Methodology and Use of Experimental Techniques in Analyzing Wound Dynamics of Penetrating Injuries

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Abstract. This research paper focuses on the experimental studies of the process of high-speed object penetration into human body simulators and the automated registration of physical phenomena parameters related with this process. It highlights the need for a comprehensive understanding of the physical processes involved and the challenges posed by the lack of biomedical information. It emphasizes the importance of studying the volume and characteristics of damage around the wound channel. The paper also proposes a methodology encompassing mathematical modeling, experimental studies using non-biological simulators, and data processing techniques to investigate wound dynamics. An experimental setup with a distributed information and measurement system is presented, enabling the collection and analysis of physical parameters during penetration impacts. The structure of a distributed information-measuring system has been developed that allows recording the parameters of physical processes that occur during the penetration of a high-speed object into the simulator. The issues of receiving and transmitting data from sensors using wireless communication channels are considered. The problem of synchronization of many distributed sensors, which is important for recording the parameters of short-term processes, is analyzed in detail. An example of obtaining data when launching a high-speed object into a simulator using an electric mass accelerator within the framework of the proposed system is given. The research aims to enhance medical practices, and protective equipment design, contributing to improved treatment outcomes and patient care.

Keywords: Distributed monitoring system, Wound dynamics, Human body simulators, Data processing, Wireless communication, Medical diagnostics

1 Intorduction

Penetrating-type wounds caused by injury to the patient by extraneous objects with high kinetic energy during an explosion, gunshot, or other causes [1] have characteristic features in the form of thermal and mechanical effects on the human body. At the same time, the penetrating element usually creates a cavity, which in terms of size significantly exceeds the size of the element.

In addition, there is the formation of local disorders around the wound channel, which can cause pathologies in the human body during the healing process. The listed features from a medical point of view lead to the diagnostic complexity of determining effective surgical and therapeutic actions [2]. In this sense, an in-depth understanding of the physical processes accompanying the process of intervention of a high-speed element in the human body is of crucial importance for successful wound treatment [3].

The problem is complicated by the lack of necessary biomedical information that would allow us to quickly and efficiently classify the patient's condition, determine the features and severity of the clinical case, control and monitor his condition based on the presence of objective biomedical indicators.

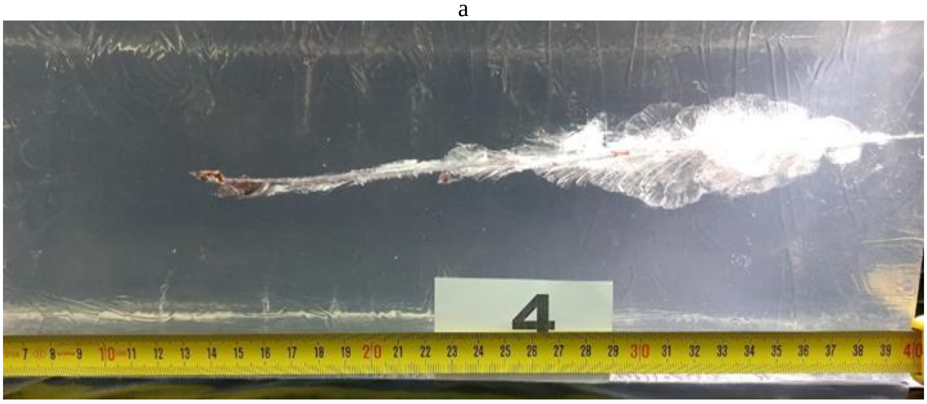
2 Analytical Review of Existing Research Methods

The recent scientific approaches to the study of the mechanisms of deformation of soft tissues due to the penetration of high-speed elements are divided into natural experiments and computer simulations. Experimental studies use various bio-models - laboratory animals. However, due to differences in animal anatomy, physiology, and behavior, as well as ethical standards, the use of such models has no significant prospects. This leads to the need to create and use in experimental tests non-biological full-scale imitation models made of ballistic gelatin or clay [4], or more complex composite models. The results of experimental studies on such simulators are recorded by technical means, for example, pulse X-ray machines or computer tomography [5]. Good visualization can be obtained using ballistic gelatin models, as it has significant optical transparency, which also allows for high-speed video recording of the wound channel formation process [6].

Existing experimental studies [7] mostly focus on the descriptive processing of the geometry of the formed wound channel depending on the input characteristics (mass, speed, angle of attack) of penetrating elements (various models of fragments, bullets, balls, etc.). The obtained experimental results have so far created an understanding of the general processes taking place. Obviously, experimental research has significant limitations due to the need to conduct a large number of experiments, and, as a result, the high cost and difficulties associated with life-size reproduction of the human body. Previous investigations [6, 9] made several attempts to characterize the mechanics of creating wound channels, as well as applying sutures using computer modeling methods. 2D and 3D models with one and several tissue layers, with different wound geometries and loading conditions, were developed. The basis of computer modeling in these studies is the finite element method. It should be noted that such an approach has a wide range of prospects for practical application: the creation of information systems supporting treatment decisions [11], algorithms for conducting operations with the help of medical robots [11-13], designing structures of protective elements, etc. But, despite significant progress in the means of computer modeling of wound ballistics, at present, such models mostly have the character of reproducing natural experiments.

Analyzing the current situation in wound ballistics from experimental and computational points of view shows us the existence of several important issues that are required to develop both approaches. In this paper, we would like to underline the problem that was initially formulated in the study [8]. An experimental assessment was conducted to examine the non-localized damage of ballistic gelatin surrounding the wound channel. The authors analyze the volume of small cracks and damage in the material that formed after penetrating action. In fact, it was established that a high-speed penetrating injury has two components: a wound channel, which is a direct destruction of tissues, as well as a significant zone of non-localized damage that forms around it (Fig. 1 a-b).

a



b

Fig. 1. Wound channel in ballistic gel with a bullet of 5.45×39 mm for different distances: a-b.

The study does not give enough information on the volume of the damaged tissue but gives the evidence of such additional influence. The physical phenomena taking place within the material around a penetrating object in the human body remain insufficiently studied.

From the experimental side, here it is important to study not only the geometry of the wound channel and cracks around it but also to obtain the signals of physical parameters, like acceleration, pressure, or mechanical stresses in different points around the wound. Such information will allow receiving additional supplementary data for medical decisions and also will be super important for the justification of the computer models that surely might be the most used tool for the statistical and multi-variant analysis of different types of wounds. The work [6] should be underlined regarding the mentioned problem.

In that paper, the signal of pressure changes in the simulator material at a certain distance from the wound channel was experimentally determined. Unfortunately, the obtained data are of a rather point-like, local nature and also require further clarification. This issue could become extremely important in the case of non-homogeneous bio-models, i.e. for the models of the human body with different organs inside.

A general analysis of the current state of the problem regarding the study of dynamic processes of deformation and damage of soft tissues during penetrating action due to a gunshot wound shows that these scientific tasks require further research, both in the direction of experimental study of a wide range of physical processes, and in the direction of developing improved mathematical models and computer modeling algorithms. Both directions are connected and require systematic consideration. The potential results of solving the corresponding problem, or even its individual parts, are relevant and will have practical importance for medicine, and could be used in the forensic-pathological study of wounds, as well as in the evaluation and design of protective equipment.

3 General Methodology for Researching the Parameters of Penetrating Wounds

The general methodology of the research of penetrating type injuries is based on the creation of a refined physical model of the process of penetrating damage to human soft tissues, and a computer model corresponding to it, which together will allow the development of a physically based approach and software and information tools for assessing the volume and depth of damage to biological tissues as a result of gunshot wounds. At the same time, it is envisaged to carry out a connected set of experimental and computational studies, which can be presented in the form of three parts:

1. Development of mathematical models and algorithms for computer modeling of processes that occur when an extraneous element is inserted into the human body. In fact, a three-dimensional computational model is created, which is based on the finite element method [14].

2. Experimental studies, which include both the planning of a natural experiment using a physical model and the direct conduct of the experiment. Research is carried out within the framework of conducting ballistic shooting on a non-biological model (simulator) of human soft tissues at a specialized laboratory.

3. Processing and generalization of the results of natural and computational experiments, and adaptation of the obtained results to medical purposes.

Within the framework of the implementation of the last part, the results of research obtained at the previous stages are used. Modeling and experimental data are processed using regression analysis and statistical processing methods. After that, the obtained results are adapted to medical practice, using the methods of medical physics and comparison of the results of medical research and the obtained data.

It's very important here to notice that the computational models that are the main tool for medical analysis, but their reliability requires experimental data for the justification of correctness and accuracy. In this paper, we will focus on the development of the experimental setup that ensures the gaining of information on different physical processes during the penetration impact by extraneous objects.

4 Experimental Stand and Information and Measurement System

An experimental stand was developed, which includes: a simulator - a dense block of ballistic clay, in which a number of sensors of various types can be placed, which are selected according to the parameters of the movement of the penetrating element, taking into account the properties of the material, and an information and measurement system (IMS) for processing signals that coming from sensors.

IMS is a distributed system of information collection and primary processing, based on variable sensor nodes, in which controllers, data input-output modules, and sensors are distributed in space. The characteristic features of this type of IMS are decentralized data processing and the presence of distributed information input-output systems, increased resistance to failures, and a standard and unified database structure [15].

The organization of data transmission from the sensor to the information gathering node (IGN - information gathering node) (Fig. 2), and further to the Main Computer of the system, requires the organization of a communication channel, as well as the provision of reliable power.

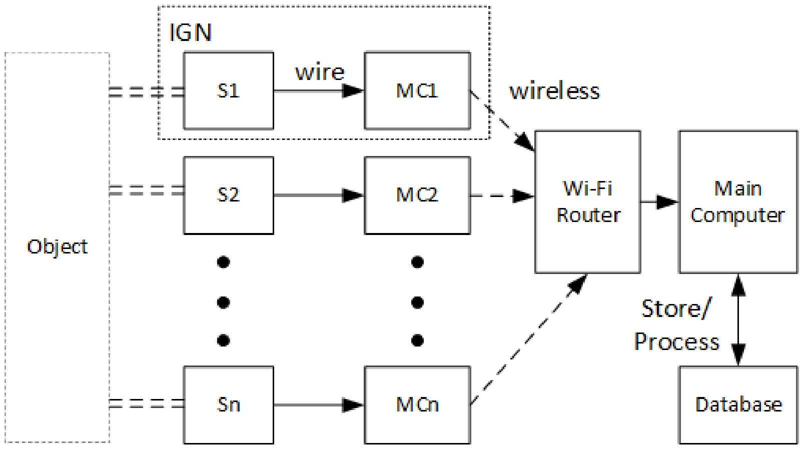


Fig. 2. The structure of the information and measurement system [17]

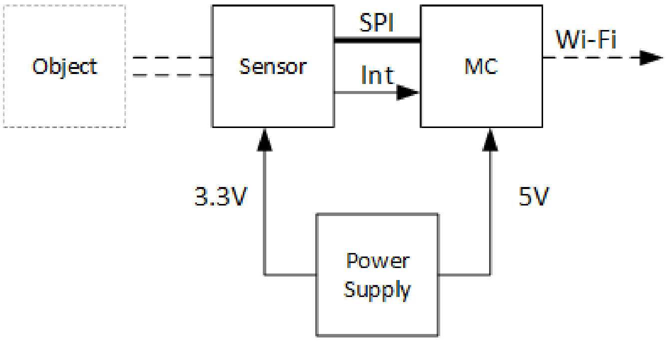
The main limitation is the need to lay wire lines from the equipment, which leads to an increase in the impact of various interferences associated with the process of element intervention in the simulator during the experiment. The nodes (IGN) of the developed system use a wired connection only directly with the sensors (S), but transmit information to the central computer via a wireless communication channel, which ensures stability and reliability even when the system elements are partially damaged during the experiment.

In order to ensure efficient and reliable operation of the system, modern equipment is used, such as low-power sensors and microcontrollers for data processing and transmission. A microcontroller (MC) with a built-in Wi-Fi module is used as a control element for building an IMS node (IGN). In fact, the node (IGN) consists of three parts: the MC, the sensor connected to it, and the power supply circuit.

In the experiment, to obtain data from the simulator, an accelerometer connected to the MC via a high-speed SPI bus was used as a sensor, which made it possible to obtain the maximum possible speed of reading data from the sensor (Fig. 3).

The accelerometer has a physical connection with the simulator's body, and is configured for continuous operation, with buffering of the calculated values in the internal memory. The module also includes 5 and 3.3V stabilized power sources. Thus, one node (IGN) works completely autonomously and has no electrical or mechanical connection with the central computer of the system or with other nodes. The data received from the accelerometer is stored and transmitted via a wireless Wi-Fi communication channel using the UDP protocol.

Fig. 3. Structural diagram of the node (IGN) of the system.



The software developed by IGN works in asynchronous mode. When the internal buffer of the accelerometer is partially filled, a signal is activated, according to which the MC carries out a batch reading of data from the accelerometer memory into the RAM of the MC through the SPI bus on each of the channels. The obtained values are stored in the form of a single packet, which is sent over time (or after the end of the experiment) via a wireless communication channel to the central computer of the system.

But, unlike the systems considered in [15, 16], which work in a long-term mode and monitor processes that take a significant amount of time, IMS for the study of short-term processes, which is precisely the process of the intervention of a high-speed element in the simulator, must have a node synchronization system. This is necessary so that during further research it is possible to compare data from sensors of different nodes in time, and to obtain the state and changes of the process as a whole.

In order to carry out such synchronization, a time source (for example, a local SNTP server) is added to the system, according to which synchronization will be carried out, and before the start of the test, the corresponding packet is sent with a countdown of time *t0*. After that, during the experiment, a time stamp $t = t0 + t1$ is added to each data packet, where t1 is the local time that has passed since the start of the experiment (receiving a synchronization packet with a time count), which is counted by the internal clock (Real Time Counter) of MC.

Another feature of the system is the need to measure the speed of the interfering element and automatically start testing. To measure the speed, a chronograph with the possibility of recording the measured speed value is used, which is located directly in front of the simulator material. The diagram of the stand and IMS, taking into account the changes, is shown in Fig. 4.

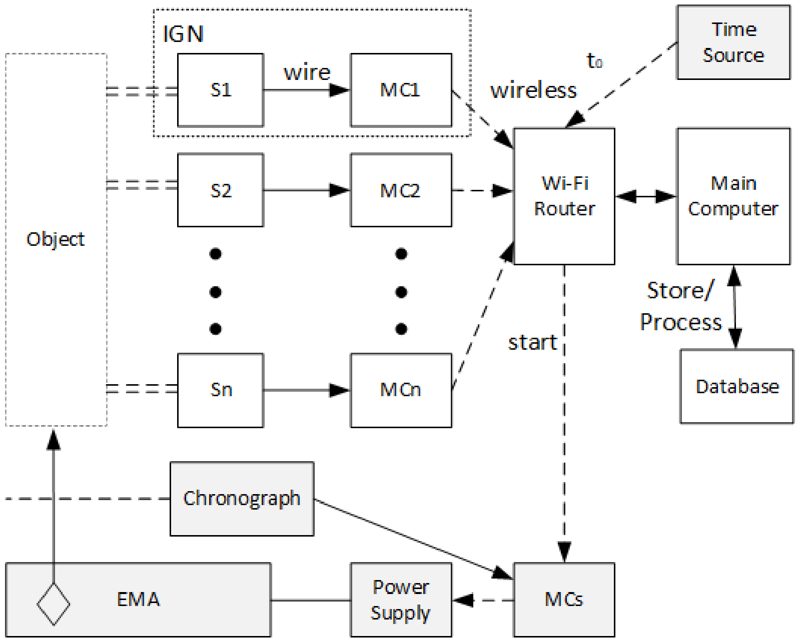


Fig. 4. Structural diagram of the stand and IMS with a synchronization system.

In order to automatically start testing, the Electric Mass Accelerator (EMA) power supply switching scheme is added to the system, which is connected to the IGN, which is also synchronized, but unlike the others, it does not read values from sensors, but controls the power supply of the EMA. This allows to fully automate the process of conducting the experiment (the human operator only presses the appropriate start button), and to record the start time of the experiment in the same frame of reference as the data from the other sensors of the system.

The obtained test responses when the element is hit in the simulator in two directions are shown in Fig. 5.

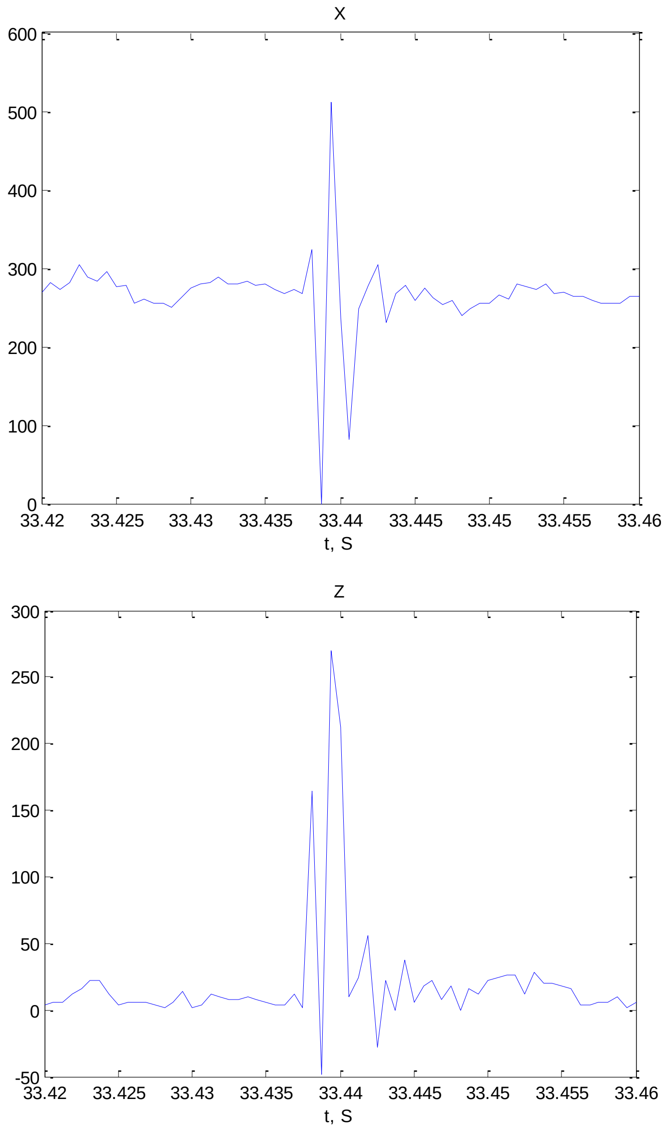


Fig. 5. Responses from the accelerometer during penetration:
x) vertical direction, z) horizontal direction.
The unit on the vertical axis is equal to 0.035g.

To check the suitability of the system for measurement, a test bench was developed that allows investigating of the process of penetration of a cylindrical fragment weighing 1 g into a simulator made of ballistic clay, with fixation of the response from the accelerometer in two directions. The accelerometer was embedded in ballistic plasticine and connected to the IGN, which sent data to the IMS.

The central computer of the system allows to connect any number of IGNs, receives and saves information coming from the nodes, and monitors their status. For this, when the control software of the central computer is started, a local computer network is created, after which the computer goes into standby mode for the IGN connection. When the next module is connected, a separate section with a unique identifier (module identifier, date, time) is created in the database, in which the data packets coming from the module, as well as its state, will be recorded. This section of the database also records information about the frequency of data read from the sensor and the number of data channels transmitted by the node.

The distributed IMS developed within the framework of the project has a number of key advantages, the given algorithm of its functioning has proven its efficiency and high reliability also in research related to the processing of information from technical objects [15-16].

The key features of the proposed system are as follows:

1. If any IGN fails, the system will continue to work, a short-term failure in the operation of a separate module does not lead to a long-term loss of performance, after a certain time the module will be rebooted using a hardware timer and will return to operation;

2. All IGNs are physically separated from each other, and have separation by power source, which also increases the reliability of the system as a whole;

3. Modules of the system are autonomous, work according to a single protocol and are easily replaced, which provides scalability and ensures a low cost of the system;

4. Data transfer within the system is conducted asynchronously, it is not affected by the failure or failure of other IGNs, which ensures high availability.

Conclusions

In conclusion, the study of penetrating wounds caused by high-speed extraneous objects presents significant challenges in the field of medical diagnosis and treatment. The complex nature of these wounds, characterized by thermal and mechanical effects on the human body, as well as the formation of cavities and local disorders, requires a comprehensive understanding of the physical processes involved for effective medical interventions. A refined methodology combining experimental and computational approaches is proposed. As a part of the methodology, the information and measurement system with distributed sensors and wireless communication allows for real-time data collection and analysis is developed. The experimental setup, including the simulator and IMS, provides a means to capture physical parameters such as acceleration and pressure during the penetration impact. The synchronized system enables the comparison and integration of data from different sensors, enhancing the reliability and accuracy of measurements.

The potential results obtained through this methodology can contribute to medical decision-making, forensic-pathological studies of wounds, and the design of protective equipment. Overall, further research is needed to advance the understanding of dynamic processes involved in penetrating wounds. The integration of experimental and computational approaches, supported by sophisticated measurement systems, holds promise for improving medical practices and facilitating the analysis of various types of wounds.

References

1. Myrhorodsky D.S. Gunshot wounds: care tactics and prevention of thrombotic complications. In Specialized medical portal HEALTH-UA.COM. (03.06.2022). (in Ukraine). https://health-ua.com/article/69898-vognepaln-poranennya--taktika-nadannya-dopomogi-taproflaktika-trombotichnih
2. Roy I.V., Borzykh N.O., Katyukova L.D., Borzykh O.V. Modern approaches to the rehabilitation of servicemen with polystructural gunshot wounds of the upper extremity. Klinichna khirurhiia. 86(5), 34-38 (2019). (in Ukraine). https://pdfs.semanticscholar.org/ae94/b6499c110dfe356d67c02e6e3d348da7ebde.pdf
3. Kutovy O.B., Sergeev O.O., Kosulnikov S.O., Sokolov O.V. Experience in the treatment of gunshot injuries of soft tissues and main vessels at the stages of evacuation. Acute and emergency conditions in the practice of a doctor. №5(47) 31–33 (2015). (in Ukraine). https://urgent.com.ua/uploads/issues/2015/5(47)/oins2015_5_31-33_09f07c3879c0178be2f4a77cf06c1fa5.pdf
4. Cronin D. Ballistic gelatin characterization and constitutive modeling. Dynamic Behavior of Materials. In: Springer (1) 51–55 (2011). DOI: 10.1007/978-1-4614-0216-9_7
5. Fountain A.J., Corey A., Malko J.A., Strozier D., Allen J.W. Imaging Appearance of Ballistic Wounds Predicts Bullet Composition: Implications for MRI Safety. American Journal of Roentgenology. vol. 216 (2) 542-551. (February 2021). DOI: 10.2214/AJR.20.23648
6. Yaoke Wen, Cheng Xu, Haosheng Wang, Aijun Chen, R.C. Batra. Impact of steel spheres on ballistic gelatin at moderate velocities. International Journal of Impact Engineering, vol.62, pp. 142-151 (2013). DOI: 10.1016/j.ijimpeng.2013.07.002
7. Pinto A., Russo A., Reginelli A., et al. Gunshot Wounds: Ballistics and Imaging Findings. Seminars in Ultrasound, CT and MRI, vol. 40 (1), 25-35 (2019). ISSN 0887-2171. DOI:10.1053/j.sult.2018.10.018
8. Bolliger S.A. et al. Gunshot energy transfer profile in ballistic gelatine, determined with computed tomography using the total crack length method, Int. J. Legal Med. 124 (6) 613–616 (2010). DOI: 10.1007/s00414-010-0503-z
9. Chanda A., Unnikrishnan V. A Realistic 3D Computational Model of the Closuer of Skin Wound with Interrupted Sutures. Journal of Mechanics in Medicine and Biology, vol. 17 (1), pp. 1-21 (2017). DOI: 10.1142/S0219519417500257
10. Kolisnyk K., Zamiatin, P. Perfection of methods for constructing remote monitoring sys-tems for patients in emergency situations. In proc. 3rd International Conference on Intelli-gent Energy and Power Systems (IEPS), Kharkiv, Ukraine, pp. 371-376 (2018). DOI: 10.1109/IEPS.2018.8559526

11. Sokol E.; Avrunin O.; Kolisnyk K.; Zamiatin P. Using Medical Imaging in Disaster Medicine. In proc. IEEE 4th International Conference on Intelligent Energy and Power. September 7 – 11, 2020. Istanbul, Turkey. pp. 287–290, (2020).
DOI: 10.1109/IEPS51250.2020.9263175
12. Kolisnyk, K. Sokol, Y. Avrunin, O. Kolisnyk, V. Klymenko, V. Applying discriminant analysis to improve telemedicine diagnostics quality. In proc. IEEE EUROCON 19th International Conference on Smart Technologies, Lviv, Ukraine, pp. 280–283 (2021).
DOI: 10.1109/EUROCON52738.2021.9535576
13. Halvorsen F. et al., Virtual reality simulator training equals mechanical robotic training in improving robot-assisted basic suturing skills/ Surg.l Endoscopy, vol. 20, no. 10, pp. 1565–1569, (2006). DOI: 10.1007/s00464-004-9270-6
14. Tsymbalyuk V.I., Lurin I.A., Usenko O.Y., Gumeniuket K.V. al. Results of experimental research of wound ballistics of separate types and calibers of modern bullets. Journal: Medicni perspektivi. 26(4): 4-14 (2021).
DOI: 10.26641/2307-0404.2021.4.247409
15. Zuev A., Ivashko A., Lunin D. Diagnosis methods for mechanisms and machines based on empirical mode decomposition of a vibrosignal and the wilcoxon test. Modern information systems. vol. 6 (4) (ISSN 2522-9052) pp. 51-57 (2022).
DOI: 10.20998/2522-9052.2022.4.07
16. Zuev A., Vodka O. Development of a Distributed Wireless Vibration Measurement and Monitoring System. In proc. IEEE 3rd KhPI Week on Advanced Technology (KhPIWeek), Kharkiv, Ukraine, pp.915-920 (2022).
DOI: 10.1109/KhPIWeek57572.2022.9916375