Computational Modeling and Analysis of Wound Formation in Gunshot Injuries

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Abstract. This research aims to investigate the physical processes accompanying high-speed element penetration in gunshot wounds and understand the formation of wound channels, trajectory characteristics of bullets, and damaging effects on surrounding tissues. The study utilizes 3D computer modeling to simulate high-speed element penetration based on the 3D finite element method (FEM).

The paper presents a methodology of computer simulation with mathematical basics and algorithmic descriptions. The approach uses direct explicit numerical integration over time for the impact of the metallic bullet into the gelatin block specimen that analyses within the framework of its plasticity considering the non-linear pressure dependence in a shock wave. The algorithm of simulation incorporates the process of material destruction, where elements that reach critical strain values are removed from the model. The study provides insights into the behavior of different bullet types and their impact on tissue deformation from computational experiments that simulate the penetration into ballistic gelatin of two types of bullets, the 7H6M type, and the V-max type. The simulation results reveal the distribution of equivalent stresses in the wound channel at different moments in time. Additionally, the study analyses the penetration depth and diameter of the damaged material for both bullet types. The developed 3D computer modeling method can serve as a valuable tool for further investigations, facilitating the development of advanced medical treatments.

Keywords: Gunshot injuries, Soft tissue damage, Wound dynamics, Finite element method (FEM), Penetrating impacts.

1 Introduction

Military conflicts that take place in the modern world are accompanied by a high number of various penetrating wounds. Gunshot and shrapnel wounds, characterized by high kinetic energy, create cavities within the human body that far exceed the size of the penetrating elements [1]. Moreover, the formation of local disorders surrounding the wound channel can lead to pathologies. These peculiarities make the diagnosis and effective treatment of gunshot wounds complex, as the assessment of the lesion's degree, nature, and scope becomes challenging [2-4]. Thus, a thorough understanding of the physical processes accompanying the intervention of high-speed elements in the human body is paramount for successful treatment.

The study of soft tissue deformation mechanisms caused by the penetration of high-speed elements is currently approached through natural experiments and computer simulations. Existing experimental studies primarily focus on describing the geometry of the wound channel based on the characteristics of the penetrating elements, such as mass, speed, and angle of attack.

The above experimental data made it possible to obtain general pictures regarding the formation of wound channels for several variants of damage to a non-biological simulator of human soft tissues (bullets of various types) [5-7]. However, these results only show the actual effect on the wound channel, but do not provide insight into the damaging effect that occurs in penetrating action around this channel. Relevant information can be obtained from the analysis of the development in the time of the penetration of the ball into the soft material with the analysis of the distribution of the pressure field (equivalent stresses). Experimental studies of this type [6] are extremely complicated and quantitatively impossible at all, since the determination of pressure (equivalent stress) can be experimentally carried out only by point sensors - therefore, only individual points in the material can be analyzed experimentally - and then quite far from the wound channel (the latter is due to the risk damage to the sensor itself). To solve this problem, mathematical modeling based on 3D computer simulations is used in the biomechanical research and impact problems study [7-9]. Numerical experiments make it possible to obtain, for different moments of time, the distribution of equivalent stresses in ballistic gelatin during the passage of a wounding projectile (this material was chosen for mathematical modeling, the properties of which are the most studied in the literature and provide a better approximation to the behavior of soft biological tissues). Appropriate calculations allow you to study the shape of the wound channels, the characteristics of the trajectory of bullets, and compare these characteristics between bullets. Existing experimental studies [10] are used to determine the constants of the material included in mathematical models, and also play a decisive role in assessing the justification of the model's correctness and the reliability of the results.

2 Methodology of numerical 3D modeling

A mathematical formulation of the problem of the penetrating action of one body into another at high speed involves writing down the basic equations of the physics of a solid-deformable body for the 3d case. The mathematical description involves the formation of equations of mechanical dynamic equilibrium, which must be provided separately for the body of the bullet and for the material of ballistic gelatin at each moment of time and equations of the physical state of the material, which describes the existing dependencies between the internal equivalent stresses and deformations (strains). The mentioned equations regarding the physics of the processes must be predefined by geometric relations that connect all points of the material into a single system, and actually describe the relationship between strains and displacements of each point of both bodies. The conditions of the interaction of bodies (a bullet and a sample of ballistic gelatin block) should also be added to the mathematical formulation, as well as the conditions of the destruction of the material, which should be checked and reviewed over time.

The described conceptual mathematical statement formally leads to a multi-dimensional system of nonlinear partial differential equations, which have no known analytical methods of solution. In modern practice, solving this kind of complex mathematical problem uses numerical methods, which are implemented in the form of computer simulation tools. In this work, the finite element method (FEM) is used within a realization of a three-dimensional computer modeling approach.

In this work, an explicit integration scheme is used, which involves an iterative change in the research time (step-by-step modeling of the deformation process), which allows you to explicitly calculate the acceleration of all nodes of the FE model at each new time step. For this, the central difference formula for the approximation of accelerations is used.

In addition, in order to correctly model all the processes that occur during the penetration of the solid body of the bullet into the gelatin material, it is also necessary to model the process of destruction of the material, which is not taken into account in the framework of the ratios and statements described above.

In this work, an approach known as "elements death" was used to reproduce the process of destruction of ballistic gelatin. This is an algorithm for computer modeling of destruction, which involves the assessment in each FE at each moment of time of reaching a critical value of strains that determine the occurrence of damage. Then, algorithmically, if the critical values in a specific FE are reached, this element is programmatically removed from the model (that is, it is no longer used in calculations at the next time integration step). A new FE model is created (however, with a known distribution of nodal displacements, deformations, stresses, and pressures), which is further analyzed under the conditions of actual geometry.

In this work, plastic deformations in the gelatin material were analyzed - if the equivalent plastic strains (according to the Mises criterion) reached a critical value. Therefore, the destruction criterion is as follows:

$$\varepsilon_i \geq \varepsilon_c$$

where ε_c=0.9 according to recommendations in the literature.

Fig. 1. presents the general computer simulation algorithm that was used in the work, where the following introduced: […] – notations for the matrixes; the bold letters indicate the vectors and non-bold - scalars; the dot above symbol indicates its derivative over time. In particular: [$\boldsymbol{M}$] – FE mass matrix; ρ – material density; $\boldsymbol{N}$ **–** vector of FE shape functions; [$\boldsymbol{D}$] – matrix of derivatives operators corresponds to Cauchy formulas; $\boldsymbol{a}$ – vector of nodal displacements; t is a time; Δt – increment time step; $\boldsymbol{\varepsilon}$ and $\boldsymbol{\sigma}$ – vectors of FE strains and stresses (the Voight notation for the corresponding tensors)*;* [$\boldsymbol{E}$] – the matrix of material elastic characteristics that represents Hooke's law; S_{ij} and e_{ij} – components of deviator part of stress and strain tensors; P – hydrodynamic pressure; μ –

relative density; C –constants that describe the shock wave peculiarities in material; δ_{ij} – Kronecker symbol; $\boldsymbol{f}$ – vector of external forces (contact forces).

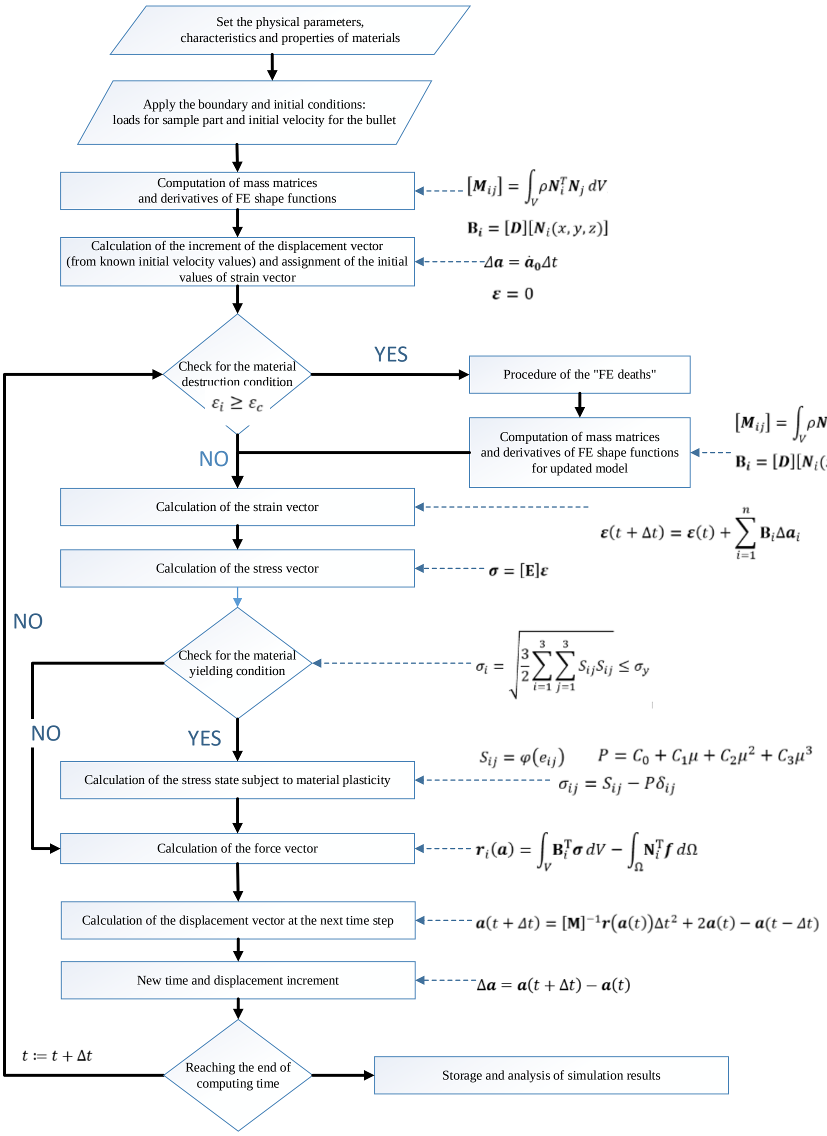


Fig. 1. Block diagram of the algorithm of computer modeling of the wound channel formation process and analysis of deformation waves around it.

To simulate the movement of the bullet, the FE model was built taking into account the peculiarities of its geometry and internal structure (different materials inside) (Fig. 2).

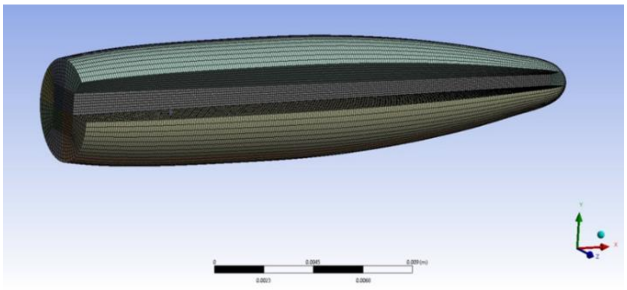
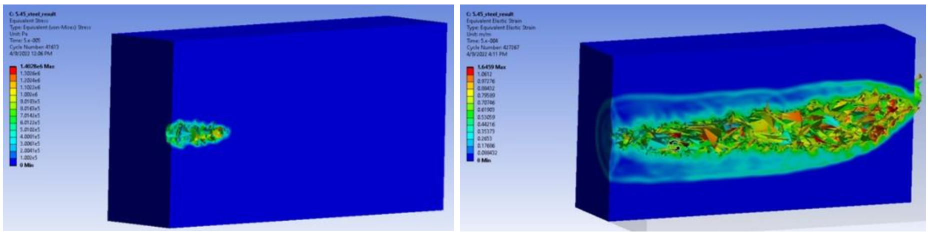


Fig. 2. FE mesh of the bullet.

3 Results of 3D Computer Modeling of the Wound Channel when Shot with Bullets of Different Calibers

A series of computational experiments were done in this work using the given approach for computer modeling. Calculations and comparative analysis were carried out regarding the processes of penetration of two types of bullets into a sample of ballistic gelatin.

The results of mathematical modeling of the damaging effect of a 5.45x39 (7H6M) caliber bullet after 0.05 msec and 0.5 msec after the start of interaction with a biological simulator (at the beginning of penetration and at the end of through penetration) are shown in Fig 3.



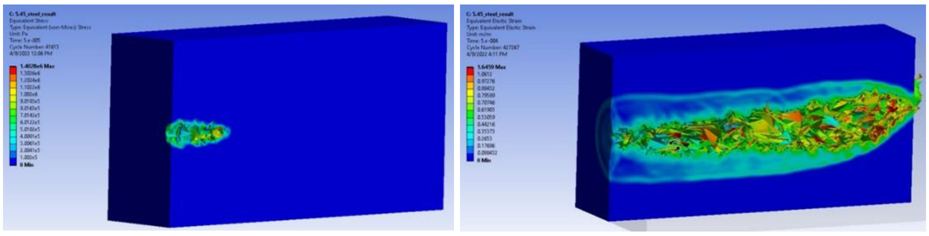
a) b)

Fig. 3. Equivalent stresses in wound channel of the block of imitator (cross-section of a ballistic gelatin sample) at different moments of time caused by the penetration impact by the 5.45x39 (7H6M) calibre bullet (a) initial e=0.05 msec b) final 0.5 msec)

A wound by an ordinary bullet of the 7H6M type is characterized by the fact that it passes through gelatin and loses only part of the kinetic energy. The simulation results showed that the exit speed of the bullet is 200 m/s with an initial speed of 918 m/s and a mass of 3.4 g.

Features of the geometric shape of the bullet (the center of mass is shifted to its tail) ensure rectilinear movement of the ball in a section up to 100 mm, after which the bullet loses speed and makes a turn of almost 180°. It is at this moment that the main part of the energy is transmitted, which, accordingly, makes a significant im-pression on the organs that are on the trajectory of the bullet.

The paper also carried out modeling of the damaging action of a 5.45x39 (V-max) calibre bullet. The results of the damaging effect after 0.05 msec and 0.2c msec after the start of interaction with a biological simulator (at the beginning of penetration and at the end bullet movements) are shown in Fig. 4.



a) b)

Fig. 4. Equivalent stresses in wound channel of the block of imitator (cross-section of a ballistic gelatin sample) at different moments of time caused by the penetration impact by the 5.45x39 (V-max) calibre bullet (a) initial e=0.05 msec b) final 0.2 msec)

The obtained results of the numerical modeling showed that a wound with an expanding V-max bullet has a significantly larger area of tissue damage. Mathematically, this can be explained by the fact that the expanding bullet has a soft core that deforms and transfers all kinetic energy to the tissues immediately after penetrating the tissues.

The obtained calculated data on the geometry of the wound channel are in general qualitatively and quantitatively consistent with live ballistic tests. The 7N6M type bullet passed through the gelatin block, while the V-max penetrated only half of the block. In fig. 5 shows the dependence of the bullet penetration depth on time.

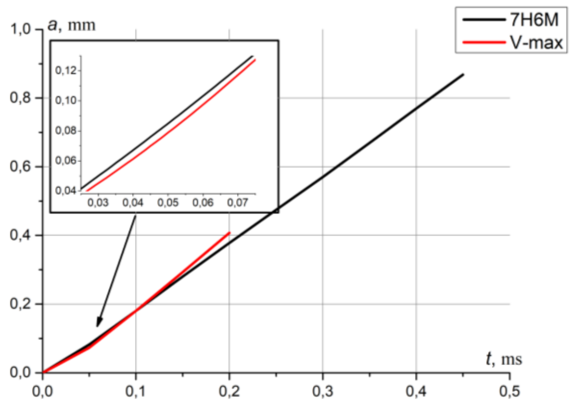


Fig. 5. Dependence of bullet penetration depth over time

From the generalization given, it can be seen that the bullet type 7H6M has an almost constant speed of penetration, that is, the formation of the wound channel occurs in time linearly along the depth of penetration. Instead, the V-max type bullet has a somewhat graded dependence, which is characterized by a lower penetration speed at the beginning, which can be explained by the characteristics of the bullet itself, which deforms the plate by itself during the impact.

From a practical point of view, a comparative analysis of the diameter of the wound channel for different bullets is more interesting. A feature of computer modeling is the ability to analyze not only the actually damaged material (wound channel), but also the surrounding material that has undergone significant stress. In fig. 6 shows a generalized graph of the time dependence of the maximum diameter of the neighborhood around the wound channel, which received stress during bullet penetration

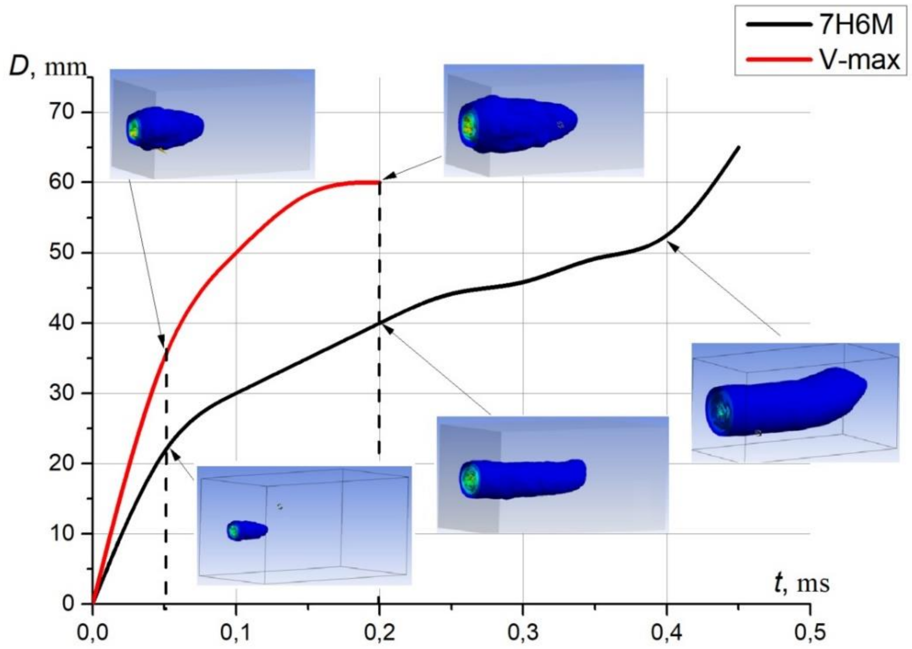


Fig. 6. Time dependence of the maximum diameter of the edge of the wound channel, which undergo stress for two types of bullets

The graph clearly shows that the V-max type bullet has a significantly greater destructive effect on the material and does it faster than the 7H6M type bullet. Formally, the maximum diameter of the damaged material for both balls almost coincide at the final moment of time, but here you should pay attention to the fact that the 7H6M bullet maximum damage is related to the process of its "going out". Indeed, the indicated maximum zone with stresses is on the back surface of the gelatine block. While inside the body of the imitator the diameter of the material subjected to stress for the V-max ball 1.25 times larger than for the classic 7H6M type bullet, and in the middle section is 1.5 times larger for the same moment of penetrating time.

Conclusions

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Conflict of Interest. The authors declare that they have no conflict of interest.

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