IS THE THREAT POSED BY AIR WEAPONS UNDERRATED? – ANALYSIS OF THE IMPACT OF A PROJECTILE FIRED FROM AN AIR RIFLE ON A SANDY SUBSTRATE

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Purpose

We live in times when people are overwhelmed by their responsibilities. Parents' time dedicated to children is limited and most of the time some extreme interests of their children are unknown to them (Macuka, Petani & Reić Ercegovac, 2023). Some people are not aware of the dangers that life brings, others manipulate some and some simply have bad intentions.

On the other hand, today's youth, as well as all people from various classes of society, have access to a wide range of side activities and hobbies. Furthermore, the violent video games, as a new digital medium, have attracted the increasing attention of children and adolescents in recent decades, causing numerous harmful consequences, of which aggressive behavior stands out. (Stojanović, 2019) The problem is even more serious if we take into account the data that more than 85% of video games contain violence, while half involve serious acts of violence (Anderson, Bushman & Carnagey, 2006), where violent content is shown more brutally and realistically from year to year. More and more often, very low-quality content and inadequate authorities are fashionable. In this way, people, especially young people, are subject to bad influences, often of a dangerous nature (Ninčić, 2022).

Considering the situation from the last decade of the past century, it is well known that Serbia started the reformation process with a delay comparing to other countries in transition. (Paunović, Dimić & Arsenijević, 2019) The consequences of this delay have a great impact on society development regarding the stability. In terms of stability, we consider economic and political, as well as personal, psycho-

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logical stability of an individual and of the choices one make. These factors are mostly influenced by poverty. The poverty is a direct consequence of an unemployment rate, which is much higher in Serbia then in the European Union (EU) member countries (Paunović et al., 2019). The rules and laws must or should be in accordance with a temporary situation in a country of interest.

A current Law on Arms and Ammunition ("Official Gazette of the RS", no. 20/2015, 10/2019, 20/2020 and 14/2022) allows the free acquisition of air weapons by persons over 18 years of age, and even possession without any report to the competent authorities. With this paper, we want to point out that although less dangerous than firearms, air weapons are also unsafe and should not be available to anyone with the sole requirement of having an ID.

Diabolos and pellets are non-spherical projectiles intended for use in air weapons. An air rifle fires a projectile with compressed air. (Ceylan, McGowan & Stringer, 2002) The air is compressed by bending the tube with a spring or with the help of a gas ampoule. In terms of pressure, pistol diabolo differs from weapon bullets: air rifles function at a pressure of only 50 atmospheres, whereas firearms operate at thousands of atmospheres. Diabolos and balls are frequently constructed to be stable because they can be placed via a smooth tube. Diabolos can be sharp for hunting, rounded and flat for target practice, or both.

This work arose from an idea related to the study of physics, that is, the distribution of the energy of a projectile impact on a certain surface. It is not the first time that experiments used to study pure physics found application in much more important fields in a practical sense. (Ivanković et al., 2018) On the other hand, it is very important to apply a scientific approach to solving any practical problem, especially problems of this importance. By investigating the physics of the impact of the projectile and the distribution of energy, the type of injury that can be caused, as well as the danger of it, can be assumed. A detailed analysis of the image at the moment of impact and after it reveals various parameters that, through further analysis, can be connected to other scientific branches and lead to a complete profile of the threat posed by the use of air weapons.

This kind of investigation is also significant to understand the behavior of granular materials during the effect of different energy distributions.

Methods

The High-Speed Camera Measurements

For the research described in this paper, optical methods for analyzing the impact of a projectile on a surface fired from an air rifle were applied. First, the shooting was monitored by a high-speed camera. A photographic camera Panasonic DMC-FZ-200 with 40 fps and resolution 2560 x 1920 pixels (5 MP) was used. This kind of recording collected a large amount of data summarized in photographs that faithfully show the effect of the projectile on the surface. The advantage of the fast camera is that the moments preceding the impact are clearly distinguished from the moments of the breakthrough and those that follow the breakthrough itself. The digital photos were obtained in the form of a burst record of a series of high-resolution photos at equidistant time intervals.

The Image Analysis Method

Afterwards, the obtained recordings were analyzed using the image analysis program ImageJ. ImageJ is an open source Java-written program created by Wayne Rasband. (Abràmoff, Magalhães & Ram, 2004) This program is used to calculate different dimensions related to the impact of projectiles, which are important for research, based on the known dimensions of the sample boxes. This program was used for some similar investigations in impact analysis (Ravindran, Kumar, Rangasamy & Kumar, 2022), as well for granular matter (Ari & Akbulut, 2022). Some additional analyses were also performed, which support the obtained results.

Fractal Analysis

This type of analysis is a special function also analyzed as a part of imageJ program analysis. It is important for the analysis of complex surfaces, and a more detailed explanation is given in the results section of the paper.

Findings

At the beginning of the research, the analysis of the problem was carried out in terms of gathering information. The fact is that there are quite a few cases of injuries from air weapons. In Serbia, only in the last two years, numerous cases have been recorded. There are well-known cases of abuse when the owner of an air weapon injures a person unknown to him (Blic, 2022, April 7), to injury in the household when the weapon is in the hands of a child (Telegraf, 2022, August 22). Unfortunately, we have also witnessed more serious injuries caused by this type of weapon (021, 2023, May 5).

In studies done at the end of the last century in America, it was established that air weapons could cause serious and fatal injuries. For example, an eye injury very often results in permanent vision loss; in intracranial injuries, 30 percent are fatal. (Bratton, Dowd, Brogan & Hegenbarth, 1997) Although perhaps "not often enough", deaths from air gun injuries are a reality (Bratton et al., 1997; Bakovic, Petrovecki, Strinovic & Mayer, 2014; Guenther, Chen, Wozniak & Leshikar, 2020). Are percentages an appropriate benchmark for leaving one's life to chance? Are the statistics that talk about rare cases enough to pass a law that potentially threatens the safety of people, and above all more sensitive groups such as children?

Air Weapons vs. Firearms

The authors of this paper have thoroughly investigated the effects of air rifle pellets. In terms of physics, the authors have shown the effects of projectiles for air weapons. Unlike firearms manufacturers, who describe the best effects of firearms, airgun manufacturers only show the possibility of injury. If the analysis of the complexity of the construction of firearms and air weapons is taken into consideration, one can easily come to the conclusion that the technology of making air weapons is simple compared to the construction of firearms. On the other hand, projectiles for air weapons are commercially available and readily available to all users.

Furthermore, firearms manufacturers provide details how to use firearms, and airgun manufacturers probably take into account the simplicity of firearms and very briefly state the same. The same is the case with safety measures, as well as measures for safe handling and storage. The storage of firearms

requires special conditions, which is not the case with air weapons. Shooting positions are prescribed for shooting with firearms (standing, lying down, kneeling, etc.), while this is not the case for shooting with air weapons. Air rifle shooting gives its user the freedom to shoot from a position that suits them best. As a very important fact, it should be pointed out that there is no precisely defined instruction for the training of persons who carry out shooting from aerial weapons, except in the aerial ranges where the training of competitors takes place. One of the reasons for injuries resulting from improper air gun handling is an unsafe shooting stance. Shooting positions are prescribed for the purposes of shooting training and competitions in air ranges. Based on all of the above, we are of the opinion that people who shoot from air weapons are in a large number of cases unprepared for the realization of shooting from air weapons. Injuries caused by improper handling of air weapons leave lasting consequences. The author's desire was to show in this paper the effects of air weapons that result in permanent or serious injuries.

Safety and Security

The following safety measures are taken for shooting in air ranges (Ranđelović, 2016; Kokelj & Ranđelović, 2016; Kokelj & Ranđelović, 2018):

- shooting can only be performed by fully trained personnel;
- air weapons from which are fired must be inspected before and after use;
- the use of defective and untested air weapons is prohibited;
- before performing any actions, the weapon is unloaded and checked to see if it is empty;
- during filling, emptying and removal of blockages, movement in front of the pipe is not allowed;
- mandatory inspection of ammunition before use;
- ammunition is protected from unfavorable atmospheric influences (moisture, direct sunlight, low and high temperatures).

Shooting protection is the process of taking concrete measures in a given situation on the ground. Measures protection is undertaken by all authorities at the training ground in order to create conditions during preparation and execution shootings that do not lead to injuries and that create conditions for full physical and psychological safety of the executor of the shooting.

The following protective measures are taken for preparation and execution:

- the barrel of the weapon is always turned in the direction of shooting towards the area of effect;
- all personnel at the test site must comply with prescribed safety and security measures;
- ammunition is inspected and issued correct and undamaged for the purpose of shooting, other measures are taken to protect personnel during the preparation and execution of shooting. The authors suggest that any person who plans to use firearms must undergo adequate training in sports associations that deal with shooting, and after obtaining a certificate that those persons are allowed to purchase and use air weapons.

Experimental Analysis

Further research was based on experimental testing. After the experimental shooting, filmed with a high-speed camera, the recorded frames on the target were analyzed.

The photographic camera Panasonic DMC-FZ200 was used in experiments. The camera has Leica DC Vario-Elmarit zoom objective with fixed aperture F2.8 across entire zoom range from 4.5 mm till 108 mm. The resolution of the camera is 4256 x 2832 pixels (12.1 MP). When camera is used for high-speed recording resolution is 2560 x 1920 pixels (5 MP) and speed is 40 fps.

The impacts on the ground-fine sand during shooting from two different angles of 0° and 15° were observed. The density of fine sand is 1700 kg/m^3. An air rifle Steyer LG 110, 4,5 mm, with a projectile speed of about 100 m/s was used. The distance from which the test was performed was 20m. Sand was used as a representative of granular materials that have a huge military application. (Simović Pavlović, Nestorović, Janković, Radulović & Pagnacco, 2023) It was precisely the impact of the projectile on this substrate that was examined in terms of fundamental physics. (Janković et al., 2023) The projectile had a conical tip. Since the mass of the projectile for air weapons is less than 2 g (in this particular case of the order of 1 g), and the speed is approximately 100 m/s, using the classic formula for kinetic energy, it can be calculated that the applied kinetic energy does not exceed 10 J. It is obvious that the kinetic energy of an air rifle projectile impact is hundreds of times smaller than that of firearms and real ammunition, but the sensitivity of the human body, that is, organs, is essential in this representation. (Myre & Black, 1987) It was observed that despite the fact that the applied kinetic energy is less than 10 J, penetration is evident as well as the power of deformation, i.e. destruction of the substrate. All important parameters for the experiment are given in the Table 1.

Table 1 *Important Parameters for the Experiment*

Shooting angles		**Granular matter**	**Sand density**	**Air rifle type**	**Projectile type**	**Projectile speed**	**Shooting distance**
0°	*15°*	*Fine sand*	*1700 kg/m^3*	*Steyer LG 110 4.5mm*	*Conical tip*	*100 m/s*	*20m*

The discussion on the dimensions of penetration and traces in the sand is redundant, bearing in mind that the sample that represented the target had dimensions that exceeded the depth of penetration. No less important, this data also speaks in favor of the high energy of the impact of a prjectile on the observed surface. What is taken as the main result for the analysis in this paper is the deformation of the surface. By observing the recordings respectively, a very destructive effect on the substrate is observed (*Figure 1*). Shooting images at 0 degree angle were taken for analysis.

On the frame showing the moment of penetration, a hole can be seen at the point of penetration of the projectile with a diameter of 11.18 mm and a sand scattering wave with a diameter of approximately 147 mm. These initial results are a parameter for comparing further obtained results. Already by themselves, these dimensions testify to the not so small penetration power of air ammunition grains. Further analysis is determined in the direction of tracking the diameter of the projectile penetration hole as a function of time after impact. Although in some conditions of a different, solid substrate, we would not witness this expansion of the penetration hole, this analysis was done with the aim of showing that there is a large energy that is transferred to the rest of the substrate through which the projectile penetrates.

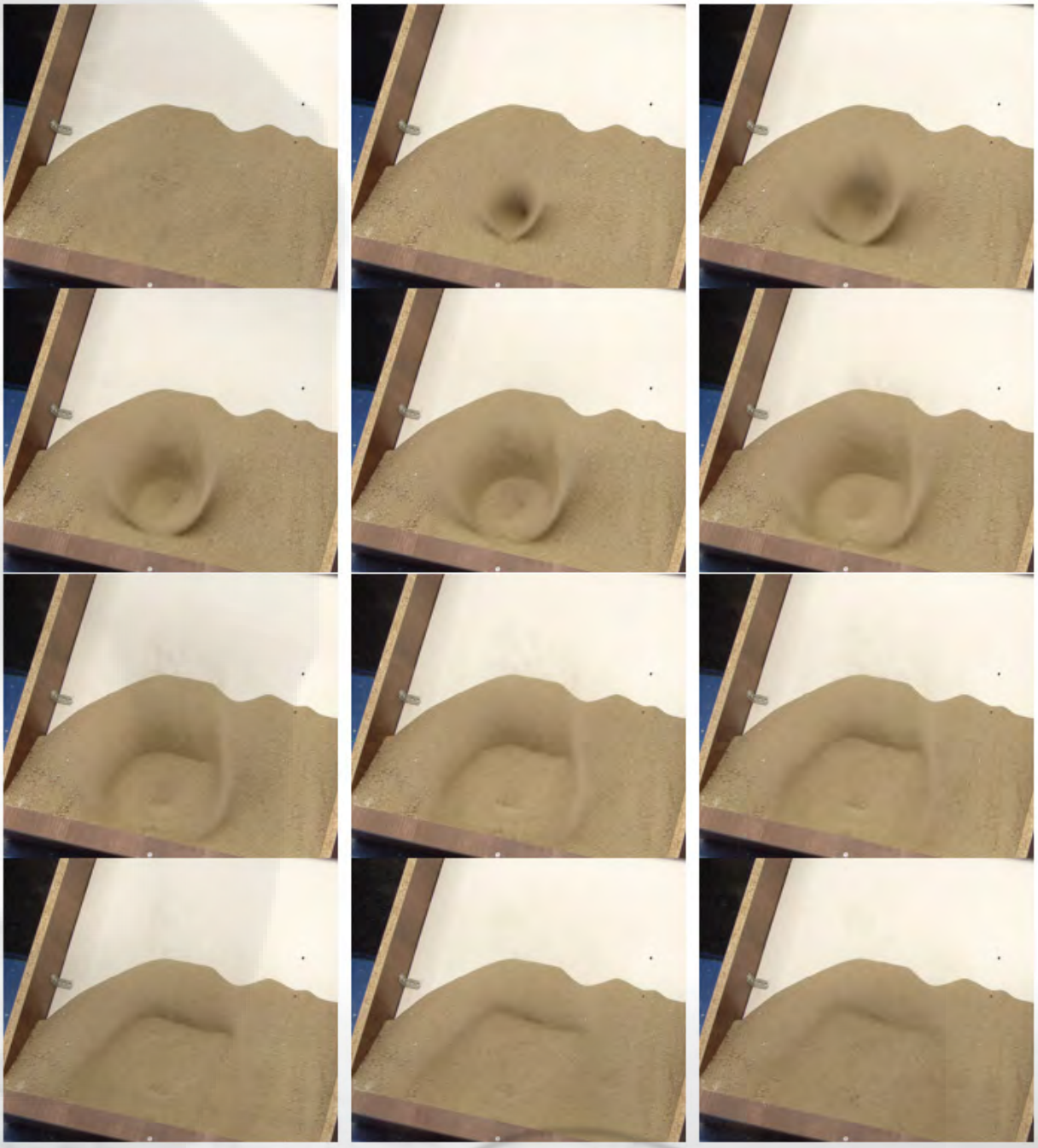

Figure 1 *Panel Image Representing Different Consecutive Frames Due to the Penetration of the Projectile into the Substrate and a Few Moments After the Penetration*

For further analysis, a representative image was taken that represents the moment after the projectile hit the ground.

The following diagram (*Figure 2*) is obtained by measuring the diameter of the crater created at the moment of penetration, and then its subsequent expansion. The graphic shows the maximum measured diameter values at a given moment. Of course, it is important to note that due to the granular substrate, the depth of the crater decreases with the increase in crater diameter.

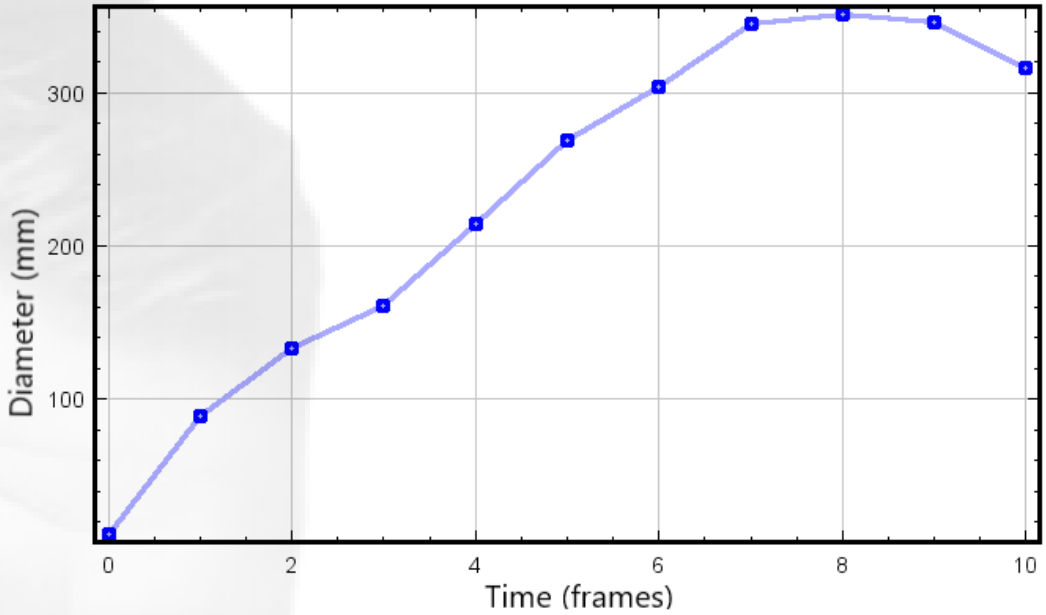

Figure 2 *Diagram of penetration hole diameter dependence on the time. The diameter is the largest possible measured diameter of the hole formed due to penetration, and later expansion of the initial hole due to energy transfer. The time is presented in the recorded frames after the penetration*

Further analysis revealed an increase in the scattering diameter (*Figure 3*), which at one point shows a large jump. The scattering diameter does not show a decrease but the scattering just disappears at one point so that part is not shown in the diagram. Again, these are secondary results that contribute to the data on the transfer of energy to the environment of the substrate, that is, that the impact of projectile penetration is not only related to the exact location of penetration.

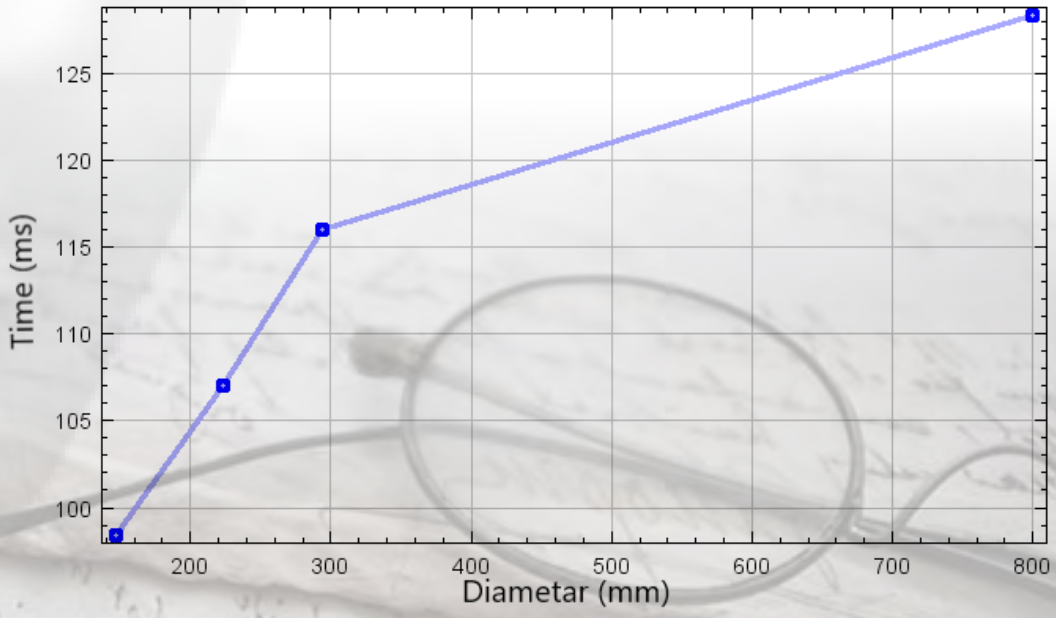

Figure 3 *Diagram of the sand scattering in a function of a time. The diameter of sand scattering was measured at different moments of penetration and after it*

The fractal dimension of the granular surface was measured at different moments of recording the substrate (*Figure 4*). Fractal analysis measures the so-called surface complexity. This complexity refers to the change in detail in the scaling function. It is measured in values from 1 (line complexity) to 2 (square area complexity). High complexity values of approximately 1.9 were definitely measured for the granular surface. The fractal dimension measured on the recording of the very moment of projectile penetration is 1.8712. In the image of one of the following frames, this dimension is 1.9056, while in the last analyzed image it is calculated as 1.9219. What was also observed is that the complexity is impaired at the moment of penetration of the projectile, and then its values increase again after the subsidence of the substrate. Here, the homogeneity of the structure is actually disturbed due to penetration and transferred energy. The panel shows three images with corresponding diagrams of the fractal dimension.

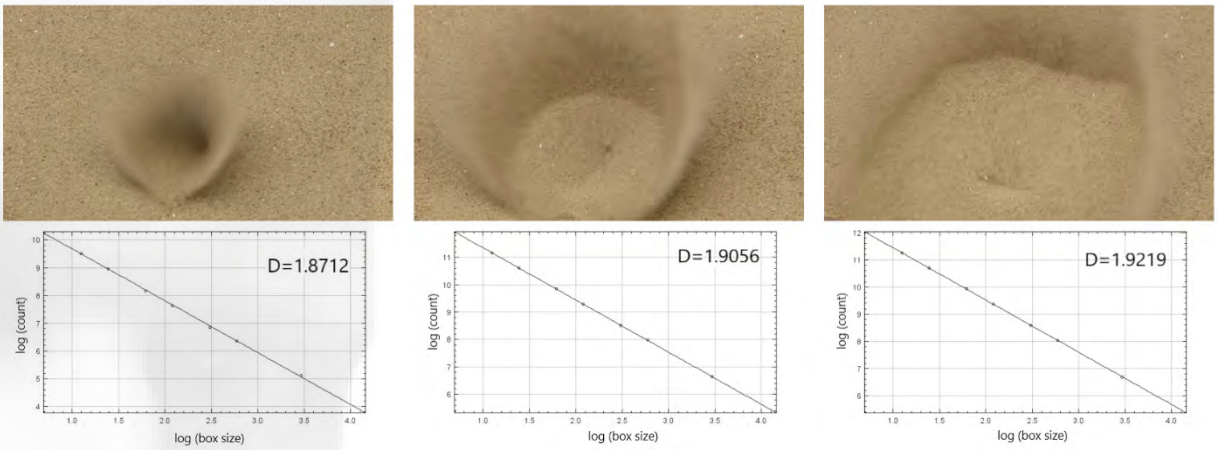

Figure 4 *Panel image representing three frames due to the penetration of the projectile into the substrate and after (top row), with corresponding diagrams showing the fractal dimension for each of them (bottom row). The fractal dimension is similar for all images and is approximately 1.9.*

Regarding the presented results, it is important to mention that standard deviation is calculated and there is no significant dispersion.

The presented results testify to the transfer of energy to the surrounding substrate due to the penetration of the projectile. The analysis of the surface itself defines its complexity. The complex granular structure proved to be convenient for observing the deformation of the obstacle due to the action of air weapons projectiles. The tests within the framework of this research were performed on a granular substrate. The next step is to examine the impact on some biological materials, that is, artificial systems made of biological materials (Simović Pavlović, Bokić, Vasiljević & Kolarić, 2022) and analyze the effect in that case. It is also planned to observe the deformation of the substrate in more detail using the triple rec method (Simović Pavlović et al., 2022). In this way, the plan is to monitor and analyze the formation of certain patterns (Pagnacco et al., 2023) due to the impact of projectiles. However, the obtained results open new possibilities for connection of different scientific fields (material science, optics, and non-linear dynamics) with military science.

Originality/Value

In accordance with current events in the world, especially in Serbia, it is very important to take into account all the dangers that different types of weapons bring. The presented research is based on a real simulation of events and analyzed using a scientific approach. The results lead to the conclusion that it would be very useful to consider changes to certain laws related to air weapons. It would also potentially be convenient to introduce a certain system for the selection and possibility of distribution of such weapons in the civilian domain. The systems based on the Decision expert (DEX) method (Jokić, Delibašić & Randjelović, 2021) would probably be appropriate in this case.

It is necessary to take into account many more circumstances during the analysis, which is crucial for making some decisions that may put safety in question. Danger lurks at every moment and it is not enough to make a simple comparison, in the sense of which weapon is less dangerous, but to exclude every possibility of potential danger.

Such a conjugation of scientific fields is very interesting and once again proved that the study of physical phenomena has a direct impact on the world that surrounds us, in this case on our everyday safety.

Acknowledgements

All authors acknowledge the support of the Office of Naval Research Global through the Research Grant N62902-22-1-2024.

References

Abramoff, M. D., Magalhaes, P. J. & Ram, S. J. (2004). Image processing with ImageJ. *Biophotonics international*, 11(7), 36-42.

Anderson, C. A., Bushman, B. J. & Carnagey, N. L. (2006). The effect of video game violence on physiological desensitization to real-life violence. *Journal of Experimental Social Psychology*, 43(3), 489-496.

Ari, A. & Akbulut, S. (2022). Effect of particle size and shape on shear strength of sand-rubber granule mixtures. *Granular Matter*, 24(4), 126.

Bakovic, M., Petrovecki, V., Strinovic, D. & Mayer, D. (2014). Shot through the heart - firepower and potential lethality of air weapons. *Journal of forensic sciences*, 59(6), 1658-1661.

Beta (2023, May 05). Uhapšen mladić u Leskovcu koji je ranio druga iz vazdušne puške. *021*, Belgrade. Accessed on August 26, 2023. https://www.021.rs/story/Info/Srbija/339796/Uhapsen-mladic-u-Leskovcu-koji-je-ranio-druga-iz-vazdusne-puske.html

Bogosav, B. (2022, April 07). DIJABOLA JOJ JE OSTALA U GLAVI! Ranjavanje iz vazdušne puške sve češća pojava: Evo ko sme da poseduje ovo oružje i kakve kazne prete onima koji ga imaju, a NISU TO PRIJAVILI POLICIJI. *Blic*, Belgrade. Accessed on August 26, 2023. https://www.blic.rs/vesti/hronika/dijabola-joj-je-ostala-u-glavi-ranjavanje-iz-vazdusne-puske-sve-cesca-pojava-evo-ko/d9k4fw0

Bratton, S. L., Dowd, M. D., Brogan, T. V. & Hegenbarth, M. A. (1997). Serious and fatal air gun injuries: more than meet the eye. *Pediatrics*, 100(4), 609-12.

Ceylan, H., McGowan, A. & Stringer, M. D. (2002). Air weapon injuries: a serious and persistent problem. *Archives of Disease in Childhood*, 86, 234-235.

Guenther, T., Chen, S., Wozniak, C. & Leshikat D. (2020). Fatal cardiac injury sustained from an air gun: Case report with review of the literature. *Int J Surg Case Rep.*, 70, 133-136.

Ivanković, N. D., Rajić, D. S., Karkalić, R. M., Janković, D., Radovanović, Ž., Stupar, S. Lj. & Janković, D. D. (2018). Influence of the aerosol flow and exposure time on the structural changes in the filtering half masks material. *Journal of the Serbian Chemical Society*, 83(4), 463-471.

Janković, D., Simović Pavlović, M., Pagnacco, M., Nikolić, Z., Bokić, B., Kolarić, B., Tomić, Lj. & Vasiljević, D. (2023). Revealing Self-Organization of Granular Matter: From Fundamental Physics to Military Technology Applications. Belgian Physical Society - General Scientific Meeting, May 2023, Namur. Abstract book (page 67), Namur.

Jokić, Ž., Delibašić, B. & Randjelović, A. (2021). Selection of Rifle Caliber in Rearming Process of the Serbian Army. *Management: Journal Of Sustainable Business And Management Solutions In Emerging Economies*.

Kokelj, T. & Ranđelović, A. (2016). Zbirka rešenih zadataka iz pravila gađanja naoružanjem pešadije. *Medija centar "Odbrana" Beograd*, ISBN 978-86-335-0502-4.

Kokelj, T. & Ranđelović, A. (2018). Teorija gađanja. *GLOSEC Globalna bezbednost,* Beograd, COBISS. SR-ID 26921012.

Law on Arms and Ammunition, Official Gazette of the RS, No. 20/2015, 10/2019, 20/2020 and 14/2022.

Macuka, I., Petani, R. & Reić Ercegovac, I. (2023). U razgovoru sa roditeljima: Kvalitativna analiza izazova roditelja djece različite dobi. *Društveno istraživanje: časopis za opća društvena pitanja*, 32(2), 347-365.

Myre, L. E. & BLACK, R. E. (1987). Serious air gun injuries in children: update of injury statistics and presentation of five cases. *Pediatric emergency care*, *3*(3), 168-170.

Ninčić, Ž. (2022). Vršnjačko nasilje kao oblik socijalne destrukcije. *Kultura Polisa*, 19(2), 201-222.

Pagnacco, M. C., Simović Pavlović, M., Grujić, D. Ž., Vasiljević, D. M., Bokić, B., Mouchet, S., Verbiest, T., Caudano, Y. & Kolarić, B. (2023). Stochastic Phase Transition Dynamics in Nonequilibrium System: Holographic Study. *J. Phys. Chem.C.*

Paunović, S. S., Dimić, M. S. & Arsenijević, O. M. (2019). Analiza društveno-ekonomskih kretanja u Srbiji u uslovima krize. *Baština*, 48, 153-170.

Ranđelović, A. (2016). Gađanje streljačkim naoružanjem. *Medija centar "Odbrana" Beograd*, ISBN 978-86-335-0544-4.

Ravindran, P., Kumar, K. M., Rangasamy, S. & Kumar, K. R. V. (2022). Experimental and numerical investigation of ballistic impact analysis on kevlar reinforced polymer composites and shape memory alloy sheet reinforced kevlar epoxy polymer composites. *46*(4), 470-475.

Simović Pavlović, M., Bokić, B., Vasiljević, D. & Kolarić, B. (2022). Bioinspired NEMS - Prospective of Collaboration with Nature. *Appl. Sci.*, 12, 905.

Simović Pavlović, M., Nestorović, K., Janković, D., Radulović, A. & Pagnacco, M. (2023). Different Butterfly Wing Structures as an Inspiration for Military Applications. 9th International Congress of the Serbian Society of Mechanics. July 2023, Vrnjačka Banja, Serbia.

Simović Pavlović, M., Pagnacco, M., Grujić, D., Bokić, B., Vasiljević, D., Mouchet, S., Verbiest, T. & Kolarić, B. (2022). Uncovering Hidden Dynamics of Natural Photonic Structures using Holographic Imaging. *J. Vis. Exp.*, e63676.

Stojanović, M. (2019). Efekti igranja nasilnih video-igrica na decu i mlade. *Specijalna edukacija i rehabilitacija*, 18(2), 199-220.

Vučić, J. & Lisinac, N. (2022, August 22). Dečak (10) pogodio rođenog brata iz vazdušne puške u Aleksandrovcu. *Telegraf*, Belgrade. Accessed on August 26, 2023. https://www.telegraf.rs/vesti/srbija/3544732-decak-10-pogodio-rodjenog-brata-iz-vazdusne-puske-u-aleksandrovcu