann Arbor, MI) was inserted into the eye bulb near the optic nerve in order to measure the pressure of the eye during impacts. Eyes were mounted in 10% ballistic gel which had the double function to simulate the fatty tissue surrounding the eye and to hold the eye in place during the tests. Wilgeroth *et al.* [10] found small differences in the dynamic response of the adipose material and 20 wt % ballistic gelatin at lower particle velocities. Although ballistic gelatin cannot be fully representative of fatty tissues, or the varying types of smooth muscle which make up the hollow organs [10], it is the best and most commonly employed tissue simulant material. The eye was placed in a dummy orbit to reproduce the eye orbit configuration. The dummy orbit was reconstructed by rapid prototyping using human eye orbit dimensions and geometry. Displacements of the eye and projectile speed were recorded using high speed video. A Phantom v7.3 camera (Vision Research, Wayne, NJ) captured video at 67796 frames per second with a resolution of 224 x 128. The velocity was measured from the high speed video taking as reference length the known bullet diameter. The softair gun launched the bullet at an average speed of 86 m/s. The displacement of the corneal apex as a function of time and the maximum projectile rebound velocity were taken as target functions for the optimization process. A series of 10 impact experiments where there was little variation was performed. The indentation and rebound velocity used in the model parameter calibration are representative of the average macroscopic observed behavior. Not all the tests allowed the measure of the bullet rebound speed due to oblique rebound. The maximum rebound speed was measured from the videos of two experimental tests. The speed measure was repeated 5 times for each video obtaining respectively the average values of 15.6 ± 0.33 m/s and 13.5 ± 0.02 m/s. The mean of these speed values was 14.6 m/s. The input variables were the Young modulus of the cornea and sclera and the fluid model parameters for the vitreous and lens (bulk modulus, viscosity and artificial shear modulus). Table 1 summarizes all the constitutive models and associated parameter values used in the FEM. The comparison of the indentation given by the optimized simulation with the experimental data is shown in Figure 2(a). Although the numerical simulation predicts slightly higher indentation velocity in the rebound phase, the overall comparison is in a very good agreement. With the same parameters set, the numerical simulation returned a calculated bullet rebound velocity of -14.1 m/s against an average experimental value of -14.6 m/s (Figure 2(b)).

Table 1. Constitutive models and mechanical properties of the materials represented in the FEM. The values given by modeFRONTIER for the input variables are highlighted in bold.

Material	Constitutive model	Young's modulus E [MPa]	Poisson's ratio ν	Bulk modulus K [MPa]	Viscosity μ [MPa·s]	Artificial shear modulus G [MPa]
Cornea	Linear elastic	**6.1**	0.494	-	-	-
Sclera	Linear elastic	**48.0**	0.454	-	-	-
Retina	Linear elastic	0.105	0.499	-	-	-
Orbital fat	Linear elastic	1.0	0.499	-	-	-
Aqueous	Fluid	-	-	2200	1.0e-9	-
Vitreous	Fluid	-	-	**2115**	**1.815e-6**	**4.0006e-3**
Lens	Fluid	-	-	**2360**	**5.545e-5**	**2.0008e-3**

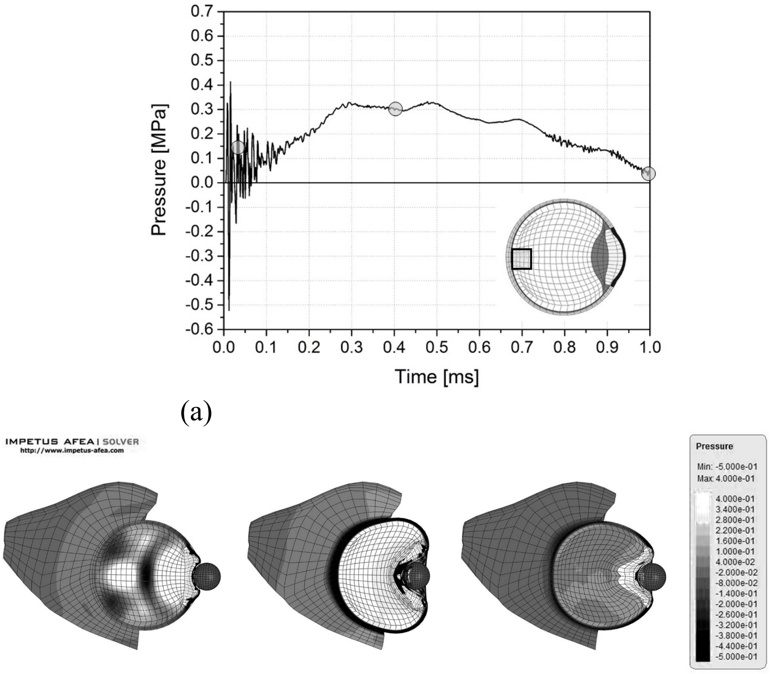


(a) (b)

Figure 2. Comparison of experimental corneal apex indentation (a) and softair bullet rebound speed (b) with the numerical results obtained from the optimized impact simulation.

3. Results and discussion

The results of the numerical simulations show that a wave train is generated by the impact with the bullet. The pressure waves propagate within the eye bulb and traction waves can reach the macular area. Maximum traction at macular area is reached immediately after impact, when the deformation of the ocular globe is still limited. The pressure evolution during impact on the vitreous in front of the macula, obtained from the simulations performed using IMPETUS-AFEA, is reported in figure 3. Snapshots of FE simulation taken at the time corresponding to the dots on the graph are also shown.



(a)

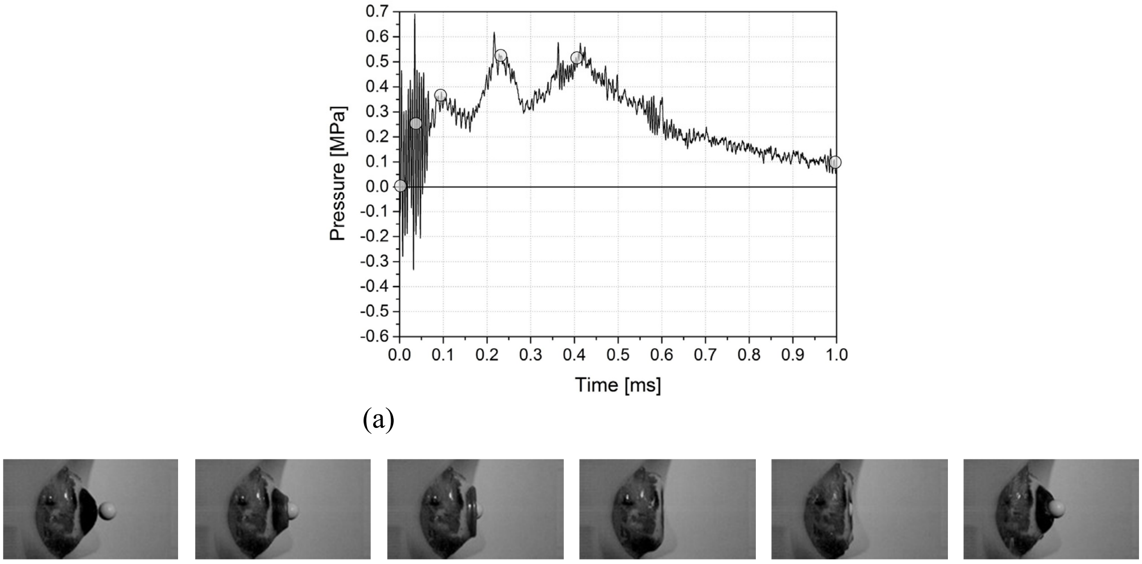
(b) (c) (d)

Figure 3. Pressure evolution during impact (a) calculated in the numerical optimized simulation on the vitreous in front of the macula (the square on the eye section highlights the area of interest). FE analysis snapshots showing pressure wave propagation in the sagittal section of the eye and orbit are taken at the time: (b) 0.036 ms after impact, (c) 0.4056 ms after impact, (d) 0.9948 ms after impact.

The overall trend gives evidence of the presence of two phenomena: initial high frequency wave propagation and a lower frequency increase in intraocular pressure. High negative peak pressures (traction) are present in the first phase.

Based on a previous numerical analysis of blast loading on the eye, the dynamic effect of pressure propagation phenomenon is the prevalent one in this case and it is amplified by the orbital geometry. This peculiar geometry (similar to a frustum cone) can induce a resonance cavity effect and generate a pressure standing wave particularly hazardous for eye tissues [6].

In order to verify the real existence of the numerically identified phenomena, blunt impacts to fresh enucleated pig eyes were performed. The experimental pressure measurement along with the corresponding frames taken from the video recorded during the impact is shown in figure 4.



(a)

(b) (c) (d) (e) (f) (g)

Figure 4. Pressure signal acquired during impact test (a) and a series of 6 frames taken from the video at the time corresponding to the dots on the graph: (b) 0 ms (impact time), (c) 0.036 ms after impact, (d) 0.095 ms after impact, (e) 0.228 ms after impact, (f) 0.405 ms after impact, (g) 0.995 ms after impact.

The signal was acquired in wide-band operation (125 kHz, -3 dB) and it consequently highlights the initial dynamic pressure oscillations.

Although there are some differences mainly due to the simplifications made in the numerical models, the comparison between experiment and simulation shows a good agreement on the presence of initial pressure wave propagation and reflection, consequently suggesting a possible role of this phenomenon in the retinal damage associated with blunt impact.

4. Conclusions

The experimental pressure-time histories show a very interesting trend with the presence of positive and negative peaks within the first 0.15 ms from the impact, indicating the occurrence of compression and traction waves generated by the impact. The comparison between the pressure evolution inside the eye calculated from the numerical simulations and the pressure measured during the experimental tests shows a good agreement supporting our theory which ascribes to shockwave dynamics a crucial role in the retinal damage associated with a blunt trauma. Therefore, the numerical and experimental results give evidence of the presence of two phenomena during impact: initial high frequency wave propagation followed by a lower frequency increase in intraocular pressure.

The deformation of the eye is constrained by the orbital cavity geometry preventing an excessive equatorial deformation of the globe.

In conclusion, the preliminary results seem to indicate that shockwave propagation and negative pressures generated immediately following the impact could lead to retinal break and consequently pull the retina away from the supporting tissue. The plans for the future involve understanding and minimizing the still present differences between numerical and experimental results. In order to distinguish the two identified phenomena an experimental investigation of primary blast injury is also ongoing.

References

[1] May D R, Kuhn F P and Morris R E 2000 The epidemiology of serious eye injuries from the United States Injury Registry *Graefes Arch. Clin. Exp. Ophthalmol.* **238** 153-7

[2] Rodriguez J O, Lavina A M and Agarwal A 2003 Prevention and treatment of common eye injuries in sports *Am. Fam. Physician* **67** 1481-8

[3] Fleischhauer J C, Goldblum D, Frueh B E and Koerner F 1999 Ocular injuries caused by airsoft guns *Arch. Ophthalmol.* **117** 1437-9

[4] Rossi T, Boccassini B, Esposito L, Iossa M, Ruggiero A, Tamburrelli C and Bonora N 2011 The pathogenesis of retinal damage in blunt eye trauma: finite element modelling *Invest. Ophthalmol. Vis. Sci.* **52** 3994-4002

[5] Esposito L, Rossi T, Bonora N and Clemente C 2012 The pathogenesis of retinal damage in human eye under impact and blast load *AIP Conf. Proc. Shock Compression of Condensed Matter 2011* Chicago **1426** 135-8

[6] Esposito L, Clemente C, Bonora N and Rossi T 2013 Modelling human eye under blast loading *Comput. Methods Biomech. Biomed. Engin.* 2013 Mar 22 *(Preprint)*

[7] MSC Software Corporation 2012 *MSC/DYTRAN User's Guides* (Santa Ana, CA)

[8] Kennedy E A and Duma S M 2008 The effects of the extraocular muscles on eye impact force-deflection and globe rupture response *J. Biomech.* **41** 3297-302

[9] Comley K and Fleck N 2012 The compressive response of porcine adipose tissue from low to high strain rate *Int. J. Impact Eng.* **46** 1-10

[10] Wilgeroth J M, Hazell P J and Appleby-Thomas G J 2010 The shock response of a rendered porcine fat *J. Appl. Phys.* **108** 093527