Experimental Mechanics (2023) 63:415–427
https://doi.org/10.1007/s11340-022-00923-w

RESEARCH PAPER

Lethality Evaluation of Japanese Tanegashima and Korean Seungja-Chongtong via Projectile Penetration and Mass Drop Experiments

H.M. Lee[1] · D.-Y. Kim[1] · T.H. Kim[1] · J.H. Kim[1] · S.-G. Sim[1] · J. Moon[2] · H. Kim[3] · Y. Choi[2] · G.H. Yoon[1]

Received: 22 June 2022 / Accepted: 25 October 2022 / Published online: 1 December 2022

Abstract

Background The Japanese invasion of the Korean peninsula lasted from 1592 to 1598, where Japan had the upper hand in infantry warfare based on superior firepower. The representative portable personal firepower weapons were the Japanese Tanegashima (matchlock musket) and the Korean Seungja-Chongtong (hand cannon).

Objective To provide an engineering aspect and explanation for the firepower difference in infantry warfare, this work aims to evaluate the lethality of the two weapons using projectile penetration and mass drop experiments.

Methods The projectile penetration experiment was conducted by firing the weapons at ballistic gelatin blocks and capturing the images of the projectiles using a high-speed camera. The mass drop experiment was conducted by dropping impactors on wooden specimens to obtain data on impact force values. Analyses were conducted using the captured projectile images and impact force data to compare the diameters of temporary cavities formed in gelatin blocks, shooting ranges, and projectile energies of the two weapons. Additionally, finite element method (FEM)-based simulations using ANSYS Workbench Explicit Dynamics were performed to further investigate the degree of injuries caused by the two weapons.

Results From the experiments, it was found that the Tanegashima is more lethal compared to the Seungja-Chongtong in terms of wounding potential, shooting range, and energy value. Simulation revealed that more energy is transferred from the projectile to impacted object when Tanegashima is utilized.

Conclusions The results allow the lethality evaluation of the main weapons used by the two countries. They also demonstrate the engineering aspect of Japanese dominance in infantry warfare at the time of the invasion.

Keywords Tanegashima · Seungja-Chongtong · Ballistic gelatin · Projectile penetration experiment · Mass drop experiment

Introduction

This study evaluates the lethality of the main weapons used during the Japanese invasion of Korea in 1592. The Japanese Tanegashima (matchlock musket) and the Korean Seungja-Chongtong (hand cannon) were investigated using projectile penetration and mass drop experiments. The experiments were performed using ballistic gelatin blocks and wooden specimens. Images of projectiles penetrating gelatin blocks and impact force data were obtained. Based on the obtained images and data, analyses were

✉ G.H. Yoon
gilho.yoon@gmail.com

H.M. Lee
hoominlee95@gmail.com

D.-Y. Kim
roykim1011@gmail.com

T.H. Kim
woongpapa4@gmail.com

J.H. Kim
junhwan128@gmail.com

S.-G. Sim
sim950214@gmail.com

J. Moon
themoon@kbs.co.kr

H. Kim
stella6300@naver.com

Y. Choi
distantbom@gmail.com

1 School of Mechanical Engineering, Hanyang University, Seoul 04763, South Korea

2 Korea Broadcasting System, Seoul 07334, South Korea

3 Korea TV and Radio Writers Association, Seoul 07236, South Korea

performed to compare the temporary cavity diameters, shooting ranges, and projectile energies of the two weapons. Additionally, finite element method (FEM)-based simulations were conducted to analyze the energy transfer from projectiles to gelatin blocks. Comparisons were made to determine the more lethal weapon of the two when utilized in infantry warfare.

The Japanese invasion of the Korean peninsula occurred during the time of the Joseon dynasty and lasted from 1592 to 1598; it caused significant damage to Korea in terms of the economy and population [1, 2]. The Japanese had initial success on land, taking over the Korean capital, Hanyang (now known as Seoul), in just 20 days after the invasion. The Japanese forces were halted after Korea managed to rearrange troops and form allied forces with the Chinese Ming dynasty. However, the allied forces were unable to dislodge the Japanese from various occupied fortresses and entrenched positions. Both sides became locked in a long military stalemate, and the war continued for several years. It ended in 1598, when the Japanese forces in Korea were ordered to withdraw owing to various reasons, such as the death of their leader, Toyotomi Hideyoshi, limited progress made on land, and continued disruption of supply lines by the Korean Navy.

The war mainly consisted of naval and infantry warfare. In naval warfare, Korea was able to prevent Japanese aggression using battleships and large cannons suitable for naval battles. However, in infantry warfare, it was difficult for Korea to reverse the unfavorable situation because of inferior firepower. Various weapons were mobilized in infantry battles, and the representative portable personal firepower weapons of the two countries were the Japanese Tanegashima and the Korean Seungja-Chongtong. The Tanegashima was a matchlock musket, suitable for firing a powerful single shot at enemies from a distance, whereas the Seungja-Chongtong was a hand cannon that fired multiple projectiles simultaneously, like the modern-day shotgun, making it more suitable for close-range battles. Both firearms took approximately one minute for reloading. Thus, to our best knowledge, the firearms were mainly used in long-distance combats due to their long reloading time [3]; that is one of the limitations of the present study. The Japanese forces took advantage of their firearms and caused concern in the Korean army from the start of the war [4, 5]. Figure 1 illustrates the infantry battle during the invasion, and the Japanese forces armed with the Tanegashima are circled in red. The goal of this paper is to compare the lethality of the two weapons and provide an engineering aspect to the superiority of Japanese infantry warfare.

Relevant studies on muskets and cannons have been conducted by comparing the velocity and energy values of projectiles [6–9]. Studies have also been conducted to investigate the projectile positions of muskets, by considering the velocity variation and drag coefficient [10]. Based on the projectile analyses, various studies have been conducted with gelatin blocks to evaluate the effect of projectiles on wound formation in humans. Studies have been conducted to evaluate the similarity in physical properties of gelatin blocks and human tissue using gunpowder weapons [11, 12]. Gelatin blocks have been used for various ballistics research, such as investigations of the effectiveness of infantry armor systems against musket projectiles used in the British Civil War [13]; the experimental study on the effects of head angle and projectile diameter on penetration tendency [14]; and the comparison of projectile velocity and weight of muskets used in the American Civil War and American-Spanish War [15]. Analyses of human tissue damage caused by projectiles have also been conducted by evaluating the temporary cavities formed in gelatin blocks [16, 17].

Apart from projectile experiments using gelatin blocks, mass drop experiments have been conducted to evaluate the projectile energy and velocity quantitatively or approximately. Through mass drop experiments, the energy absorption capacity of composites [18] and aluminum foam [19] has been analyzed. Based on the results of previous research, this study aims to conduct projectile penetration and mass drop experiments to evaluate the lethality of the Tanegashima and

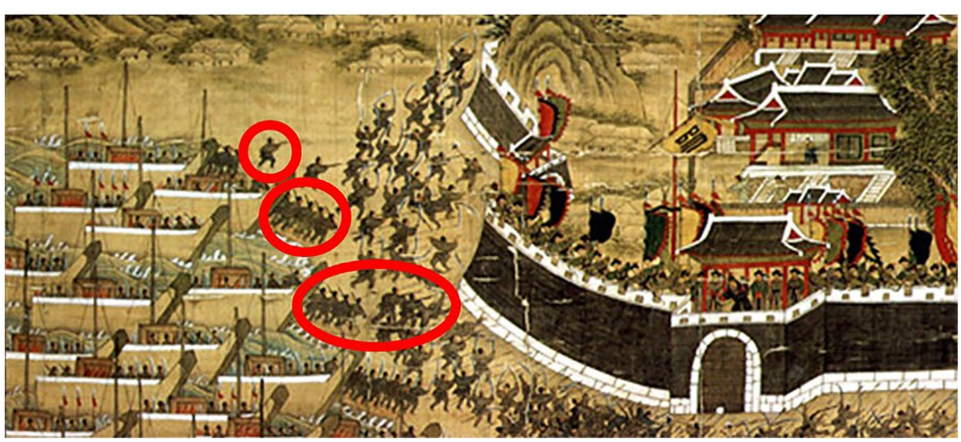


Fig. 1 Busanjin sunjeoldo [Patriotic Martyrs at the Battle of Busanjin Fortress] (Courtesy by Cultural Heritage Administration via www.heritage.go.kr/heri/cul/imgHeritage.do?ccimId=1613362&ccbaKdcd=12&ccbaAsno=03910000&ccbaCtcd=11) Japanese forces with the Tanegashima are circled in red

Seungja-Chongtong. The two weapons are compared based on the diameters of temporary cavities formed in gelatin blocks, shooting ranges, and projectile energies.

The present research aims to evaluate the lethality of the Tanegashima and Seungja-Chongtong. For experimental studies, a Tanegashima replica was brought in from Japan by the War Memorial of Korea in accordance with administrative procedures. A Seungja-Chongtong replica was restored based on the relic managed by the Jinju National Museum. After preparing the replicas, experiments were performed to evaluate their lethality. Projectile penetration experiments were conducted by firing the weapons at ballistic gelatin blocks and capturing images of the projectiles using a high-speed camera. Unlike the Tanegashima, the Seungja-Chongtong fires multiple projectiles simultaneously like a modern-day shotgun. This resulted in the dispersion of the Seungja-Chongtong projectiles with only a single projectile hitting the gelatin block each trial; all the other simultaneously fired projectiles hit the wooden backboard that was installed behind the block during the experiment. Thus, difficulties existed in capturing images of all the projectiles due to their dispersion. A mass drop experiment was conducted using the wooden backboard to supplement the data of all simultaneously fired Seungja-Chongtong projectiles. The board was cut into pieces to be used as specimens. An impactor was dropped on the specimens to obtain impact force data. After the experimental procedures, analyses were conducted using the captured projectile images and impact force data to compare the diameters of temporary cavities formed in gelatin blocks, shooting ranges, and projectile energies.

To further investigate the degree of injuries caused by the two weapons, FEM-based simulation using the ANSYS Workbench Explicit Dynamics was conducted to analyze the energy transferred from the projectiles fired by the two weapons to the gelatin blocks. This was done by finding the kinetic energy and internal energy values of the gelatin blocks using FEM simulation. Comparisons of temporary cavity formations were made during the process to validate the consistency of the experiment and simulation results. Analyses and comparisons were made to determine which weapon was more lethal when utilized in infantry warfare based on the temporary cavity sizes, shooting ranges, projectile energies, and gelatin energies.

The remainder of this paper is organized as follows. "Experimental Method" section provides some background on the preparation of weapons and the experimental methods. "Data Processing" section presents the data processing of experimental results and mathematical theories. "Results and Discussions" section presents the analyses of the experimental and simulation results to evaluate the lethality of the Tanegashima and Seungja-Chongtong. Conclusions and directions for future research are discussed in "Conclusions" section.

Experimental Method

Two experimental studies were conducted to investigate the lethality of the Tanegashima and Seungja-Chongtong weapons. A projectile penetration experiment was conducted to observe the temporary cavities formed in gelatin blocks by the two weapons and evaluate the shooting ranges and projectile energies by analyzing the images captured by a high-speed camera. During the projectile penetration experiment, some projectiles hit a wooden backboard, which was installed behind the gelatin block. In this process, some projectiles penetrated only the thin wooden panel, while the others penetrated both the wooden panel and the thick wood block. Additionally, a mass drop experiment was conducted on the wooden specimens to evaluate the projectile energies of the two weapons by analyzing the impact force required by the projectiles to penetrate the wooden panels and wooden blocks used in the projectile penetration experiment.

Preparation of Weapons

The Tanegashima and Seungja-Chongtong were used in the 16th century; the original weapons used during the war could not be utilized due to safety reasons and difficulties in preparation. Therefore, replicas were used throughout the experimental procedures. The replicas were prepared with the support of the War Memorial of Korea and Jinju National Museum, as shown in Fig. 2(a). In the case of Tanegashima, the replica was originally kept and managed in Japan. The War Memorial of Korea brought in the replica in compliance with the procedures for firearms and managed it during the experimental period. In the case of Seungja-Chongtong, the replica was restored based on the Seungja-Chongtong relic (Relic No.13816/6-1) managed by the Jinju National Museum. The replica was manufactured using a computerized tomography (CT) scan and material analysis to have identical geometry, size, and material composition as the relic. The gunpowder was prepared by an explosive specialist, and identical gunpowder was used for both weapons.

Projectile Penetration Experiment

A projectile penetration experiment was conducted to observe the temporary cavities formed in the gelatin blocks and evaluate the shooting ranges and projectile energies of the Tanegashima and Seungja-Chongtong. The experiment was conducted at an indoor testing facility managed by the Agency for Defense Development. The weapons were fired at gelatin blocks (Clear Ballistics 20% ballistic gelatin blocks) developed for ballistic testing of human tissue from a distance of 10 m. For precise control and minimization of recoil, a firearm lock device was positioned on a wooden desk and used when firing the weapons. The gelatin block used in the experiment had a length,

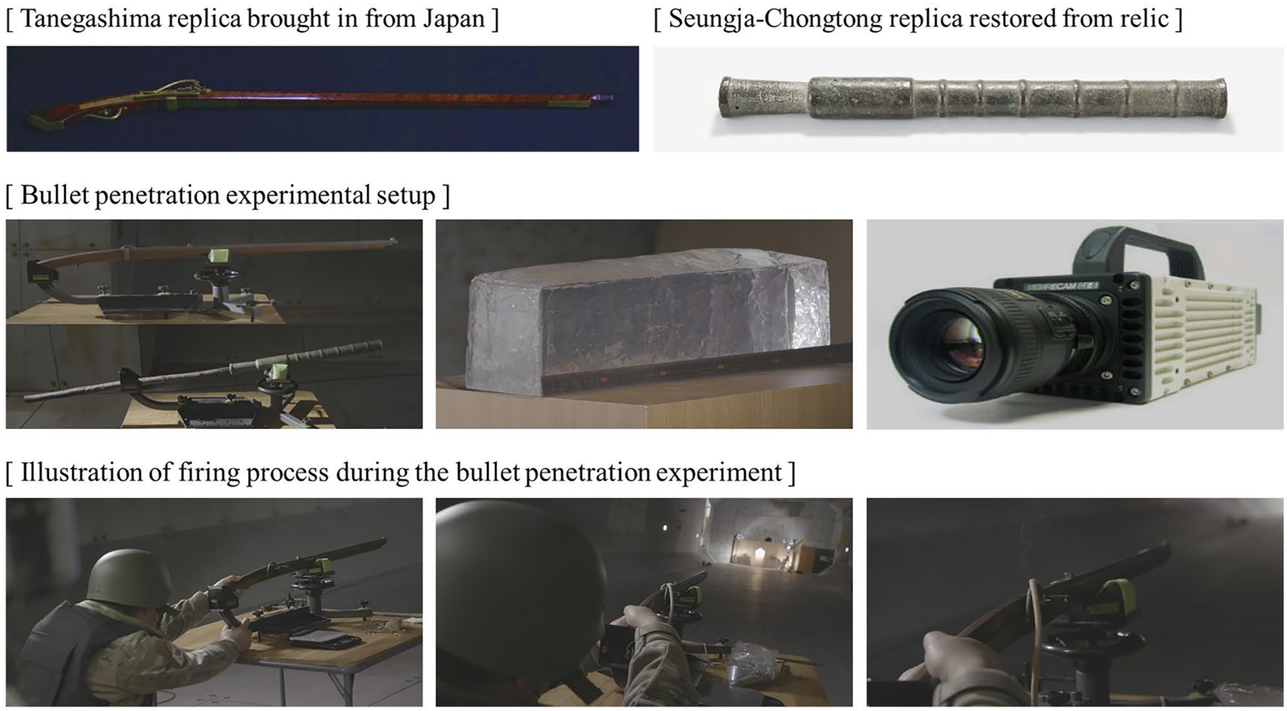


Fig. 2 (**a**) Preparation of Tanegashima and Seungja-Chongtong (Seungja-chongtong image courtesy by Jinju National Museum), (**b**) weapons, ballistic gelatin block, and high speed-camera used in the projectile penetration experiment, and (**c**) illustration of weapon firing during the projectile penetration experiment by Suk Young Lee of Kim's Guns

width, and height of 50 cm, 15 cm, and 15 cm, respectively. The gelatin block was placed on a wooden box at the same height as the wooden desk, to ensure that the projectile trajectories remained parallel to the ground. To prevent misfired projectiles from causing damage to the facility, a backboard composed of a wood panel and wood blocks was installed behind the gelatin block. The experimental setup and the firing process are shown in Fig. 2(b) and (c). For each shot, the Tanegashima used 3.0 g of gunpowder and fired a single spherical lead projectile with a mass of 7.70 g and a diameter of 11.0 mm. Meanwhile, the Seungja-Chongtong used 9.0 g of identical gunpowder and fired nine spherical steel projectiles simultaneously, with each projectile having a mass of 2.05 g and a diameter of 8.0 mm. The resultant images of projectiles penetrating the gelatin block and forming temporary cavities were captured using a high-speed camera (Memrecam GX-8F) that was installed beside the gelatin block. The geometries of the temporary cavities formed in gelatin blocks, shooting ranges, and projectile energies of both weapons were observed and analyzed based on the images captured by the high-speed camera.

Mass Drop Experiment

A mass drop experiment was conducted to supplement the data of all simultaneously fired Seungja-Chongtong projectiles and evaluate the total projectile energies per shot. In the projectile penetration experiment, only one of the nine Seungja-Chongtong projectiles hit the gelatin block. Thus, the data for only one Seungja-Chongtong projectile could be obtained. However, this projectile does not represent all the nine simultaneously fired Seungja-Chongtong projectiles. The other Seungja-Chongtong projectiles and one misfired Tanegashima projectile hit the wooden backboard, which comprised a wooden panel and thick supporting blocks, as shown in Fig. 3(a). The misfired Tanegashima lead projectile penetrated both the panel and the block, while all the Seungja-Chongtong steel projectiles managed to penetrate only the wooden panel. After conducting the projectile penetration experiment, the wooden backboard was cut into pieces of dimensions of 15 cm × 15 cm each, to be used as specimens for the mass drop experiment.

The mass drop experiment was conducted using an impactor tester and a data acquisition device (NI USB 6351). The experimental setup and the tester are shown in Fig. 3(b). The wooden specimens were fixed using a round hydraulic clamp. Round-ended impactors were connected to the latch block for the experiment. To obtain accurate results, impactors of the same diameters as the projectiles were used. Impactors with diameters of 11.0 mm and 8.0 mm were used in the experiments for the Tanegashima case and Seungja-Chongtong case, respectively. The total mass of the impactor and latch block was approximately 2 kg in all cases. To evaluate the penetration energy, several trials were conducted by dropping

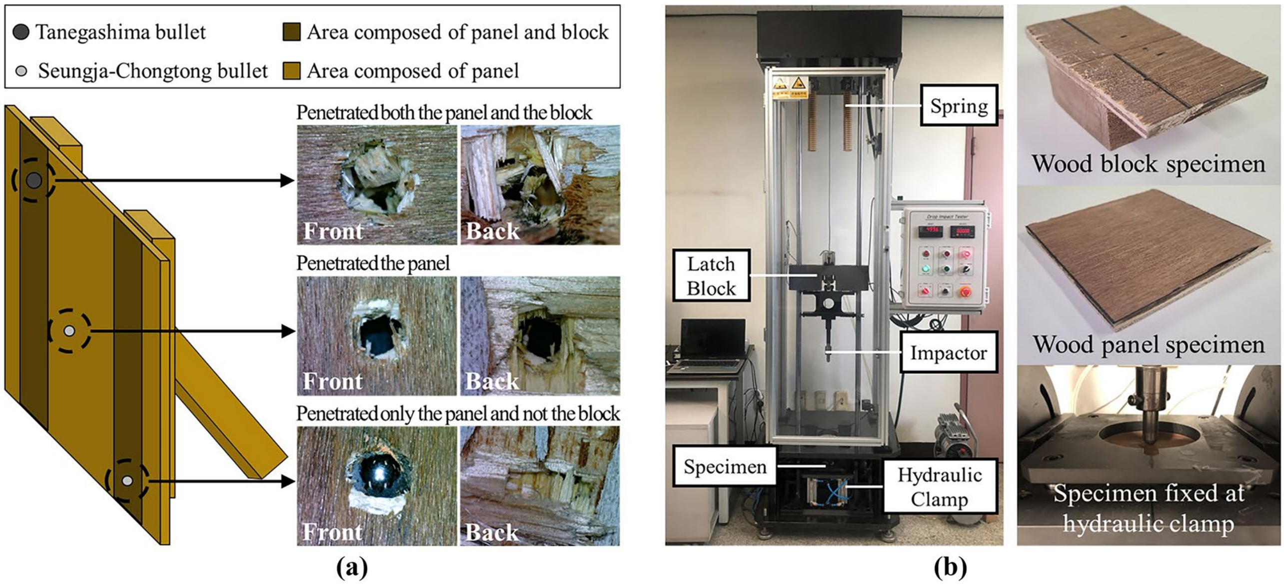


Fig. 3 (**a**) The penetration of misfired projectiles in the wooden backboard during the projectile penetration experiment and (**b**) mass drop experiment setup

the impactor from various heights. The spring connected at the top of the impactor tester was used to add supplemental impact force when the specimens did not penetrate, even when the impactor was released from the maximum height. The sensor attached to the latch block and the ISG software connected to the impactor tester were used to measure and record the magnitudes of the impact forces. The energies of the Tanegashima and Seungja-Chongtong projectiles were evaluated based on the measured impact forces required to penetrate the wooden backboard.

Data Processing

To compare the lethality of the two weapons, the following analyses were conducted: shooting range, projectile energy, and penetration energy analyses using the data collected from the projectile penetration and mass drop experiments. Note that the observation of temporary cavities formed in ballistic gelatin blocks during the projectile penetration experiment requires the analysis of the videos of the ballistic experiments with the high-speed camera.

Shooting Range and Projectile Energy Analyses Using Projectile Tracking

In the projectile penetration experiment, images of the projectiles moving towards and penetrating the gelatin block were captured by a high-speed camera. In the data processing procedure, the projectile positions at each frame were tracked using the Tracker program to mark and record the projectile positions in the reference x-y coordinate system as shown in Fig. 4. At the post-processing step, projectile velocity and acceleration values at each frame were calculated by the Tracker program based on the projectile positions. The post-processed data allowed the evaluation of the shooting range and projectile energy values of the Tanegashima and Seungja-Chongtong.

The shooting range can be evaluated using mathematical formulations considering the velocity, mass, cross-sectional area, and drag coefficient of the projectile of interest. The velocity equation of a projectile can be formulated as follows:

$$v_p = v_0 e^{-\frac{ct_p}{m_p}} \tag{1}$$

where v_p, v_0, and m_p are the velocity, initial velocity, and mass of projectile, respectively. The damping coefficient and the time at velocity v_p are denoted by c and t_p, respectively. The damping coefficient c is calculated as follows:

$$c = \rho v_p A C_D \tag{2}$$

where A and C_D are the cross-sectional area and drag coefficient of the projectile, respectively. The density of air is denoted by ρ. Integrating equation (1) with respect to time gives the displacement equation of the projectile. Considering that the projectile displacement is zero when $t_p = 0$, the displacement equation can be formulated as follows:

Fig. 4 Projectile position tracking using the captured images and Tracker software

$$x_p = -\frac{m_p v_0}{c}(e^{-\frac{ct_p}{m_p}} - 1) \tag{3}$$

where x_p is the distance traveled by the projectile. To consider the effects of gravity, the following equation is considered for the change in height of the projectile trajectory:

$$y_p = h - \frac{1}{2}g{t_p}^2 \tag{4}$$

where y_p, h and g are the projectile height, initial projectile height, and gravitational acceleration, respectively. Using equations (3) and (4), the change in projectile height can be formulated using the distance travelled as follows:

$$y_p = h - \frac{1}{2}g(-\frac{m_p}{c}\ln(1 - \frac{cx_p}{mv_0}))^2 \tag{5}$$

The formula allows the evaluation of shooting ranges when gravitational effect is considered and the firearms are shot horizontally. The shooting ranges can be assessed by finding the corresponding x_p values when each y_p value becomes zero.

The projectile energy refers to the kinetic energy of the projectile and can be evaluated using the mathematical formula considering the mass and velocity values of the projectile. As the projectiles do not rotate, the projectile energy can be approximated as follows:

$$K = \frac{1}{2}m_p{v_p}^2 \tag{6}$$

where K is the kinetic energy of the projectile. By considering the projectile mass and the average projectile velocity before contact with the gelatin block, the energy values of the Tanegashima and Seungja-Chongtong projectiles before impact with the gelatin block can be evaluated using equation (6).

Penetration Energy Analysis Using Impact Force

In the mass drop experiment, the impact force values required for the penetration of wood specimens were obtained by the force sensor and the ISG software. The impact force values can be used to evaluate penetration energy values using mathematical formulae considering mass drop accelerated by gravity and relevant studies have been conducted in [20]. Thus, the impact force values obtained in the experiment were processed to calculate the penetration energy values required for the penetration of wood specimens. Note that the normalizations of projectile and impactor diameters are not included as they have identical values for both Tanegashima and Seungja-Chongtong cases. For a simple one-dimensional system, the governing equation of the impactor is as follows:

$$m_i g - F_i = m_i\frac{dv}{dt}, \ \frac{dv}{dt} = g - \frac{F_i}{m_i} \tag{7}$$

where m_i and F_i are the impactor mass and the average external force applied by the impactor, respectively. The acceleration due to gravity, velocity, and time are denoted by g, v, and t, respectively. Integrating equation (7) gives the velocity at any time.

$$v = v_i + gt - \frac{1}{m_i}\int_0^t F_i dt \tag{8}$$

$$x = v_i t + \frac{gt^2}{2} - \frac{1}{m_i}\int_0^t \left(\int_0^t F_i dt\right)dt \tag{9}$$

The displacement obtained by integration is denoted by x in equations (8) and (9). The initial velocity, denoted as v_i, indicates the velocity during the initial contact between the impactor and the specimen. The penetration energy, U, during collision can be obtained from the following equation.

$$U = \int F_i dx \tag{10}$$

$$U = v_i\int_0^t F_i dt + g\int_0^t tF_i dt - \frac{1}{2m_i}\left(\int_0^t F_i dt\right)^2 \tag{11}$$

The penetration energy values required by the projectiles to penetrate wooden blocks and wooden panels can be used to evaluate the energy values of the Tanegashima and Seungja-Chongtong projectiles, respectively.

Results and Discussions

Experimental data such as temporary cavities in gelatin blocks, approximate shooting range, and projectile energy of the two weapons were analyzed and are presented in this section. In addition, finite element simulations were carried out to analyze the energy transferred to gelatin blocks by the projectiles. The analyses of the experimental data and simulations were conducted to quantitatively compare and evaluate the lethality of the two weapons.

Comparison of Temporary Cavity Formations

A temporary cavity is defined as the radial stretching of soft tissue surrounding the permanent cavity [21]. It is one of the critical mechanisms of firearm wounds or injuries as its formation increases the wounding potential. The formation of a temporary cavity may result in more extensive bone fractures [22], larger wound sizes [23], and an increased probability of fragmented ribs being pushed into the lungs [16]. This indicates that the formation of temporary cavities with larger diameters is more lethal to the human body. In other words, the lethality of a weapon can be evaluated by comparing the size of the temporary cavity formed by the respective weapon. Transparent ballistic gelatin blocks are often used to mimic soft tissues to observe the formation of temporary cavities. Therefore, the research evaluates the wounding potential of the two weapons by observing the temporary cavities formed inside ballistic gelatin blocks and comparing their sizes.

The images of the temporary cavities captured by the high-speed camera are shown in Fig. 5. From the images, it can be observed that a lead projectile fired by the Tanegashima penetrates a gelatin block completely, while a steel projectile fired by the Seungja-Chongtong does not fully penetrate and gets lodged in the gelatin block. In the case of the Tanegashima projectile, it makes contact with the gelatin block at 0.4 ms. As the kinetic energy of the projectile is transferred to the block, the diameter of the temporary cavity is increased gradually and maximized to 6.75 cm at 2.1 ms. The projectile penetrates further and leaves the block at 3.3 ms. The cavity continues to change in geometry due to the presence of a pressure wave and is stabilized to become a permanent cavity at approximately 30 ms. In the case of the Seungja-Chongtong projectile, the projectile makes contact with the block at 0.5 ms. The temporary cavity is maximized at 1.2 ms with a diameter of 2.67 cm. The projectile is unable to penetrate the block and reaches the maximum penetration depth of 16.6 cm at 2.8 ms. Surprisingly, the projectile bounces back due to the elastic behavior of the gelatin block, as observed at 4.5 ms and 10 ms. The motion of the projectile is stabilized at approximately 15 ms, and the projectile reaches its final penetration depth of 8.3 cm. All times mentioned above are obtained from the image frames. Considering that the average male chest breadth is approximately 30 cm [24], the temporary cavity diameter values of 6.75 cm and 2.67 cm suggest that both weapons would have been lethal to the human body. Nevertheless, the Tanegashima shows greater lethality than the Seungja-Chongtong; in terms of the diameter, the Tanegashima managed to create a cavity that was 2.5 times larger than that created by the Seungja-Chongtong. Thus, in terms of the wounding potential in soft tissue, it can be inferred that the Tanegashima would have been much more lethal compared to the Seungja-Chongtong.

Comparison of Shooting Range

The shooting range was evaluated to compare the utility of the Tanegashima and Seungja-Chongtong in infantry warfare. In infantry warfare, the shooting range is an important aspect that determines casualties in warfare. Equations (1), (2), and (5) were used to evaluate the shooting ranges of the Tanegashima and Seungja-Chongtong. For the calculation of the shooting range, some of the required variables were experimental values, and the rest were theoretical values. The velocities, masses, and cross-sectional areas of the projectiles were obtained from the projectile penetration experiment, while for the air density and drag coefficient, theoretical

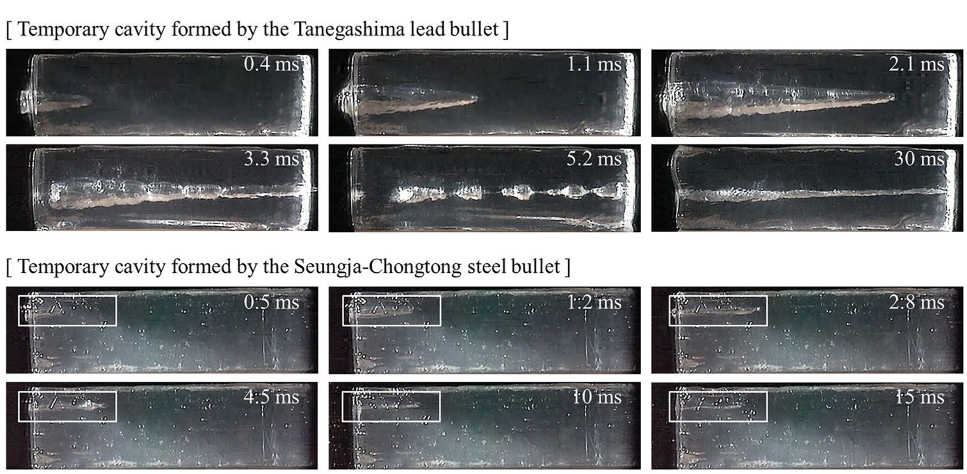


Fig. 5 Temporary cavity observation and analysis using the images captured by the high speed camera

values of 1.2 kg/m^3 and 0.074, respectively, were used. The air density value was taken at standard atmospheric temperature, and the approximated drag coefficient of spheres in ballistic measurements with a high Reynolds number [25, 26] was used for the drag coefficient value. It was assumed that the initial heights of the projectiles were 1.5 m, based on the shoulder height for a typical human body [27].

The calculated trajectories of Tanegashima and Seungja-Chongtong are shown in Fig. 6. Note that identical theoretical air density and drag coefficient values were used for both weapons to calculate the trajectories. The velocity, mass, and cross-sectional area of the lead projectile fired by the Tanegashima were 275.55 m/s, 7.70 g, and 380.13 mm^2, respectively. Based on the experimental values, the shooting range of the Tanegashima was calculated to be approximately 116.0 m. The velocity, mass, and cross-sectional area of the steel projectile fired by the Seungja-Chongtong were 117.87 m/s, 2.05 g, and 201.06 mm^2, respectively. The shooting range of Seungja-Chongtong was calculated to be approximately 54.9 m. Thus, the shooting range of Tanegashima is greater than that of Seungja-Chongtong by 2.11 times. In terms of shooting range, it can be inferred that the Tanegashima would have caused a greater number of casualties. With the Tanegashima, the Japanese army had the advantage that it could inflict greater damage on the opponent while staying out of the enemy's shooting range.

Comparison of Projectile Energy

The projectile energy values were analyzed to compare the lethality of the Tanegashima and Seungja-Chongtong when shot from an identical distance. In the field of ballistics, projectile energy is one of the measures for the degree of injury; more deformation of human tissue is induced by shock waves of greater magnitudes when impacted by projectiles with higher energies. Note that the degree of injury can differ with different projectile diameters and geometries even with identical projectile energies. The comparison of projectile energies was carried out as both firearms used spherical projectiles with the similar geometries. The projectile energies were evaluated using two methods. The first method used projectile velocity values obtained from the projectile penetration experiment and applied to equation (6). The projectile velocities of the entire penetration process were used to calculate the projectile energy. This included the projectile velocities before the gelatin block impact and after the gelatin block penetration. To compensate for the measurement error caused by the spread of the Seungja-Chongtong projectiles during the projectile penetration experiment, a second method involving the impact force values obtained from the mass drop experiment was applied using equations (10) and (11).

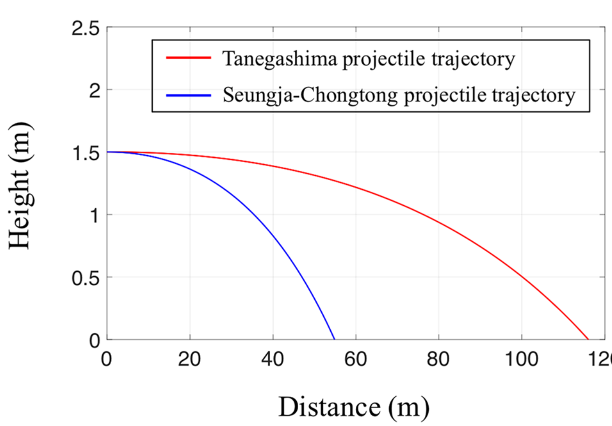
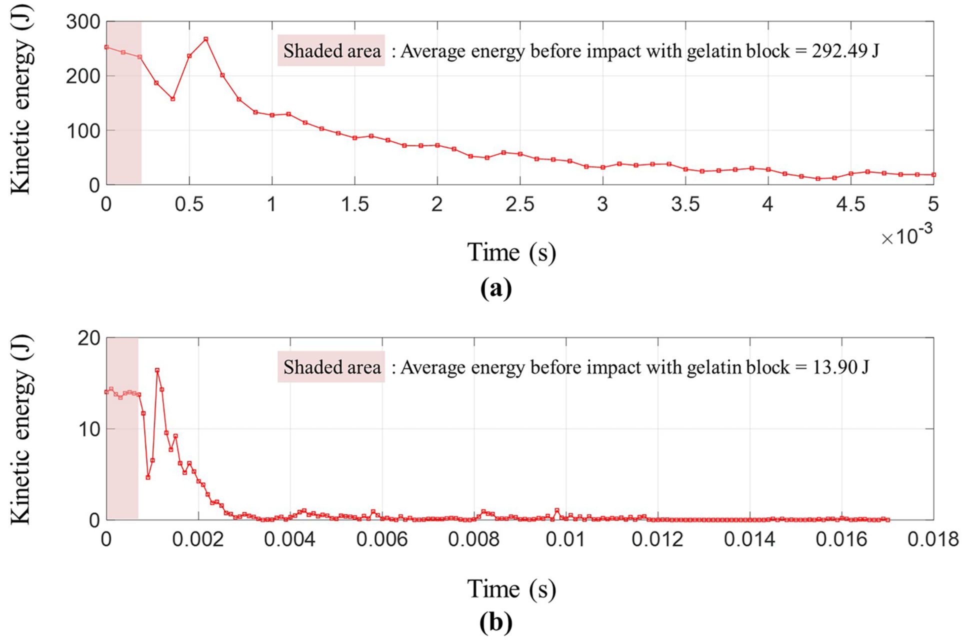


Fig. 6 Comparison of the Tanegashima and Seungja-Chongtong shooting ranges (Note that the graphs were obtained from a single experiment due to the limitation of the experiment environment)

The results of projectile energies evaluated using the first method are shown in Fig. 7. The shaded area of the graph indicates the time frame before projectile impact with the gelatin block. As mentioned in "Comparison of Shooting Range" section, the average velocity before impact and mass of the lead projectile fired by the Tanegashima were 275.55 m/s and 7.70 g, respectively. Based on the average velocity value, the kinetic energy value of the lead projectile before impact was calculated to be 292.49 J. The average velocity before impact and mass of the steel projectile fired by the Seungja-Chongtong were 117.87 m/s and 2.05 g, respectively. The calculated kinetic energy of the steel projectile before impact was 13.90 J. In terms of kinetic energy per projectile, it can be evaluated that the Tanegashima shows greater lethality compared to the Seungja-Chongtong, as the energy of the projectile fired by the Tanegashima was greater than that fired by the Seungja-Chongtong by approximately 21 times. In terms of the damage caused by a single projectile shot from an identical distance, it can be inferred from the results that the Tanegashima would have been more lethal than the Seungja-Chongtong. Note that the evaluated Seungja-Chongtong kinetic energy value is not the average value of all simultaneously fired projectiles but the energy value of the single projectile that hit the gelatin block during the projectile penetration experiment.

The results of impact forces and projectile energies evaluated using the mass drop method are shown in Fig. 8 and Table 1. A total of five specimens were considered to obtain the impact force required for penetration. It can be seen from the results that the wooden specimen composed of panel and block required an average impact force of 6.25 kN for penetration, while the specimen composed solely of wooden panel required an average impact force of 1.08 kN. Using the impact forces obtained from the experiment, the energy values required for penetration of each specimen were calculated, as shown in Table 1. The results show that the penetration energy

Fig. 7 Change in kinetic energy during penetration of gelatin: (**a**) Lead projectile fired by the Tanegashima and (**b**) steel projectile fired by the Seungja-Chongtong



of the wooden specimen composed of a panel and block is 105.67 J, and that of the wooden specimen composed solely of a panel is 13.44 J. Thus, the minimum energy of the Tanegashima projectile is 105.67 J, while the minimum energy of the Seungja-Chongtong projectile is 13.44 J. Note that the mass drop experiment was conducted to compensate for the measurement error in the projectile penetration experiment in the case of the Seungja-Chongtong projectiles; similar projectile energy values derived from the two methods indicate that the kinetic energy of each Seungja-Chongtong projectile is similar to that of the single projectile that hit the gelatin block during the projectile penetration experiment. As the Seungja-Chongtong fired 9 projectiles simultaneously, the total projectile energy per shot adds up to approximately 120.96 J. In terms of the total kinetic energy per shot, it can be evaluated that the Tanegashima has greater lethality, as the energies of the projectiles fired by the Tanegashima were approximately 2.4 times greater than those fired by the Seungja-Chongtong. It can be inferred from the results that even if all the projectiles fired by the Seungja-Chongtong hit the target, the Tanegashima would have been more lethal when shot from an identical distance.

Comparison of Energy Transfer Using Finite Element Method Based Simulations

FEM-based simulations were conducted to compare the energy values transferred to gelatin blocks by the projectiles. Simulations were conducted as the transferred energy could not be evaluated from the experimental results. ANSYS Workbench Explicit Dynamics was used to perform terminal ballistics, which studies the penetration of a targeted simulating body by a projectile. In terminal ballistics simulations, the Mie–Gruneisen equation of state

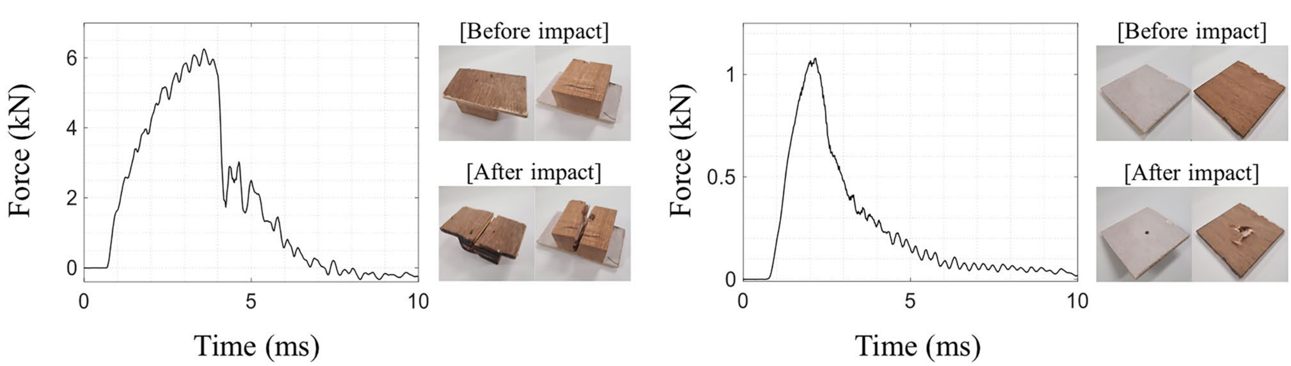


Fig. 8 Mass drop experiment results on wooden specimens: Thick specimen (block+panel) and thin specimen (panel)

Table 1 Impact energy comparison of wooden specimens

Thick Specimen (Panel + Block)			
Thickness	Peak Force	Impact Time	Impact Energy
12 mm	6251 N	6.69 ms	105.67 J
Thin Specimen (Panel)			
Thickness	Peak Force	Impact Time	Impact Energy
1 mm	1080 N	9.57 ms	13.44 J

(EOS), Johnson–Cook failure model, and the visco-elastic material model were employed to model the gelatin blocks [17]. The Mie–Gruneisen EOS is used to calculate the internal pressure when a solid material deforms at high speed and behaves like a gas or fluid. The Johnson–Cook failure model is used to specify the hardening behavior of materials experiencing high strain rates under dynamic impact. The visco-elastic model is used for elastic or viscous materials showing altered stress and strain curves under altered loading conditions. The material properties of the EOS, failure model, and material model adopted for the gelatin block are presented in Table 2. The modeled gelatin block has a length and width of 50 cm and 15 cm, respectively. The lead projectile and steel projectiles were modeled using the standard material properties of lead and steel listed in Table 3. The modeled spherical lead and steel projectiles have diameters of 11 mm and 8 mm, respectively. The lead and steel projectiles were positioned so that they were in contact with the gelatin block and were set to have initial velocities of 275 m/s and 120 m/s, respectively.

To ensure consistency between the experiments and simulations, we first checked for the formation of temporary cavities. Figure 9(a) shows the comparison between the experimental and simulated results of temporary cavities formed by the Tanegashima. The captured time frames of 0.4 ms and 2.1 ms represent the time of initial impact as the projectile hits the gelatin block and the time when the temporary cavity size is maximized, respectively. A time frame of 1.1 ms is randomly selected between the two time frames. It can be observed from the results that the geometries of the temporary cavities obtained from the simulation are similar to those obtained from the projectile penetration experiment. The diameters of the cavities obtained from the simulation agree well with the experimental values, with errors of 1.10%, 0.967%, and 1.04%, for the time frames of 0.4 ms, 1.1 ms, and 2.1 ms, respectively.

Figure 9(b) shows the comparison between experimental and simulated results of temporary cavities formed by the Seungja-Chongtong. The captured time frame of 1.4 ms represents the time when the temporary cavity size is maximized, and the other two time frames are randomly selected. Note that the time frame of initial impact could not be selected as the temporary cavity could not be observed at the respective time frame; the low projectile energy led to the absence of shock waves strong enough to create temporary cavities during the impact of the projectile with the gelatin block. It can be observed that the geometries of the temporary cavities obtained from the simulation greatly resemble those obtained from the experiment. Moreover,

Table 2 Material properties of the 20%ballistic gelatin block

Viscoelasticity						
Density, ρ	Instantaneous Shear Modulus, G_0		Shear Modulus, G_∞		Viscoelastic Decay Constant, β	
$1030\ kg \cdot m^{-3}$	40000 Pa		30000 Pa		$0.00087\ s^{-1}$	
Mie-Gruneisen Equation of State						
Gruneisen Coefficient	C_1		S_1		S_2	
0.17	$1553\ m \cdot s^{-1}$		1.93		$0\ s \cdot m^{-1}$	
Johnson-Cook Failure Model						
D1	D2	D3	D4	D5	Melting Temperature	Reference Strain Rate
−0.13549	0.6015	0.25892	0.030127	0	20 °C	0.001

Table 3 Material properties of the projectiles

Lead projectile				
Density	Young's Modulus	Poisson's Ratio	Bulk Modulus	Shear Modulus
$11340\ kg \cdot m^{-3}$	16 GPa	0.44	44 GPa	5.5 GPa
Steel projectile				
Density	Young's Modulus	Poisson's Ratio	Bulk Modulus	Shear Modulus
$7850\ kg \cdot m^{-3}$	200 GPa	0.30	167 GPa	77 GPa

the diameter values of the cavities obtained from the simulation are close to those obtained from the experiment, having errors of 31.7%, 21.3%, and 20.2%, for the time frames of 0.5 ms, 0.8 ms, and 1.4 ms, respectively. Considering the uncertainties inherent in the nonlinear characteristics of terminal ballistics, the agreement between the experimental and simulation results validates the consistency of experiments and simulations, despite the errors.

After validating that the simulation and experimental results were consistent, simulations were conducted to compare the energies transferred to gelatin blocks by the projectiles. Time histories of total energies, kinetic energies and internal energies of gelatin blocks are shown in Fig. 10. The kinetic energy is the energy of the block's motion due to projectile impact, and the internal energy is the energy of elastic and plastic deformations [28]. The total energy is the sum of the kinetic energy and internal energy and it represents the total accumulated energy on gelatin block. To evaluate the lethality of the firearms, the average thickness of the human torso was considered for comparison of energy transferred to human body. Taking into account that the average thickness of human torso is approximately 30 cm [27], a damage zone with the respective length was considered for both cases. The damage zones are highlighted in both graphs. Note that for the case of Seungja-Chongtong projectiles, the entire time frame is considered as the damage zone as the maximum penetration length was 16.6 cm. For the case of Tanegashima, it can be seen from the figure that the maximum total energy within the damage zone is 183.24 J, at the time frame of 2.0 ms. For the case of Seungja-Chongtong, the maximum total energy is 8.76 J, also at the time frame of 2.0 ms. The results show that the total accumulated energy when impacted with a Tanegashima projectile is higher by 20.9 times than that when impacted with a Seungja-Chongtong projectile. Thus, in terms of energies transferred to gelatin blocks, it can be inferred that the Tanegashima would have been more lethal than the Seungja-Chongtong.

Experimental and simulation results successfully compared the lethality of the two weapons in terms of the temporary cavity formed in the gelatin block, simulated shooting range, projectile energies, and gelatin energies. The results provide an engineering aspect and an explanation of how Japan had the advantage in infantry warfare by comparing the two main weapons used by each side during the time of the invasion.

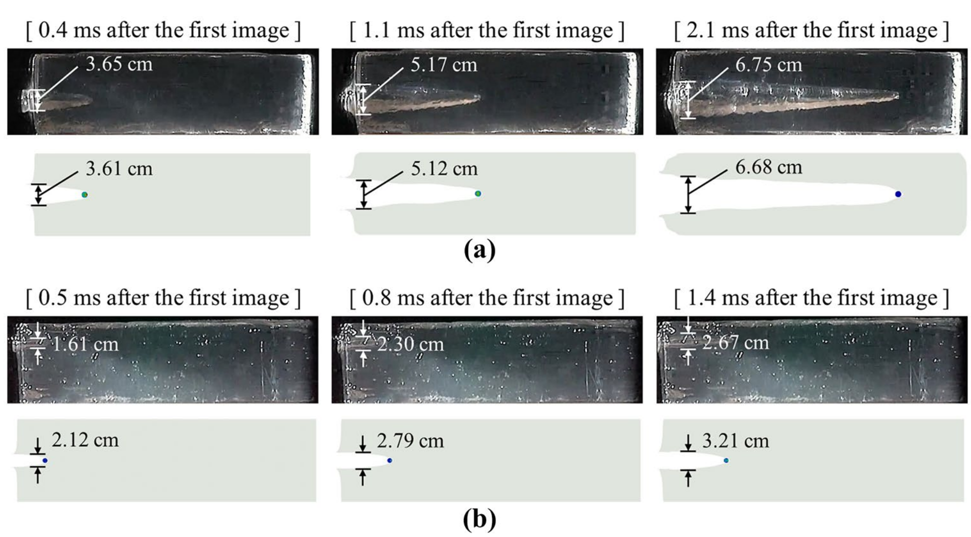


Fig. 9 Comparison of experiment and FEM simulation results: (**a**) Temporary cavity formed by the Tanegashima lead projectile and (**b**) Seungja-Chongtong steel projectile

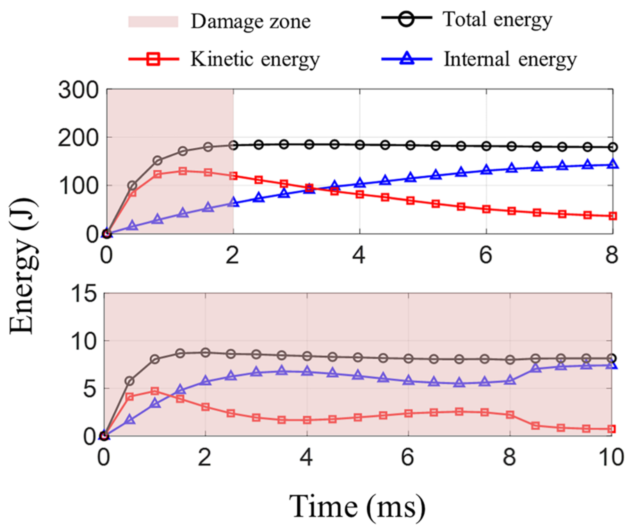


Fig. 10 Time histories of total energies, kinetic energies and internal energies of the ballistic gelatin blocks. Case of Tanegashima (top) and case of Seungja-Chongtong (bottom)

Conclusions

Experiments and finite element analyses were conducted with the Tanegashima and the Seungja-Chongtong to assess their lethality; these two personal weapons were used by Japan and Korea, respectively, during the Japanese invasion of Korea. To conduct the present research, a Tanegashima replica was brought in from Japan with the coordination of the War Memorial of Korea, and a Seungja-Chongtong was restored based on the historical and engineering investigations of a relic with the help of the Jinju National Museum, Korea. Two experimental studies, i.e., projectile penetration into a ballistic gelatin block and mass drop on wooden specimens, were conducted to observe the temporary cavity generation during firearm wound formation, assess the shooting range, and evaluate the projectile energy. In the ballistic gelatin block experiment using a high-speed camera to image the impact of the projectile with the block, it was observed that the temporary cavity formed inside the ballistic gelatin by one projectile fired from the Tanegashima using 3 g of gunpowder had a diameter that was approximately 2.5 times larger than that created by one of the many projectiles fired simultaneously from Seungja-Chongtong using 9 g of identical gunpowder. Despite the variations and differences between replicas and real weapons, we believe that these differences in the sizes of the cavities existed during the war. Considering the status of medical care and management around 1592, it would have been crucial in giving Japan an advantage in the war. Moreover, there is difference in the shooting ranges approximately by a factor of 2. The shooting range of the Tanegashima was greater than that of the Seungja-Chongtong by approximately 2.11 times. The velocity assessment with a high-speed camera and the energy evaluation using the mass drop experiment also reveal that the projectile energies had an order of magnitude difference. The analysis of the kinetic energy is intricate as a single projectile is fired by the Tanegashima and nine projectiles are simultaneously fired by the Seungja-Chongtong. The comparison of the kinetic energies of single projectiles from the two personal weapons reveals that the kinetic energy of a projectile fired by the Tanegashima was 21 times greater than that of a single projectile fired by the Seungja-Chongtong. The sum of the kinetic energies of nine projectiles from the Seungja-Chongtong was still lower by 1/2.4 times than that of Tanegashima owing to the low efficiency in transferring the chemical energy of gunpowder to the kinetic energy of projectiles. FEM-based simulations using ANSYS Workbench Explicit Dynamics were performed to analyze the energy transferred to the gelatin blocks. A comparison between experimental and simulation results for cavity formations showed consistent results despite the uncertainties induced by the nonlinear characteristics of terminal ballistics. Simulations revealed that the total energy accumulated in a gelatin block due to an impact by a Tanegashima projectile was higher by 20.9 times compared to that by a Seungja-Chongtong projectile. The data and observations of this study allow lethality evaluation of the main personal weapons of each country during the war. It can be evaluated that the superior firepower of the Tanegashima resides in long ranges, where a single projectile with greater energy could be fired at longer ranges, and result in larger temporary cavities to targets. Considering that the firearms were mostly used in long-distance combats due to their long reloading characteristics, the lethality evaluation is able to provide an explanation for why Japan was in a superior position over Korea in infantry warfare. The limitation of this study lies in the fact that only personal weapons were compared. There were larger weapons, such as canons, large firearms, and warships. In the future, it may be possible to investigate the lethality of these weapons and their impact on the war.

Acknowledgements The authors thank Dr. Young-Koo Roh (Korea National Defense University), Dr. Ilkwon Huh (National Museum of Korea), Myunghoon Kim (Jinju National Museum), and Gyeongsuk Kim (KP Communication) for providing valuable historical verification and comments. The authors thank Byung Man Min (Former Hanwha Corp. Incheon Plant) for assistance in the use of gunpowder. The authors thank Jung Hoon Kim (Kim's Gun) and Suk Young Lee (Kim's Gun) for assistance in the projectile penetration experiment. The authors thank Dr. Thomas Duvernay (Yeungnam University) for providing the Tanegashima replica for experimental studies.

Funding This study was financially supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No.2018R1A5A7025522).

Declarations

Conflicts of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Lee MW (2000) Records of the ImJin-War. JingBiRok. The Chin-Tan Society 133(8):239–268
2. Je JM (2008) Overviews of controversies and how Chosun Navy gained victory over the Myeongryang Sea Battle (鳴梁海戰) during the Jungujaeran (1597–1598). The Dong Bang Hak Chi 144(7):207–253
3. Park JG (2004) A study on the fire weapons of Joseon and Ming, Japan in Imjinwaeran (Japanese Invasion of Joseon in 1592). Mil Hist 51(4):109–149
4. Jang YH (2009) A study on Korea-Japan War in 1592 with the view of weapon system. Military Research and Development 3(1):115–151
5. Lim HW, Choi WH (2020) Restoration of Joseon's Mortar used during the Japanese Invasion of Korea in 1592. The Journal of the Korea Contents Association 20(7):56–65
6. Krenn P, Kalaus P, Hall B (1995) Material culture and military history: Test-firing early modern small arms. Material Culture Review 42(1)
7. Mol L, Gomez-Heras M (2018) Bullet impacts and built heritage damage 1640–1939. Heritage Science 6(1):1–16
8. Wills C (2017) The iluustrated history of guns: from first firearms to semiautomatic weapons. Simon and Schuster, New York
9. Heard BJ (2011) Handbook of firearms and ballistics: examining and interpreting forensic evidence. John Wiley & Sons, New Jersey
10. Miller DP, Allsop D, Carr DJ (2019) The ballistics of seventeenth century musket balls. J Confl Archaeol 14(1):25–36
11. Smędra-Kaźmirska A, Barzdo M, Jurczyk AP, Berent J (2015) Penetration depth of projectiles fired from a replica of Colt Navy of 1851 in 20% gelatin blocks correlated with fatal injuries assessed in an autopsy of a 78-year-old man. J Forensic Sci 60(5):1365–1368
12. Smędra-Kaźmirska A, Barzdo M, Kędzierski M, Antoszczyk Ł, Szram S, Berent J (2013) Experimental effect of shots caused by projectiles fired from air guns with kinetic Energy below 17. J Forensic Sci 58(5):1200–1209
13. May B, Critchley R, Carr D, Peare A, Dowen K (2020) Ballistic protective properties of material representative of english civil war buff-coats and clothing. Int J Leg Med 134(5):1949–1956
14. Park NR, Kim KH, Mo JS, Yoon GH (2017) An experimental study on the effects of the head angle and bullet diameter on the penetration of a gelatin block. Int J Impact Eng 106:73–85
15. Dougherty PJ, Eidt HC (2009) Wound ballistics: Minie ball vs. full metal jacketed bullets-A comparison of Civil War and Spanish–American War firearms. Military Medicine 174(4):403–407
16. Carr DJ, Stevenson T, Mahoney PF (2018) The use of gelatine in wound ballistics research. Int J Leg Med 132(6):1659–1664
17. Yoon GH, Mo JS, Kim KH, Yoon CH, Lim NH (2015) Investigation of bullet penetration in ballistic gelatin via finite element simulation and experiment. J Mech Sci Technol 29(9):3747–3759
18. Faur-Csukat G (2006) A study on the ballistic performance of composites. Macromol Symp 239(1):217–226
19. Cho JU, Hong SJ, Lee SK, Cho C (2012) Impact fracture behavior at the material of aluminium foam. Mater Sci Eng A 539:250–258
20. Warnet L, Reed P (1999) Falling weight impact testing principles. Mechanical Properties and Testing of Polymers 3:66–70
21. Maiden N (2009) Ballistics reviews: mechanisms of bullet wound trauma. Forensic Sci Med Pathol 5(3):204–209
22. Kieser DC, Carr DJ, Leclair SC, Horsfall I, Theis JC, Swain MV, Kieser JA (2013) Clothing increases the risk of indirect ballistic fractures. J Orthop Surg Res 8(1):1–7
23. Carr D, Kieser J, Mabbott A, Mott C, Champion S, Girvan E (2014) Damage to apparel layers and underlying tissue due to hand-gun bullets. Int J Leg Med 128(1):83–93
24. Burkhard MD, Sachs RM (1975) Anthropometric manikin for acoustic research. J Acoust Soc Am 58(1):214–222
25. Timmerman P, Van der Weele JP (1999) On the rise and fall of a ball with lenear or quadratic drag. Am J Phys 67(6):538–546
26. Almedeij J (2008) Drag coefficient of flow around a sphere: Matching asymptotically the wide trend. Powder Technol 186(3):218–223
27. Potkány P, Debnár M, Hitka M, Gejdoš M (2018) Requirements for the internal layout of wooden house from the point of view of ergonomics changes. Zeszyty Naukowe. Quality, Production, Improvement
28. Wen Y, Xu C, Jin Y, Batra R (2017) Rifle bullet penetration into ballist gelatin. J Mech Behav Biomed Mater 67:40–50