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Application of a mathematical model of a human lower limb for modeling shock-wave effects of contact explosion

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ABSTRACT

A simulation finite-element model of the destruction process of biomaterials of the human musculoskeletal system under shock-wave effects of a contact explosion is substantiated to predict the nature and extent of damage to the lower limbs, including designing special explosion-proof shoes. The physical and mechanical properties of the biological tissues of human lower limbs and their behavior under local shock-wave action were analyzed. The mechanical behavior of each biological material as part of a mathematical model of a human lower limb was selected. The original finite-element model of the human lower limb symmetrically interacted with the main components of its anatomical structures. The developed computational model was verified using data obtained from the results of experiments on mechanical and shock-wave effects. A specialized program for processing the received data was created, which implements an algorithm for processing received graphic images of changes in pressure indicators and accelerations over time to obtain tolerance curves. Several numerical calculations were performed to simulate contact detonation through the protective composition of the developed model of the lower limb. Pressure and acceleration tolerance curves were derived from the results of the calculations, animations of the behavior of anatomical structures of the lower limb under shock-wave action were created, and the propagation of the pressure field within them was visualized. In the future, the proposed method of conducting “virtual” tests can be employed to solve application issues of testing to protect the lower extremities of sappers. In general, the use of computer modeling techniques will help reduce the time and cost of producing new samples of protective products in the interests of the country’s defense capability.

Keywords: mathematical modeling; modeling of biological tissues; spatial finite element model; factors of a near explosion; mine protection; means of protecting the lower extremities; pressure tolerance curves; shock wave effect.

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Применение математической модели нижней конечности человека для моделирования ударно-волнового воздействия контактного взрыва

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АННОТАЦИЯ

Обосновывается имитационная конечно-элементная модель процесса разрушения биоматериалов опорно-двигательного аппарата человека при ударно-волновом воздействии контактного взрыва для прогнозирования характера и объема повреждения нижних конечностей человека, в том числе при проектировании специальной взрывозащитной обуви. Анализируются научные данные, описывающие физико-механические свойства биологических тканей нижних конечностей человека и их поведение при локальном ударно-волновом воздействии. Осуществлен подбор механического поведения для каждого биологического материала в составе математической модели нижней конечности человека. Обоснована оригинальная конечно-элементная модель нижней конечности человека с настроенным взаимодействием основных составляющих ее анатомических структур друг с другом. Проведена верификация разработанной расчетной модели с данными, полученными по результатам экспериментов с механическим и ударно-волновым воздействием. Создана специализированная программа обработки полученных данных, в которой реализован алгоритм обработки получаемых графических изображений изменений показателей давлений и ускорений во времени, с целью получения кривых толерантности. Проведен ряд численных расчетов, имитирующих контактный подрыв через защитную композицию разработанной модели нижней конечности. По результатам проведенных расчетов получены кривые толерантности давлений и ускорений, созданы анимации поведения анатомических структур нижней конечности человека при ударно-волновом воздействии, получена визуализация распространения поля давлений в них. В перспективе представленная методика проведения «виртуальных» испытаний может применяться для решения ряда прикладных вопросов тестирования средств защиты нижних конечностей сапера на этапе их разработки. В целом применение методик компьютерного моделирования будет способствовать сокращению времени и затрат на производство новых образцов защитных изделий в интересах обороноспособности страны.

Ключевые слова: математическое моделирование; моделирование биологических тканей; пространственная конечно-элементная модель; факторы близкого взрыва; противоминная защита; средство защиты нижних конечностей; кривые толерантности давлений; ударно-волновое воздействие.

Как цитировать

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应用人体下肢数学模型模拟接触爆炸的冲击波效应

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摘要

人体肌肉骨骼系统的生物材料在接触爆炸的冲击波冲击下的破坏过程的有限元模拟模型已得到证实，可用于预测人体下肢损伤的性质和程度，包括设计特殊防爆鞋。分析了描述人体下肢生物组织物理力学特性及其在局部冲击波作用下行为的科学数据。作为人体下肢数学模型的一部分，对每种生物材料的机械性能进行了选择。对人体下肢的原始有限元模型进行了论证，并调整了其主要组成解剖结构之间的相互作用。利用机械和冲击波效应实验结果获得的数据对开发的计算模型进行了验证。创建了一个处理所获数据的专门程序，其中采用了一种算法来处理所获得的压力和加速度指数随时间变化的图形图像，以获得公差曲线。通过所开发的下肢模型的防护组合，进行了一系列模拟接触爆炸的数值计算。根据计算结果，获得了压力和加速度的公差曲线，创建了冲击波作用下人体下肢解剖结构行为的动画，并获得了压力场在其中传播的可视化效果。今后，所介绍的进行“虚拟”测试的方法可用于解决爆炸物处理下肢防御设备开发阶段测试的一些应用问题。总之，计算机建模技术的应用将有助于减少生产新防护产品样品的时间和成本，从而提高国家的防御能力。

关键词：数学建模；生物组织建模；空间有限元模型；近距离爆炸因素；防雷保护；下肢防护；压力耐受曲线；冲击波效应。

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INTRODUCTION

At present, human body processes resulting from the effects of explosive and gunshot trauma, including the use of personal protective equipment, are primarily investigated through full-scale modeling. To achieve this, research of this kind employs various biological and synthetic materials. Biological materials include human cadavers and their constituent parts, as well as a range of experimental animals. Synthetic materials include bioimitators of human tissues and technical imitators of the human body or its parts. Nevertheless, conducting biomedical research using experimental animals presents considerable ethical challenges and poses significant difficulties in comparing the musculoskeletal systems of animals and humans owing to their inherent anatomical differences. The use of live humans or parts of human cadavers as test objects is even more problematic because it raises ethical concerns and presents practical difficulties [1, 2].

A potential solution to this problem is to incorporate various modeling techniques into the testing process. These techniques may include the use of biosimulators of living tissues, technical devices for parameter monitoring, and simulation models for comprehensive process modeling. At present, computer-aided engineering software systems are widely used in technical scientific studies. The main applied task of this methodology can be the selection of optimal parameters of complex materials and the creation of interaction models of these materials and their destruction [3, 4].

When developing numerical models of biomaterial behavior, even when solving similar problems, full correspondence between the results of modeling and in situ tests cannot be achieved because of the strong influence of geometric and physicomechanical parameters of each biological sample on the final result. In addition, calculating the expected biomaterial damage from the multifactorial effects of a close explosion is further complicated by the presence of protective structural elements to the computational model [5, 6].

Lower leg and foot injuries caused by contact explosion to the lower extremities protected by special anti-explosion footwear can be reasonably attributed to a separate type of mine explosion injury, called “barrier” mine explosion injury in individuals wearing anti-explosion footwear. If the protective effectiveness of the footwear is sufficient, characteristically, in most cases, most of the energy of a near explosion is spent on the destruction of the protective elements of the sole, and the remaining energy is transferred to the “shock shift” of the underlying foot structures. In this case, the casualty may sustain different closed injuries such as skin abrasions, soft tissue contusions, ligamentous injuries, and fractures of the bones of the foot and lower third of the tibia. In addition, if the protective structure is destroyed, injuries characteristic of a classic contact mine blast wound may be observed, with open injuries and even detachment of the foot [7, 8].

This study aimed to substantiate a finite-element model of the human lower extremity to simulate the destruction of musculoskeletal biomaterials under the shock-wave impact of a contact explosion, predict the nature and volume of damage to the human lower extremity, and solve applied problems in the design of special explosion-proof footwear.

MATERIALS AND METHODS

The finite-element technique was used to model shock-wave impact on the lower extremity and evaluate the behavior of the biological materials of which it is composed under the contact action of the blast. This modern computational mechanics is based on the decomposition of the studied structure into separate parts that are finite elements connected by nodes. The set of the interconnected finite elements attached to the base forms a design scheme called a finite-element (computational) model.

Using scientific data on the physical and mechanical properties of biological tissues of the human lower extremity and their behavior under shock-wave impact, an original full-scale finite-element model of the lower extremity of an adult male was developed with maximum consideration of all dimensional characteristics of its anatomical structures and physical and mechanical properties of the main biological tissues. With the labor-intensive and complicated process, the main stages of the model development are presented in the Results and Discussion.

The finite-element model was validated by comparing computational and experimental data (pressure and acceleration indices) obtained from detonating 75 g of explosives under a protective structure (a metal plate mimicking the protective composition of a sapper’s shoe) over which anatomical preparations of the human lower extremity were placed. This was conducted as part of the research project on the development of a sapper’s protective shoe, undertaken to advance the capabilities of the Russian engineering forces.

After research completion, radiographic signs of damage to the lower limb fragments, high-speed video recordings, and acceleration and pressure sensor data were analyzed. The schematic diagram of the full-scale experiment is shown in Figure 1.

The results of the virtual (numerical) experiment simulating the impact of blast effects on the human lower extremity were analyzed in graphical format to determine the propagation of pressure and acceleration fields and predict the potential destruction of major anatomical structures.

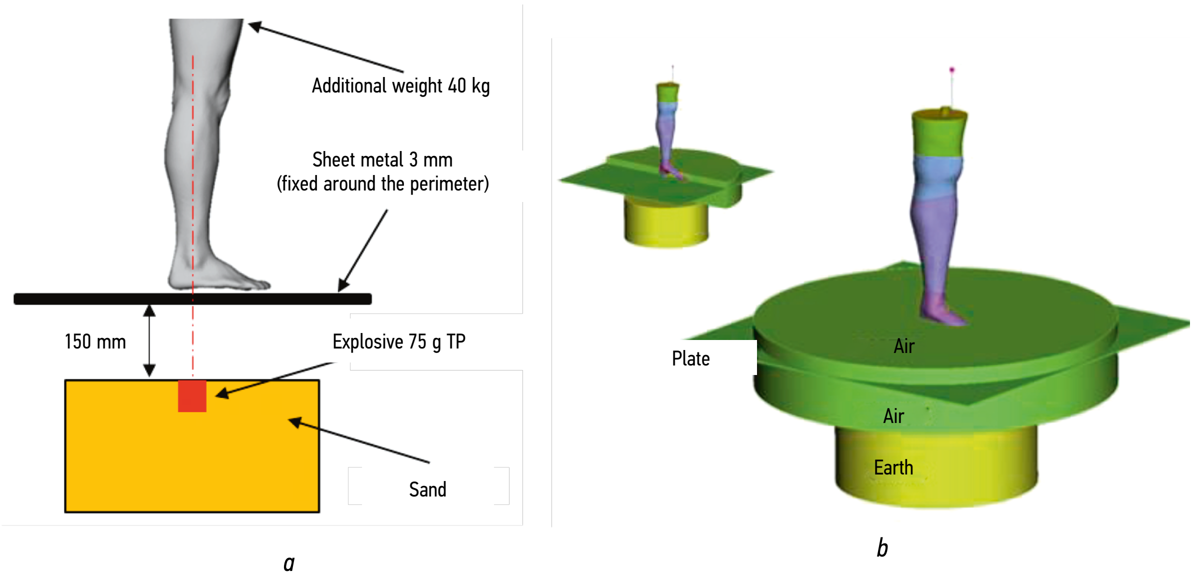

Fig. 1. Presentation of the experiment and associated calculations: *a* — experimental scheme; *b* — calculation scheme
Рис. 1. Схематическое изображение проведения эксперимента: *a* — схема эксперимента; *b* — схема расчета

The study was conducted in accordance with the project "Study of the creation of protective footwear for sappers" (project code "Foot"), which is part of the scientific work plan of the Armed Forces of the Russian Federation.

RESULTS AND DISCUSSION

The model of an elastic–viscous–plastic material with a fracture criterion based on the maximum value of effective plastic deformation was employed as the foundation for the developed mathematical model of materials comprising spongy and compact bone tissues (femur, fibula, and tibia) within the lower limb finite-element model. The effect of plasticity in this model must be considered because strain accumulation is a significant factor and, simultaneously, serves as an indicator of potential damage. The physical and mechanical characteristics of the materials comprising the patella, talus, cuboid, navicular, lateral cuneiform, intermediate and medial cuneiforms, metatarsals, and phalanges are analogous to those observed in tibial materials. Importantly, the calcaneal bone was subdivided into three distinct layers, namely. the compact substance, spongy substance, and marrow, in accordance with the expression of the "marrow component" (red bone marrow) [9, 10]. The physical and mechanical properties of the bones included in the numerical model are summarized in Table 1.

A hyperelastic material model, which allows for the specification of viscous properties, was employed for the modeling of the lower limb muscles [11, 12]. The equations embedded in the material maps are described in detail in the user manual for LS-DYNA [13]. The physical and mechanical properties of muscle tissues are summarized in Table 2.

Hyperelastic and viscoelastic material models are commonly used for human skin modeling. M. Ottenio et al. [14] presented a comparative analysis of three hyperelastic material models: Mooney – Rivlin, Ogden, and Neo-Hookean. These models were selected through an experimental process conducted using SIMULIA Abaqus. The Ogden model was chosen as a skin model given its accuracy in describing the mechanical properties of skin. The physical and mechanical properties of the skin are summarized in Table 3.

Discrete elements (springs) are usually used to model tendons. For single-degree-of-freedom discrete elements, the mathematical material model "MAT_SPRING_GENERAL_NONLINEAR" is used. This material models the properties of an elastic spring (compression or torsion) with variable stiffness. In addition, the strain rate effects can be considered using a velocity-dependent scaling factor. Therefore, the mathematical material model "S04_MAT_SPRING" with elastic mechanical behavior was used to model the tendons.

In the modeling of ligaments, the use of "flat" elements is an effective approach, as it allows for the consideration of shear deformations while reducing the computational cost compared with the volumetric element method. In scientific publications, two principal material models are presented: the elastic MAT_1 (MAT_ELASTIC), which reproduces an isotropic hypoelastic material, and the elastic–plastic MAT_19 (*MAT_STRAIN_RATE_DEPENDENT_PLASTICITY), which represents an isotropic elastic–plastic material for which the strain rate dependence can be specified [15, 16]. The physical and mechanical properties of ligaments are summarized in Table 4.

Table 1. Physical and mechanical properties of the bones of the lower limbs
Таблица 1. Физико-механические свойства костей нижней конечности

Indicators	Density (ρ), kg/m^3	Young's modulus (E), MPa	Poisson's ratio (ν), rel. unit	Shear modulus (G), MPa	Bulk modulus of elasticity (K), MPa
Compact substance of the tubular bone	2×10^3	15 000	0.3	5769	12 500
Spongy substance of the tubular bone	1.1×10^3	445	0.3	–	–
Compact substance of cancellous bone	2×10^3	14 000	0.3	5385	11 667
Spongy substance of cancellous bone	1.1×10^3	292	0.3	–	–
Cancellous red marrow	2×10^3	15 000	0.3	5769	12 500
Compact substance of the tubular bone	6×10^3	445	0.45	–	–
Spongy substance of the tubular bone	9.75×10^3	2	0.167	–	–

Table 2. Physical and mechanical properties of muscle tissues
Таблица 2. Физико-механические свойства мышечных тканей

Indicators	Value
Density, kg/m^3	1.1×10^3
Poisson's ratio, rel. unit	0.495
Shear modulus for frequency-independent damping, MPa	1
Stress limit for frequency-independent friction damping, MPa	0.001
Hyperelastic coefficients (C10), rel. unit	0.04
Additional shear relaxation modulus (GI_1), MPa	0.1
Attenuation parameter (BETAI_1), rel. unit	0.1
Fracture strain (MAT_ADD_EROSIONEFFEPS), rel. unit	1.1

Table 3. Physical and mechanical properties of the skin
Таблица 3. Физико-механические свойства кожи

Indicators	Value
Density, kg/m^3	1.1×10^3
Poisson's ratio, rel. unit	0.495
Shear modulus, MPa	0.0096
Degree index, rel. unit	35.993
Shear relaxation modulus (GI_1), MPa	0.34
Attenuation constant (BETAI_1), rel. unit	0.593
Fracture strain (MAT_ADD_EROSIONEFFEPS), rel. unit	0.7

In the final stage of developing a numerical model of the human lower limb, a three-dimensional model was constructed using published data [17]. This enabled the creation of a comprehensive numerical model comprising a tetrahedral finite-element mesh, which incorporates specific geometric parameters (Fig. 2).

To test the model, four identical experiments were conducted. These included the recording of images and videos of the human lower limb fragments, which were then analyzed to determine the motion parameters (Fig. 3). The results demonstrated a high degree of correlation between the numerical model and the full-scale experiment.

Table 4. Physical and mechanical properties of the ligaments
Таблица 4. Физико-механические свойства связок

Ligament/tendon	Behavioral mechanics	Density, kg/m^3	Young's modulus, MPa	Poisson's ratio, rel. unit	Dependence on the strain rate
Tendon of the quadriceps femoris muscle	Elastic	1.1×10^3	800	0.49	–
Patellar ligament	Elastic	1.1×10^3	800	0.49	–
Lateral meniscus	Elastoplastic	10^3	12	0.33	+
Medial meniscus	Elastoplastic	10^3	12	0.33	+
Posterior ligament (meniscus)	Elastic	1.1×10^3	53	0.49	–
Transverse ligament (meniscus)	Elastic	1.1×10^3	53	0.49	–
Posterior cruciate ligament	Elastoplastic	1.1×10^3	543	0.49	+
Anterior cruciate ligament	Elastoplastic	1.1×10^3	543	0.49	+
External collateral ligament	Elastoplastic	1.1×10^3	543	0.49	+
Internal collateral ligament	Elastoplastic	1.1×10^3	543	0.49	+
Interosseous membrane	Elastic	1.1×10^3	53	0.49	–
Transverse ligaments (phalanges)	Elastic	500	1000	0.3	–
Ligaments (metatarsus — phalanges)	Elastic	10^3	50	0.3	–
Long plantar ligaments	Elastic	10^3	1000	0.3	–
Plantar calcaneonavicular ligament	Elastic	1.1×10^3	53	0.49	–
Deltoid ligament	Elastic	1.1×10^3	401	0.49	–
Anterior intertrochanteric ligament	Elastic	1.1×10^3	53	0.49	–
Posterior intertrochanteric ligament	Elastic	1.1×10^3	53	0.49	–
Medial ligament	Elastic	1.1×10^3	401	0.49	–
Posterior talofibular ligament	Elastic	1.1×10^3	401	0.49	–
Anterior talofibular ligament	Elastic	1.1×10^3	401	0.49	–
Posterior talofibular ligament	Elastic	1.1×10^3	53	0.49	–
Fibulocalcaneal ligament	Elastic	–	401	0.49	–
Talus ligament	Elastic	1.1×10^3	53	0.49	–
Cuboidal navicular cuneiform ligament	Elastic	10^3	100	0.3	–
Cuboidal navicular cuneiform ligament 2	Elastic	1.1×10^3	53	0.49	–

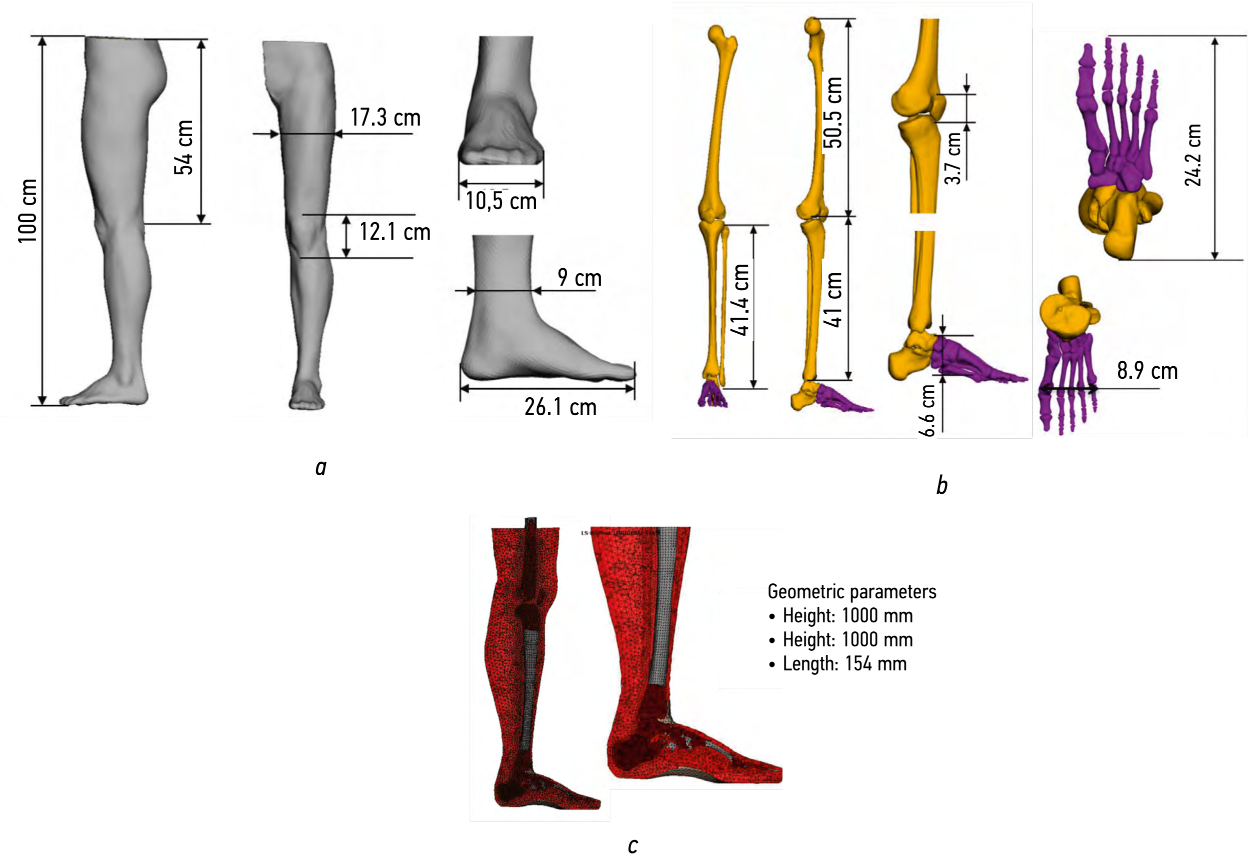

Fig. 2. Geometric dimensions of the calculated model of the human lower limb: *a* — dimensional parameters of the 3D model; *b* — dimensional parameters of the bone skeleton; *c* — parameters of the finite-element model
Рис. 2. Геометрические размеры расчетной модели нижней конечности человека: *a* — размерные параметры 3D-модели; *b* — размерные параметры костного остова; *c* — параметры конечно-элементной модели

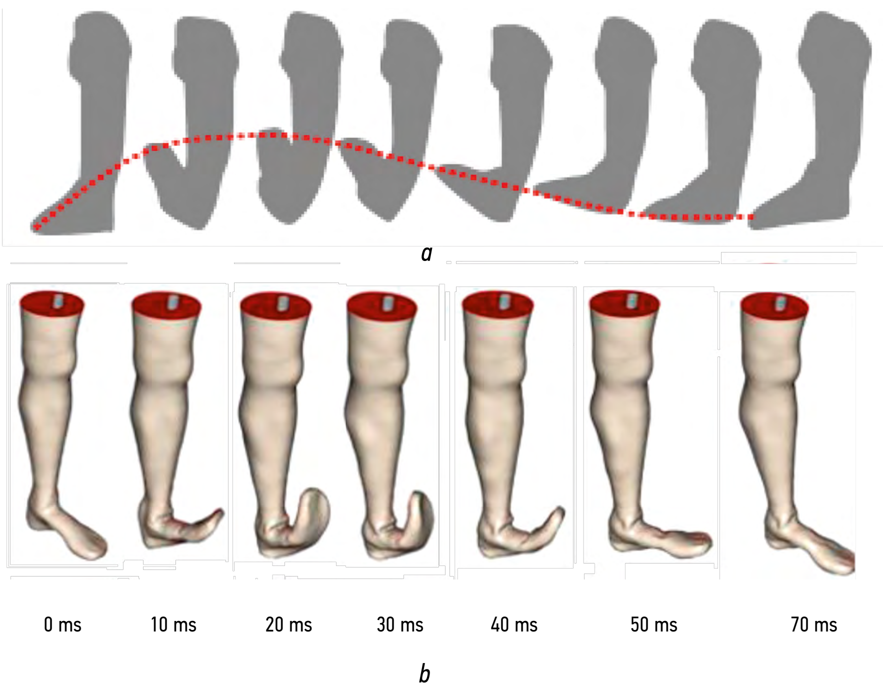

Fig. 3. Modeling of the undermining of the lower limb through the protective structure: *a* — changing the contour of the lower limb in time; *b* — moving the "toe" of the lower limb when detonating explosives weighing 75 g
Рис. 3. Моделирование подрыва нижней конечности через защитную структуру: *a* — изменение контура нижней конечности во времени; *b* — перемещение «носка» нижней конечности при подрыве ВВ массой 75 г

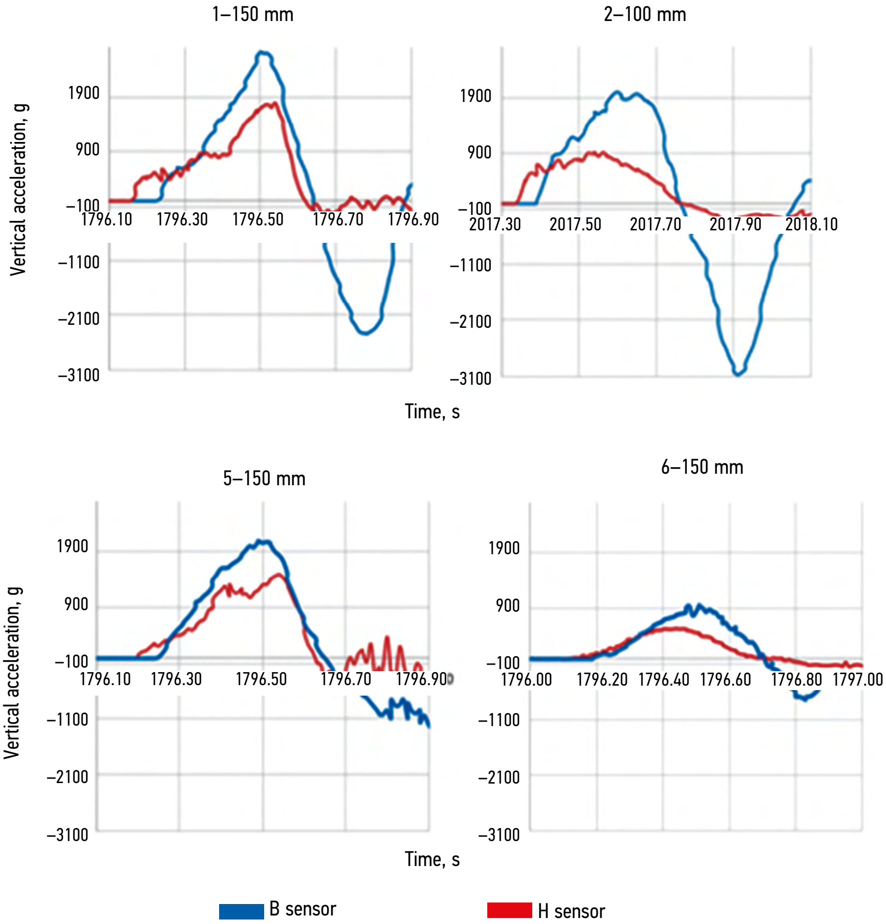

Fig. 4. Accelerations of the lower limb during the detonation of explosives weighing 75 g obtained during field tests
Рис. 4. Значение ускорений нижней конечности при подрыве взрывчатого вещества массой 75 г, полученных при натурных испытаниях

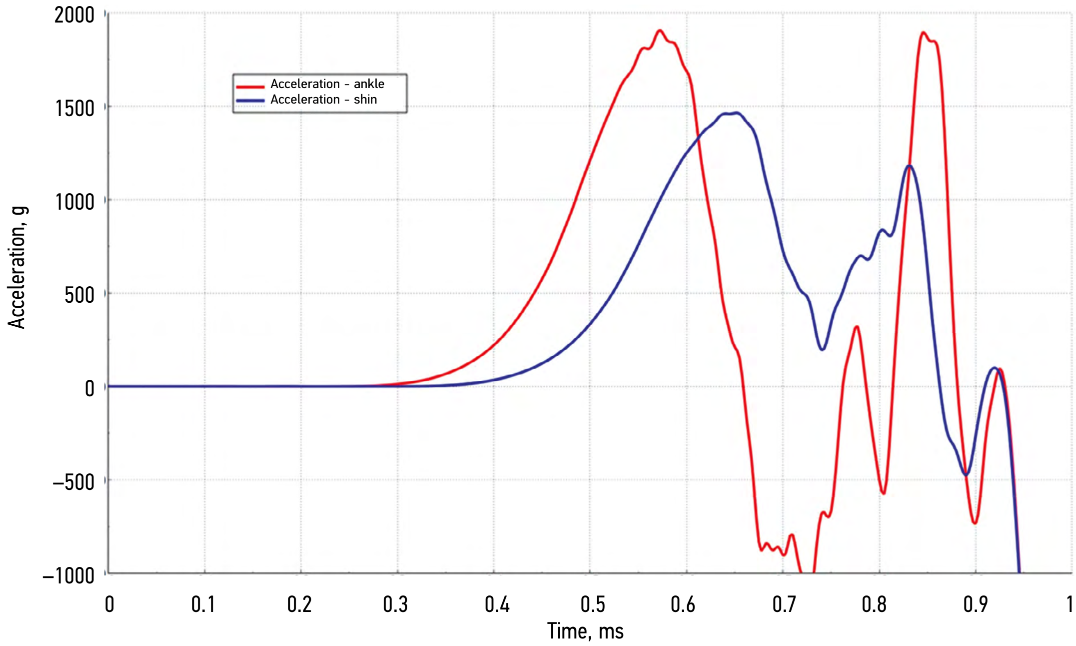

Fig. 5. Accelerations of the lower limb during the detonation of explosives weighing 75 g in numerical simulations
Рис. 5. Значение ускорений нижней конечности при подрыве взрывчатого вещества массой 75 г при численном моделировании

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Table 5. Verification of the destruction of the lower limb
Таблица 5. Верификация разрушений нижней конечности

Bone	Test result, %	
	In situ	Virtual
Calcaneum	Fracture 100	Comminuted fracture
Talus	Fracture 75, crack 25	Fracture
Cuboid	Crack: probability 25	No
Navicular	No	No
Lateral	Defect: probability 25	No
Intermediate	No	No
Medial	No	No
Fibula	Fracture: probability 50	Fracture
Tibia	Fracture: probability 100	Fracture
Patella	No	No
Femur	No	No

During the full-scale testing phase, two accelerometer sensors were installed on the studied object. These were positioned in the lower (H) and upper (B) thirds of the tibia. The sensor readings are presented as graphs in Figure 4.

In the numerical modeling phase, the calculated acceleration indices were obtained for sensor B with acceleration amplitude of 1450 g and duration of 0.39 ms, which correlates closely with the data obtained during the full-scale tests (Fig. 5). The results of the comparison of lower limb fractures are summarized in Table 5.

In principle, all lower limb fractures can be divided into those with and without displacement of bone fragments. Displacement of bone fragments in a finite-element model is defined by the detachment of its elements, resulting in a defect. Therefore, the injuries shown in the calculation model should be interpreted as follows:

- Nondisplaced fractures with the removal of a few elements or an ordered series of elements (nondisplaced fractures).
- Displaced fractures/slip fractures/bone fractures (compound fractures) with disordered removal of multiple elements.

In general, the characteristics of injuries to the lower limb bones based on numerical modeling on the finite-element model coincided by 90% with that of injuries based on the field experiment.

CONCLUSIONS

Our analysis of available scientific data describing the physical and mechanical properties of biological materials and behavior of human lower limb tissues under shock-wave (explosive) impact allowed us to create an original finite-element model of the human lower limb with tuned interaction of its main constituent anatomical structures (skin, muscles, tendons, ligaments, and bone).

The proposed program for calculations and output of the main results, in which an algorithm for processing of the obtained graphical data in image format was implemented to obtain tolerance curves, allowed for a series of numerical tests simulating contact explosion of the developed lower limb model through the protective structure. The results of the calculations yielded the tolerance curves of pressures and accelerations. In addition, animations were created to illustrate the behavior of the anatomical structures of the lower limb under impact. The pressure field propagation within these structures was also visualized.

Virtual testing may be employed in the future to address applied issues. It can be used not only to assess the effectiveness of various design solutions for lower limb protection devices but also to investigate scientific problems related to forensic medical examination and military field surgery. This includes the study of features of blast trauma.

Therefore, the mathematical modeling of the destruction of biomaterials from explosive and shock impact will contribute to a reduction in the time and costs associated with the production of new samples of protective products developed for national defense.

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ADDITIONAL INFORMATION

Authors' contribution. Thereby, all authors made a substantial contribution to the conception of the study, acquisition, analysis, interpretation of data for the work, drafting and revising the article, final approval of the version to be published and agree to be accountable for all aspects of the study.

The contribution of each author. A.V. Denisov — development of the general concept, study design, literature review, data analysis, article writing; S.V. Matveykin — development of the general concept, study design, data analysis; S.V. Zaikin — statistical processing and analysis of data; A.V. Anisin — data analysis; S.N. Vasilyeva — literature review, article writing; E.A. Selivanov — collection and processing of materials, conducting experimental research.

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ДОПОЛНИТЕЛЬНАЯ ИНФОРМАЦИЯ

Вклад авторов. Все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией.

Вклад каждого автора. А.В. Денисов — разработка общей концепции, дизайн исследования, обзор литературы, анализ данных, написание статьи; С.В. Матвейкин — разработка общей концепции, дизайн исследования, анализ данных; С.В. Заикин — статистическая обработка и анализ данных; А.В. Анисин — анализ данных; С.Н. Васильева — обзор литературы, написание статьи; Е.А. Селиванов — сбор и обработка материалов, проведение экспериментального исследования.

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

Источник финансирования. Авторы заявляют об отсутствии внешнего финансирования при проведении исследования.

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