Analysis of orbital strain and stress caused by multidirectional forces generated during a ball impact

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Abstract. Head injuries, due to the presence of the brain and sense organs, especially of the sense of sight, constitute a very serious threat to the health, and sometimes even life. The main causes of these injuries are road traffic accidents, physical violence, as well as different sport activities.

The article presents a study on the effects of dynamic forces, acting on the bones of the skull around the eye socket, while hitted by a baseball, golf or tennis ball. In the research the variability in the force magnitude during the strike, as well as its various action pathways have been taken into account.

For determination of deformations and stresses arising in bone structures of the skull in the vicinity of the operations, the finite element method has been used. The effect of numerical simulations is an indication of the places with the highest fracture probability, as well as the moment of the highest stresses occurrence. The results obtained during the investigations can be useful for the development of the construction of the specialized skull protectors, dedicated for people participating in different sport activities.

1. Introduction

The face is the most vulnerable area of the body and is usually the least protected. Approximately 11-40% of all sports injuries involve the face. These injuries are most often due to direct hits with a ball or player-to-player contacts [8,12,14]. The most common types of sports-related facial trauma are the soft tissue injuries and the fractures of the "T-Zone" bones (the nose, the zygoma, and the mandible). At the beginning of the 20th century, René Le Fort mapped typical locations for facial fractures; these are now known as Le Fort I, II, and III fractures. Le Fort I fractures involve the maxilla, separating it from the palate. Le Fort II fractures cross the nasal bones and the orbital rim. Le Fort III fractures cross the front of the maxilla and involve the lacrimal bone, the lamina papyracea, and the orbital floor, and often involve the ethmoid bone. Although the orbital fractures represent a small proportion of sports-related facial injuries, they can be very hazardous to the health of athletes. Therefore, a thorough analysis of the mechanism of fracture formation, its causes and consequences is desired by surgeons, coaches and designers of face protective masks.

2. FEM model preparation

Understanding and correct assessment of the mechanism of the fracture formation in the upper part of the facial skeleton are possible only through a numerical analysis using the finite element method [1,2,9,13].

To increase efficiency and decrease time of calculations the area covering right orbit was separated from the entire facial skull. Additionally, the nasal bone and nasal septum have been omitted, and their presence was replaced with the appropriately selected boundary conditions.

A geometric model of the aforementioned orbit part was obtained on the base of skull CT (Computed Tomography) scans of a healthy 35-year-old man by converting DICOM files into a format *.sat* acceptable by ANSYS program. This model containing only the bone structures without soft tissue was analyzed in an environment of ANSYS Workbench platform named *Transient numerical*.

The properties of bone material was assumed basing on data taken from the specialist literature: Young's modulus of elasticity E = 15 MPa, Poisson's ratio $\nu = 0.21$ and density $\rho = 1.8$ kg/m^3 [7]. The defined above material parameters values were adopted as an average for the whole structure.

As a result of discretization carried out using spatial tetrahedron elements a model containing 771716 nodes and 845591 elements has been obtained. Tetrahedron shape of spatial elements was required for accurate reproduction of the real complex geometry of the investigated bone structure. Selected size of elements from 0.5 mm up to 0.7 mm ensured 99.7% compatibility with the requirements of the grid quality criterion (Fig. 1).

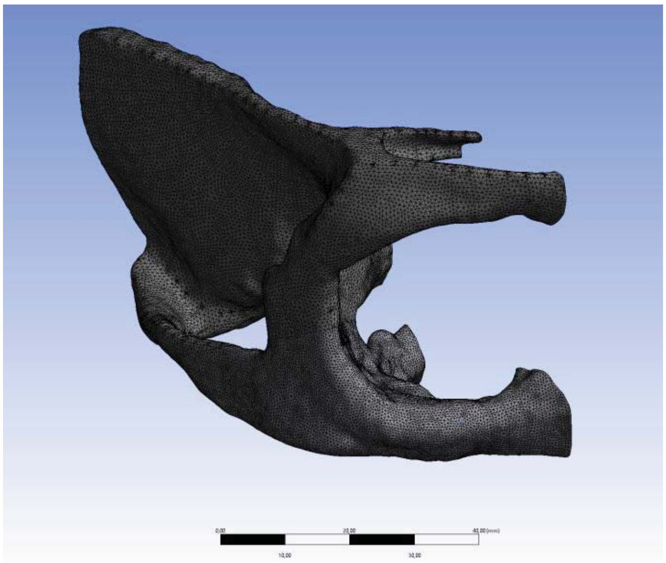

Figure 1. Mesh of orbital model

In the next stage of analysis the boundary conditions, that means the movability of the nodes in the area of connection between the considered model and adjacent facial bones (frontal, parietal, temporal and nasal bones as well as nasal septum) have been defined (Fig. 2).

a) **b)** **c)**

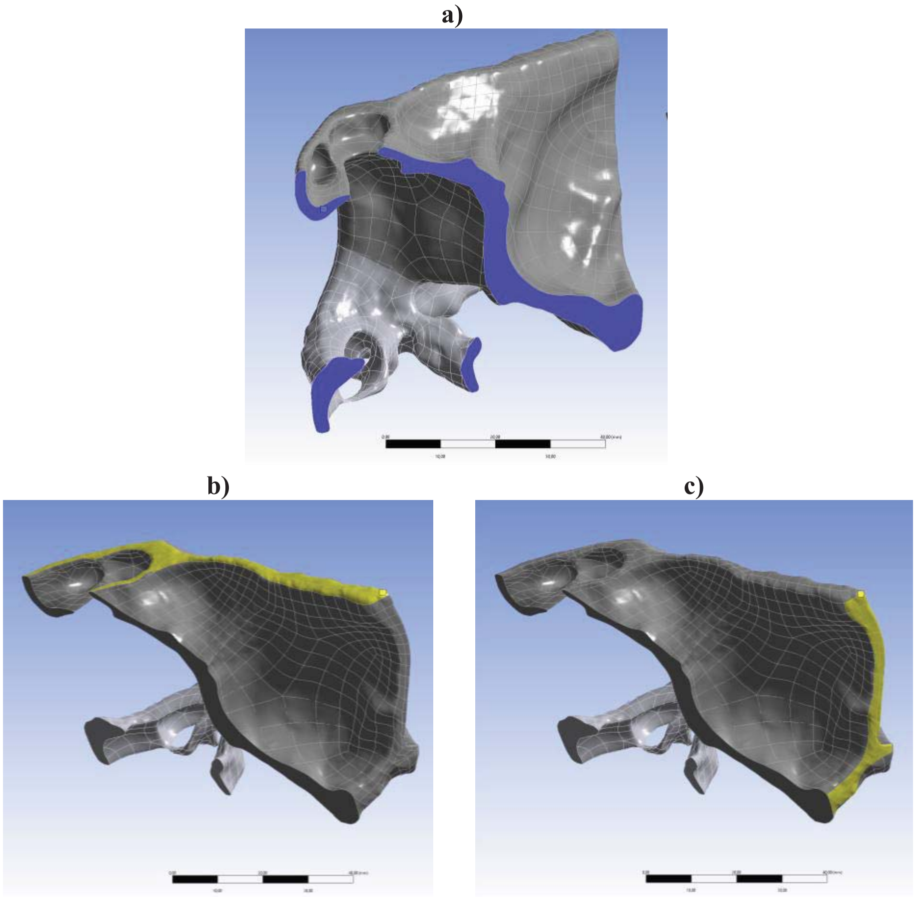

Figure 2. Areas of bone connection: a) *Fixed support*, b-c) *Displacement*

Two fixing models have been used. First, named *Fixed support*, delete six degrees of freedom at each node (in the nasal bone and in the nasal septum). Second, named *Displacement*, preclude all translational displacements at each node (delete the translational degrees of freedom directed along the axes x, y and z). This kind of fastening has been applied in junction of the model with frontal, parietal and temporal bones. The calculations taken into account geometrical non-linearity. Because the numerical simulations were of a qualitative nature, the influence of distribution of the soft tissues around the facial skeleton has been ignored. In order to determine the probable place of bone damage a bilinear material was introduced, what restricted the range of material curve to the elastic area.

In the first stage of calculations an assessment of the qualitative effects of impact in the front right part of the orbit has been carried out. Time-dependent force F of maximum value 275 N was applied for analysis (Fig. 3). Such a force can imitate a real golf or tennis ball blow, for example (Fig. 4).

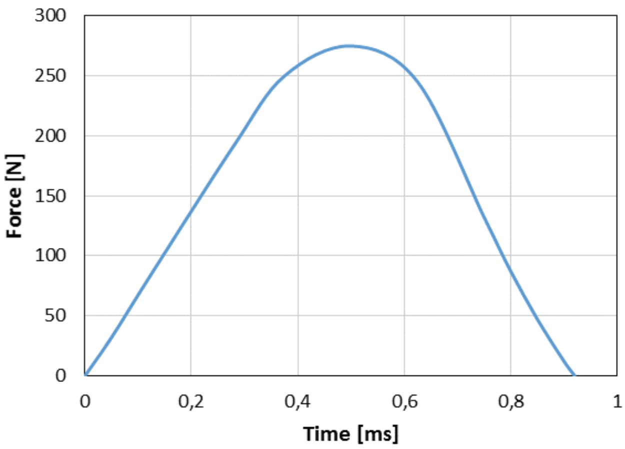

Figure 3. Variability of dynamic force during a ball impact (on the basis of [6])

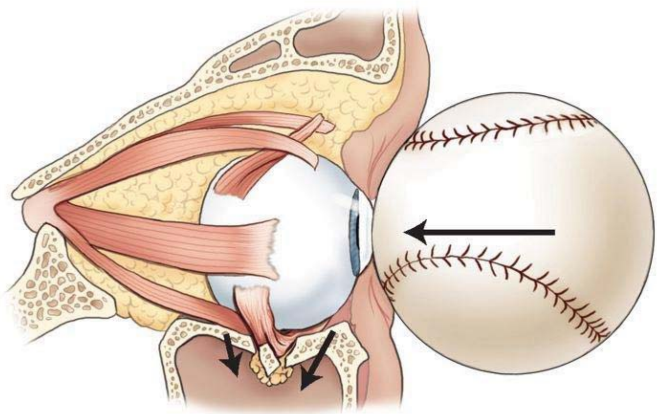

Figure 4. „Blowout“ fracture (from J. Stelmark Powerpoint presentation)

To better illustrate and evaluate the consequences of orbital injury the analysis has been performed for three different variants of force application. In the first case the force was applied to the relatively small area of the lower part of zygomatic bone (Fig. 5a), in the second one to the arch of the eyebrow (Fig. 5b), and in the third case the surface of force application covered both zygomatic bone and eyebrow arch (Fig. 5c).

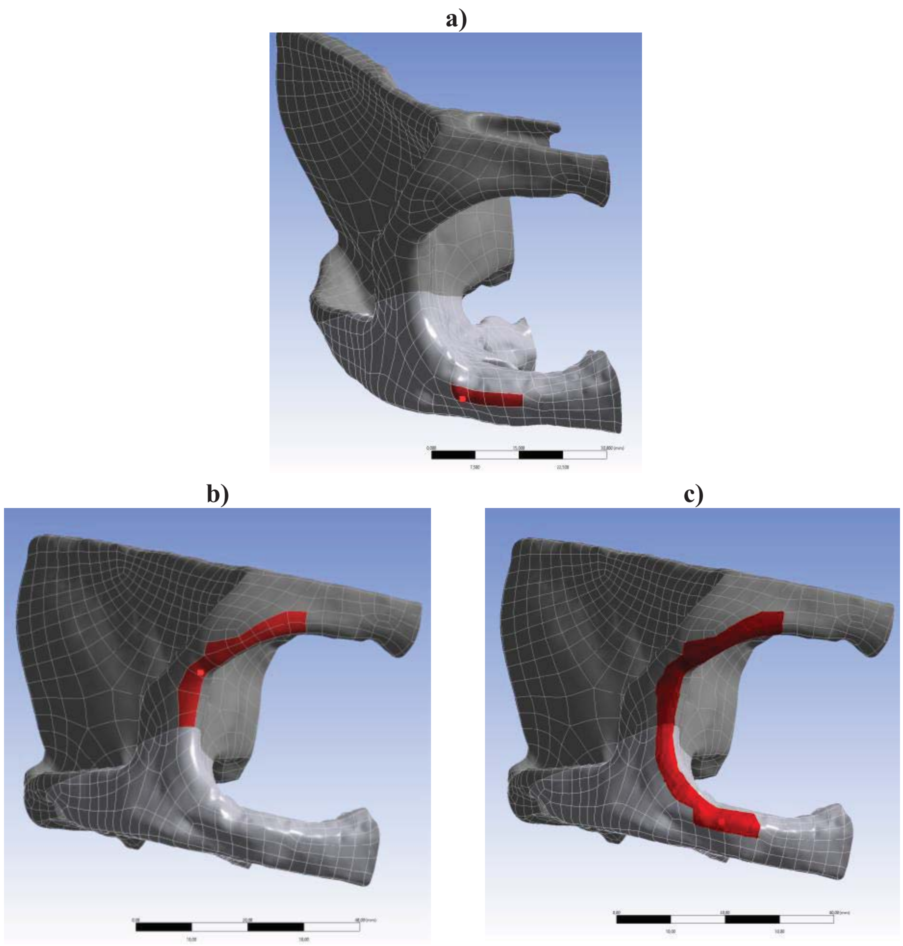

Figure 5. Three variants of force application

3. Numerical results

As a result of FEM analysis a series of reduced von Mises stress maps have been received. An example of such stress distribution is shown in Fig. 6.

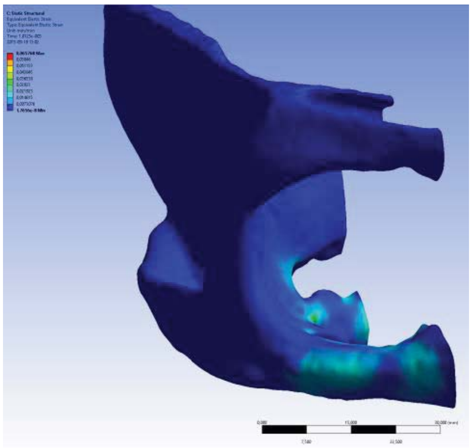

Figure 6. Map of reduced von Mises stress

According to the calculations the most unfavourable load is a force applied to the zygomatic bone. For this type of burden, the weakened area is the lower part of the zygomatic bone. In this case, the load is transferred from the front part of the eye socket on its rear part, which causes enlargement of damage threatened zone. Similar conclusions can be also reached by analyzing the displacement resulting from the same force application (Fig. 7).

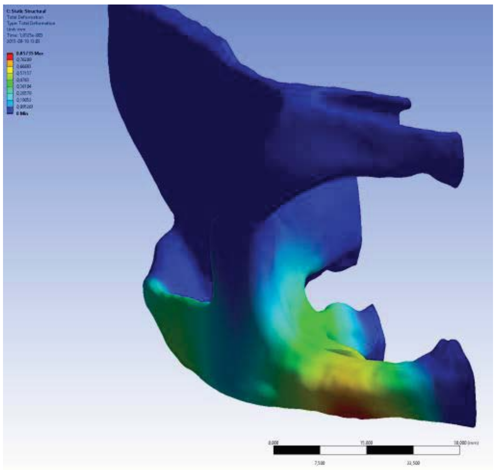

Figure 7. Map of displacements

In this case, the maximum displacement is concentrated in the lower part of the zygomatic bone and descends into the orbit and zygomatic arch, which acts as a specific bumper absorbing a significant part of impact energy.

In the framework of the research much attention was paid to the interpretation of the results concerning the analysis of the probable place of fracture. Assessment criterion was established on the basis of the maps of strain. It is known that yield deformation in the bone tissue do not occur. Therefore, this phenomenon was used to assess possible damage spots. In the analyzed case the place of potential bone damage is localized in the posterior part of the zygomatic bone (Fig. 8).

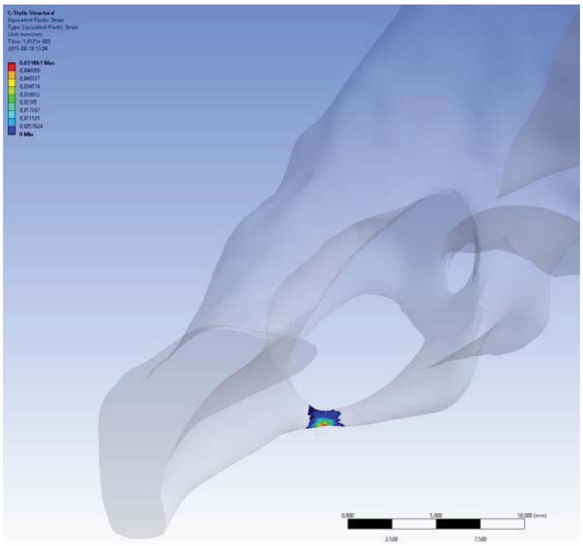

Figure 8. Region of yield stresses – probable place of fracture

Therefore, it is a possible point of bone fracture, which can result in the damage of the entire orbital cone. The consequence would be a displacement of the eyeball, manifesting in the difficulty in eye moving and diplopia.

In the next stage of calculation the loading in the form of a force applied to the bottom of the zygomatic bone, but distributed at different areas of its operation, was simulated. In this way, the real area of force application, changing over time as a result of elastic deformation of golf ball during the impact on a rigid obstacle (bone in the event), has been reflected (Fig. 9). The analysis shows that the most dangerous situation is the moment at which the force is concentrated on the smallest possible area (case 1). Breaking will get at 0.33 ms since the start of impact, that is, before reaching maximum force value. In the event, the value of yield strain (Epl) is the highest (Fig.10). Also the area covered by the operation of yield (destructive) strain is the largest. These observations indicate the risk of bone fracture in the back of the zygomatic bone what would change suddenly the bone cross section in this area (loss of support in this part of orbit). A consequence of the abrupt decrease of the bone cross section would be growth of the load exerted on the lower part of eye socket.

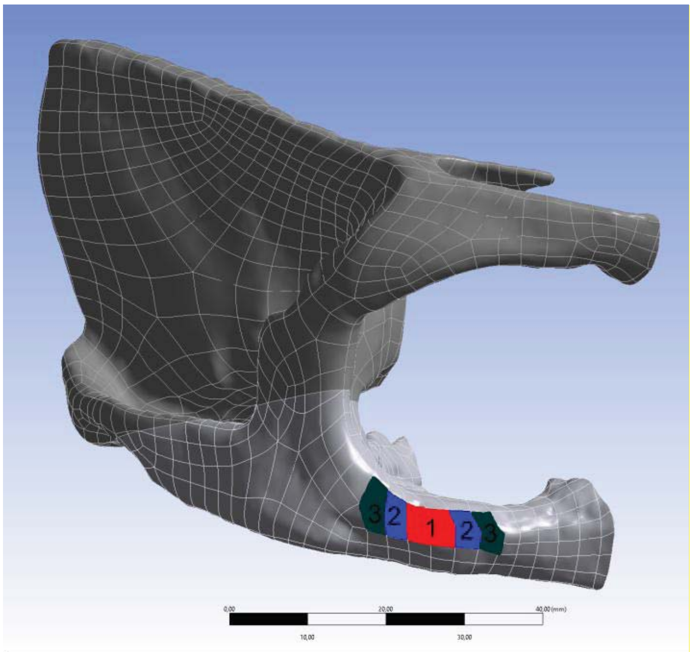

Figure 9. Change of force application area during ball impact: case 1 - region 1; case 2 - region (1+2); case 3 - region (1+2+3)

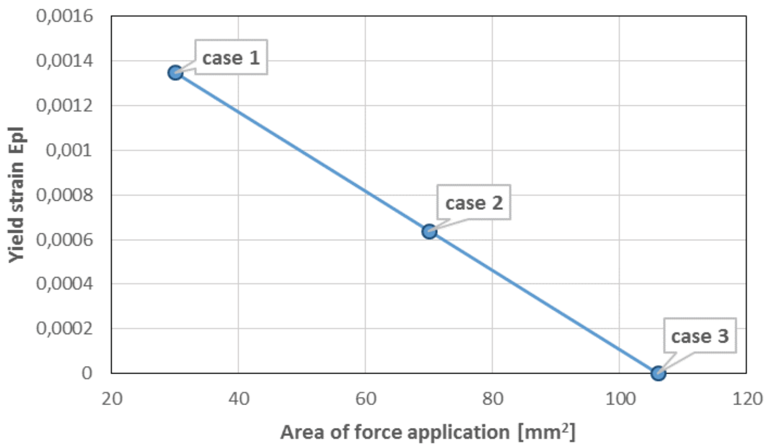

Figure 10. Yield strain vs area of force application during a ball impact

The resulting map of yield strain, shown in Fig. 11, and reduced von Mises stress distribution (Fig. 12) correspond to the *zygomaticomaxillary complex fracture* (*tripod fracture*).

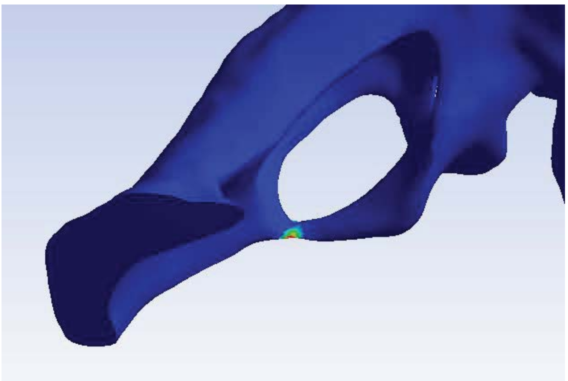

Figure 11. Map of yield stresses

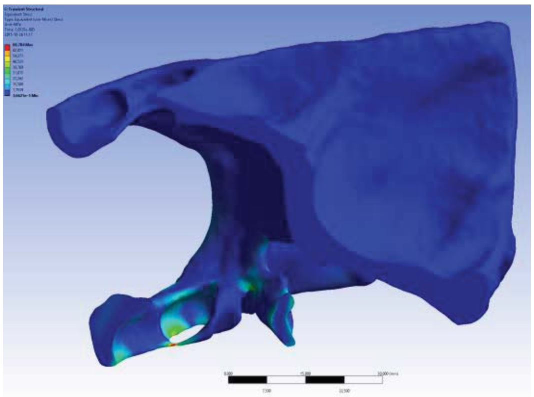

Figure 12. Reduced von Mises stress distribution

This type of fracture include the zygomatic arch, fronto-zygomatic suture and fronto-lateral wall of maxillary sinus. As in the previous case, such a failure can result in the displacement of the eyeball or even in its lasting damage. The presented numerical analysis fully reflect the real state of the load effects, which confirm the correctness of the adopted numerical model.

4. Conclusions

In the course of analysis, it was found that the greatest impact on the size of orbital injury have the place of load application, as well as the size of surface on which this load occurs. The most dangerous seems to be a situation where the force is applied to the zygomatic part of orbit, on a relatively small area (which corresponds to the early stage of impact, when the ball deformation is not yet big).

Simulation results show that under such conditions, the posterior part of the zygomatic bone, which can be defined as an strengthening (supporting) element of the orbit, would be fractured. As a consequence of such incident the entire lower zygomatic bone would be damaged due to the strong bending load. What's more, this damage would propagate to the rear part of the eye socket, causing a loss of support for the eyeball.

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