UNIVERSIDADE ESTADUAL DE CAMPINAS
FACULDADE DE ODONTOLOGIA DE PIRACICABA

FERNANDA NOGUEIRA REIS

COMPARAÇÃO ENTRE ANÁLISE EXPERIMENTAL E SIMULAÇÃO COMPUTACIONAL DO IMPACTO DE PROJÉTEIS DE ARMA DE FOGO EM GELATINA BALÍSTICA

COMPARISON BETWEEN EXPERIMENTAL ANALYSIS AND COMPUTATIONAL SIMULATION OF THE IMPACT OF FIREARM PROJECTILES IN BALLISTIC GELATIN

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Dissertação apresentada à Faculdade de Odontologia de Piracicaba da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de Mestra em Biologia Buco- Dental na Área de Odontologia Legal e Deontologia.

Dissertation presented to the Piracicaba Dental School of the University of Campinas in partial fulfillment of the requirements for the degree of Master in Oral Biology, in Forensic Dentistry and Deontology Area.

Orientador: Prof. Dr. Alexandre Rodrigues Freire

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RESUMO

A gelatina balística é amplamente utilizada em testes balísticos como simuladores dos tecidos biológicos humanos, representando uma importante ferramenta na avaliação dos efeitos em tecidos vivos dos projéteis de arma de fogo. Nos últimos anos, novas técnicas computacionais têm sido aplicadas à pesquisa em balística, e o Método dos Elementos Finitos (MEF) tem se mostrado como um mecanismo matemático eficaz na resolução de problemas mecânicos complexos em superfícies com geometrias complicadas. À vista disso, esta dissertação apresenta um estudo envolvendo os métodos experimental e computacional para análise de dados em teste balístico. O objetivo foi analisar o comportamento morfológico da gelatina balística após impactos de projéteis dos calibres .40 S&W e .380 AUTO, tanto experimentalmente quanto computacionalmente. Para a análise experimental, foi realizada a preparação de um bloco de gelatina balística, seguindo o protocolo FBI (EUA) e foram realizados disparos a uma distância de 50 cm para os dois calibres. Em seguida, as cavidades permanentes foram avaliadas, caracterizando o trajeto dos projéteis, utilizando imagens obtidas dos blocos de gelatina. Na análise computacional foi utilizado o método dos elementos finitos 3D, no qual foi realizada simulação do impacto dos projéteis nas condições realizadas experimentalmente. A construção dos modelos virtuais foi realizada por meio da aquisição da geometria dos projéteis, assim como da gelatina balística. A simulação computacional foi realizada através da caracterização dos modelos de acordo com as propriedades mecânicas dos materiais que compõem os componentes da análise. Após a simulação, foram avaliadas as cavidades temporárias, considerando sua morfologia. A análise experimental mostrou diferenças no trajeto em relação aos calibres e, além disso, foi possível observar maiores detalhes na cavidade permanente do projetil calibre .40 S&W. Na análise computacional foi possível observar diferenças na morfologia das cavidades temporárias. A cavidade formada pelo impacto do projétil calibre .40 resultou em maior deformação e, assim, maior dimensão da cavidade. Assim, foi possível notar diferenças entre os impactos dos diferentes calibres em ambas as análises, sendo que o calibre .40 S&W causou maior deformação na gelatina balística. A presença de diferenças na análise experimental foi importante para confirmar a precisão da análise computacional.

Palavras-chave: Método dos elementos finitos; Balística Forense; Ferimentos por Arma de Fogo.

ABSTRACT

Ballistic gelatin is widely used as simulators of human biological tissues in ballistic tests, representing an important tool in the evaluation of the effects of firearm projectiles on living tissue. In recent years, new computational techniques have been applied to ballistic research, and the Finite Element Method (FEM) has been shown to be an effective mathematical mechanism for solving complex mechanical problems on surfaces with complicated geometry. In view of this, this dissertation presents a study involving the experimental and computational methods for data analysis in the ballistic test. So, the aim was to analyze the morphological behavior of ballistic gelatin, after the impact of the .40 S & W and .380 AUTO caliber projectiles. For the experimental analysis, a ballistic gelatin block was prepared following the FBI protocol (USA) and shots were performed at 50 cm for the two calibers. Then, the permanent cavities were evaluated, characterizing the trajectory of the projectiles by the images obtained from the blocks of gelatin. For the computational analysis, the 3D FEM was used, in which the impact of the projectiles was simulated under experimental conditions. The construction of the virtual models was accomplished by the acquisition of the geometry of the projectiles, as well as of the ballistic gelatin. For the computational simulation, the models were characterized according to the mechanical properties of the materials that make up the components of the analysis. After the simulation, temporary cavities were evaluated considering their morphology. The experimental analysis showed differences in the path with respect to the calibers and, in addition, it was possible to observe more details in the perimeter of the projectile caliber .40 S & W. On the other hand, it was possible to detect differences in the morphology of the temporary cavities in the computational analysis. It was also observed that the cavity formed by the impact of the .40 caliber projectile resulted in a greater deformation and, consequently, a larger cavity. Thus, it was concluded that it was possible to note differences between the impacts of the different calibers in both analyzes and that the impact of the .40 S & W caliber caused greater deformation in the ballistic gelatin. The presence of differences in the experimental analysis was important to confirm the precision of the computational analysis.

Keywords: Finite Element Method; Forensic Ballistic; Gunshot Wound.

SUMÁRIO

1 INTRODUÇÃO

Não há dúvida de que a balística forense é um dos campos precursores da criminalística, entendendo-se esta como o estudo das armas de fogo, suas munições e dos fenômenos desencadeados por seus efeitos, no interesse da justiça (Rabello, et al., 1995). Através desta são estabelecidos parâmetros e procedimentos para a identificação e classificação das armas de fogo e consequentemente das características das lesões traumáticas, determinação das circunstâncias e efeitos prováveis a partir do trajeto do projétil no corpo, incluindo direção, sentido e distância dos tiros (Baruch et al., 2013).

As raízes da Balística Forense estabeleceram-se em 1835, na Inglaterra, quando Henry Goddard percebeu um defeito num projétil oriundo do cadáver de uma vítima, encontrou na casa de um dos suspeitos um molde para projéteis que produzia defeito semelhante em projétil nele moldado, fazendo com que este indivíduo fosse condenado por homicídio (SENASP, 2016). Mais tarde, em 1912, Balthazard publicou dois artigos que demonstravam as bases científicas da identificação de projéteis de armas de fogo e, a partir daí cientistas de diversas partes do mundo apresentaram inovações como a invenção do microscópio comparador balístico em 1929, por exemplo (SENASP, 2016). Outro marco foi a fundação do “Scientific Crime Detection Laboratory” por Goddard, em 1925, que em quatro anos investigou 1400 casos envolvendo armas de fogo (SENASP, 2016).

A gelatina balística é amplamente utilizada em testes balísticos como simuladores dos tecidos biológicos humanos, representando uma importante ferramenta na avaliação dos efeitos em tecidos vivos dos projéteis de arma de fogo (Wang et al., 2015). Atualmente, essas gelatinas são utilizadas em concentrações de 10% e 20% nas temperaturas de 4^o C e 10^o C, respectivamente, e após a calibração, simulam os tecidos moles e órgãos do corpo humano, replicando suas propriedades mecânicas (Zecheru et al, 2016). A validação das gelatinas 10% e 20% foi realizada em cadáveres humanos por importantes equipes internacionais de pesquisa do FBI e da OTAN, respectivamente (Defensible Ballistics, 2014). Dentre as vantagens do uso de simuladores de tecidos, destacam-se a geração de evidências fotográficas para a visualização do trajeto do projétil e o fato de não acarretar questionamentos éticos (Humphrey et al., 2018).

Nos últimos anos, novas técnicas computacionais têm sido aplicadas à pesquisa em balística, uma vez que analisar o comportamento de uma estrutura prontamente deformada é um desafio, sugerindo-se novas abordagens numéricas e experimentais (Yoon et al., 2015). O Método dos Elementos Finitos (MEF) tem se mostrado como um mecanismo matemático eficaz na resolução de problemas mecânicos complexos em superfícies com geometrias complicadas (Chen et al., 2010). Para uma simulação de elementos finitos mais precisa, deve-se adotar um modelo mecânico que possa prever o comportamento da gelatina balística, mas que seja simples o suficiente para calcular seu comportamento em um período de tempo razoável (Yoon et al., 2015).

Lesões cranianas causadas por projéteis de armas de fogo são cada vez mais comuns no cenário urbano pelo alto índice de violência, como homicídios, suicídios e outras causas não intencionais (Dawodu, 2017). No Brasil, do total das mortes por homicídio em 2014 (59.681), 71,6% incorreram por arma de fogo (Ribeiro AP et al., 2017) e a incidência de lesões na cabeça também é elevada. Ciantelli et al. (2013) relatou que em Sorocaba no ano de 2009, por exemplo, 15,2% de todos os atendimentos de ferimentos oriundos de projéteis de arma de fogo, localizavam-se na cabeça, sendo o segundo local de maior ocorrência perdendo apenas para a região do abdômen com 22,1%.

A taxa de mortalidade resultante das lesões cranianas com arma de fogo é alta quando comparada a feridas semelhantes em outras partes do corpo, mesmo com o tratamento adequado (Martins et al., 2003). Além disso, mesmo quando não fatais, tais lesões ocasionam danos irreversíveis que incapacitam o sujeito para o trabalho e originam demandas de cuidados ao setor saúde em serviços de diversos níveis de complexidade (Ribeiro AP et al, 2017). Dessa forma, tal ocorrência aumenta não apenas a taxa de mortalidade, mas também a de morbidade de indivíduos em idade economicamente ativa, interferindo também na economia do país (Ciantelli et al., 2013).

Há escassez de estudos na literatura que simulem o disparo por arma de fogo nos tecidos moles craniofaciais, assim como em outras regiões do corpo humano, utilizando o MEF. À vista disso, o presente estudo teve como principal objetivo avaliar uma simulação do impacto de projéteis com diferentes calibres em um bloco de gelatina balística, aplicando o MEF em associação a testes experimentais na gelatina balística. Avaliou-se o comportamento morfológico da gelatina balística pela morfologia das cavidades criadas após o impacto dos projéteis com calibres .40 S & W e .380 AUTO. Desta forma, essas cavidades foram analisadas experimentalmente e computacionalmente. A associação ao teste balístico experimental neste estudo teve como objetivo a busca pelo aperfeiçoamento do MEF para este tipo de teste, analisando a precisão do comportamento do bloco de gelatina balística virtual. Hipoteticamente, considera-se esperado que o calibre .40 S&W, por comprovadamente apresentar maior poder de impacto em relação ao calibre .380 AUTO, resulte em uma cavidade com maiores dimensões, analisando-se virtualmente. Assim, este estudo será importante para contribuir no aprimoramento das simulações computacionais aplicados à balística na Traumatologia Forense, aproximando a simulação cada vez mais com as condições reais para futura aplicação do software em casos reais na atividade pericial cotidiana.

Assim, o objetivo deste estudo foi analisar morfologicamente o comportamento morfológico da gelatina balística após impactos de projéteis dos calibres .40 S&W e .380 AUTO tanto experimental quanto computacionalmente.

2 ARTIGO: Computational simulation associated to experimental analysis to evaluate the impact of firearm projectiles in ballistic gelatin

Artigo submetido para análise no periódico: "*Journal of Forensic Sciences*" (Anexo 1).

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Abstract

This study aimed to morphologically evaluate the biomechanical behavior of ballistic gelatin after the impact of projectiles of .40 S & W and .380 AUTO calibers. For the experimental test, two blocks of ballistic gelatin were prepared for the test, in which one shoot for each caliber was performed. For computational simulation, the geometry of the projectiles and the gelatin block were constructed using the software Rhinoceros 3D and, then, finite element models were constructed using the software Ansys v17.2. The models were assigned according to the mechanical properties of each material. The experimental test showed differences between the calibers in the permanent cavities. The computational analysis showed differences between the calibers in the temporary cavities in the gelatin block, in which small morphological differences in shape and area size, as well as in their entrance wounds. This feature was important to determine the accuracy of the computational simulation.

Keywords: Finite Element Method; Forensic Ballistic; Gunshot Wound.

Introduction

There is no doubt that forensic ballistics is one of the precursor fields of criminology, is understood as the study, in the interest of justice, of firearms, their ammunition, and all phenomena brought about by their effects(1). Parameters and procedures are established for the identification and classification of firearms and consequently for the characterization of the traumatic lesions, besides the determination of the circumstances and probable effects of the projectile in the body, including direction and distance of the shots(2).

Ballistic gelatin is widely used in ballistic tests as simulators of human biological tissues, representing an important tool to evaluate the effects of firearm projectiles on living tissue(3). Currently, this gelatin is used in concentrations of 10% and 20% at 4 °C and 10 °C, respectively, and simulate the soft tissues and organs of the human body, replicating their mechanical properties after calibration(4). Validation of 10% and 20% gelatin was performed on human cadavers by major international research teams, FBI and OTAN, respectively(5). Among the advantages of using tissue´s simulators are the generation of photographic evidence for the visualization of the wound pathway and the fact that it does not involve ethical questions(6).

In recent years, computational methods have been applied to ballistic research, since the behavioral analysis of a readily deformed structure is a challenge, which suggests the search for new numerical and experimental approaches(7). The Finite Element Method (FEM) has been shown to be an effective mathematical mechanism for solving complex mechanical problems on surfaces with complicated geometry(8). A mechanical model that can predict the behavior of ballistic gelatin should be adopted for a more precise simulation, but this must be simple enough to calculate its behavior over a reasonable period of time(7).

There are few studies in the literature that showed the FEM applied to the shot of firearms in ballistic gelatin. Therefore, the main goal of this study was to evaluate the effect of the impact of two different calibers in the ballistic gelatin block, using the computational simulation associated with the experimental ballistic test. The ballistic gelatin was evaluated by the morphology of the cavities created after the impact and transfixation of the projectiles 40 S&W and .380 AUTO.

Materials and Methods

This study did not use any type of biological material, directly or indirectly, so there was no need for approval by the animal or human Research Ethics Committee.

Preparation of the ballistic gelatin block and experimental test

The ballistic gelatin block was prepared according to the FBI protocol(5), in which the block is composed of water and 10% of ballistic gelatin powder. After mixing the powder, the liquid was kept in refrigeration for 2 hours for the blooming process. Then, the mixture was mixed again with warm up to 35ºC to complete the powder dissolution. After the dissolution, the liquid was kept in refrigeration for 30 hours before the experimental test. The result was a ballistic gelatin block with 30 cm x 15 cm x 7,5 cm size (Figure 1).

The experimental ballistic test was performed using guns loaded with projectiles .380 AUTO and .40 S&W calibers (Figure 1). The gelatin block was positioned on a flat surface, parallel to the ground, and with stability. The gelatin block was positioned 50 cm from the shooting, featuring a short shooting. The shots were fired by an experienced shooter (police officer). The images of gelatin block after the projectile transfixation were taken to evaluate the permanent cavities.

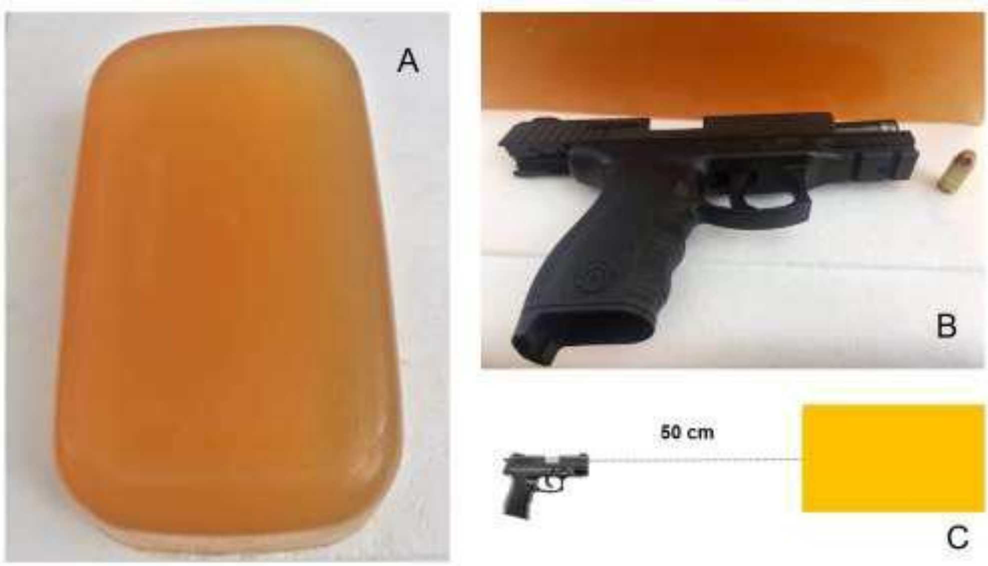

Figure 1. Ballistic gelatin block (10% gelatin) for the experimental test (A, B and C). (A) shows the gelatin block. (B) shows one of guns used in the test (.40 S&W caliber). (C) shows the distance between the gun and the block.

Preparation for computer simulation by finite element method

The computational simulations were performed by a SuperMicro workstation equipped with an Intel Xeon Eigth-Core E5-2630 v3 of 2.4 Ghz, random access memory (RAM) 24 Gb DDR4 and graphical processor Quadro K2200 of 4 GB DDR5 128Bits.

Acquisition of the geometry

The geometry of all components of the simulation (ballistic gelatin and projectile) were constructed manually using the software Rhinoceros 3D v5 (McNeel & Associates, USA) (Figure 2). The data of the dimensions and graphical characteristics of the projectiles were obtained from Companhia Brasileira de Cartuchos (CBC, Brazil), in order to achieve the accurate geometry of the projectiles. In addition, the position and coordinates of the projectile trajectory were configured and obtained using the same software. The positioning of the projectile featured a shot at 50 cm, that is, at a short distance.

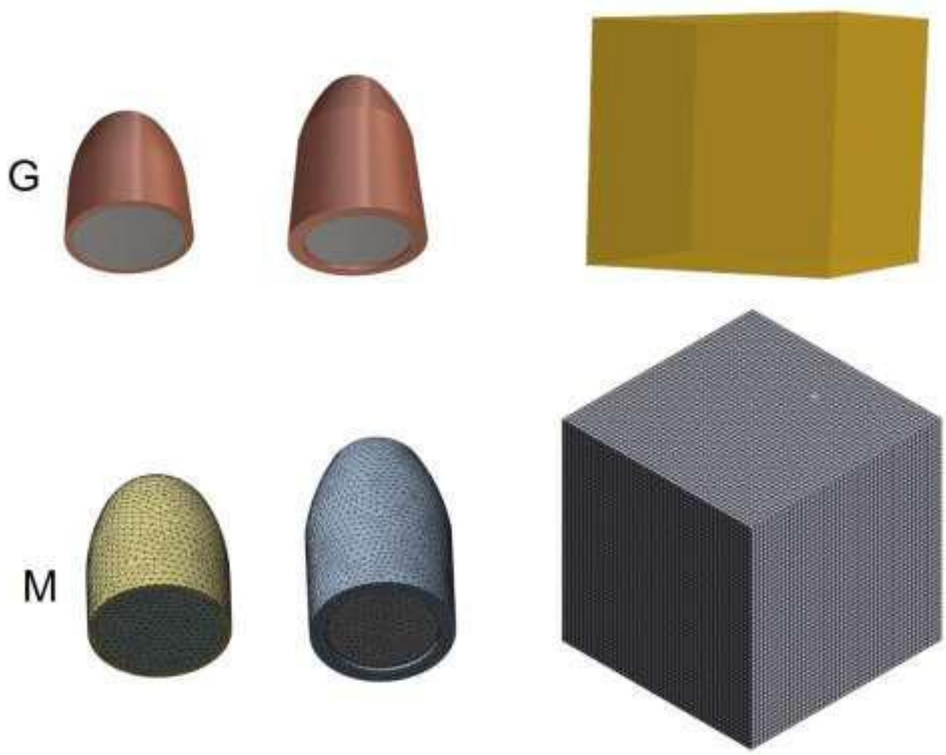

Figure 2. Geometry (G) and Finite element meshes (M) of the projectiles and the block for computer simulation by finite element analysis.

Acquisition of the finite element model and simulation of the impact of the projectile on ballistic gelatin

For the computer simulation by FEM, the software Ansys v17.2 (Ansys Inc., USA) was used. The finite element models of each component (Figure 2) were constructed from its geometry, which was subdivided into elements interconnected by nodes. The model of gelatin block and the projectiles were featured by tetrahedral and hexahedral meshes, respectively. The meshes resulted in a total of 137597 elements and 109038 nodes for the .380 caliber simulation and 181541 elements and 118016 nodes for the .40 caliber simulation. The mesh quality q = 0.937 ± 0.114 (.380) and q = 0.910 ± 0.124 (.40), on a scale of 0 to 1, featuring an accurate meshes. The models were assigned with the mechanical properties of the materials (Tables 1, 2 and 3), whose data were obtained from the study of Yoon(7).

Table 1. Mechanical properties of the 10% gelatin block*

Density	Viscoelasticidade		
	Instantaneous shear modulus	Shear modulus	Viscoelastic decay constant
1030 kg/m³	0,214 MPa	0,158 MPa	0,00087 s^{-1}
Mie-Gruneisen EOS (Shock EOS Linear)			
Gruneisen coefficient	C1	S1	S2
0,17	1553 m/s	1,93	0 s/m

Johnson-Cook failure model						
D1	D2	D3	D4	D5	Melting temperature	Reference strain rate
-0,13549	0,6015	0,25892	0,030127	0	20 ºC	0,001

*Taken from Yoon et al., 2015

Table 2. Mechanical properties of the bullet interior (lead)*

Density	Steinberg Guinan Strenght		Shear modulus
	Yield stress inicial	Yield stress máximo	
1134 kg/m³	8 MPa	0,1 GPa	11,13 GPa
Shock EOS Linear			
Gruneisen coefficient	C1	S1	S2
2,74	2006 m/s	1,429	0 m/s

*Taken from Yoon et al., 2015

Table 3. Mechanical properties of the bullet coating (copper)*

Density	Bilinear isotropic hardening		Shear modulus
	Yield strength	Tangent modulus	
8900 kg/m³	70 MPa	2 GPa	46,4 GPa
Gruneisen Coefficient	C1	S1	S2
2	3958 m/s	1,497	0 m/s

*Taken from Yoon et al., 2015

The simulation was characterized by a short shot according to the experimental test (50 cm distance of impact). The Kinect properties of the projectiles were obtained from CBC data: .380 AUTO caliber launched with an initial velocity of 288 m/s and .40 S&W caliber launched with an initial velocity of 300 m/s. Due to the high speed of the projectiles, the simulation was configured with an ending time of 3,4 x 10^{-3} seconds. This time was obtained after a calculation for the projectile displacement necessary to a complete transfixation. For this analysis, the standard earth gravity was considered. However, due to a short distance, the air resistance was not considered(9).

For the results, the total deformation (cm) was considered, to evaluate the morphological characteristics of the temporary cavity.

Results

For the experimental test, the permanent cavity in the gelatin block was evaluated qualitatively, considering the trajectory and morphological characteristic. The two calibers presented different trajectories. Both assumed a descendent trajectory from the entrance site to the exit site (Figure 3 and 4). The .380 showed an irregular trajectory and the .40 showed a straight trajectory. Also, it is possible to observe the effect of projectile rotation in the .40 test. Regarding the cavity, both calibers presented similar width.

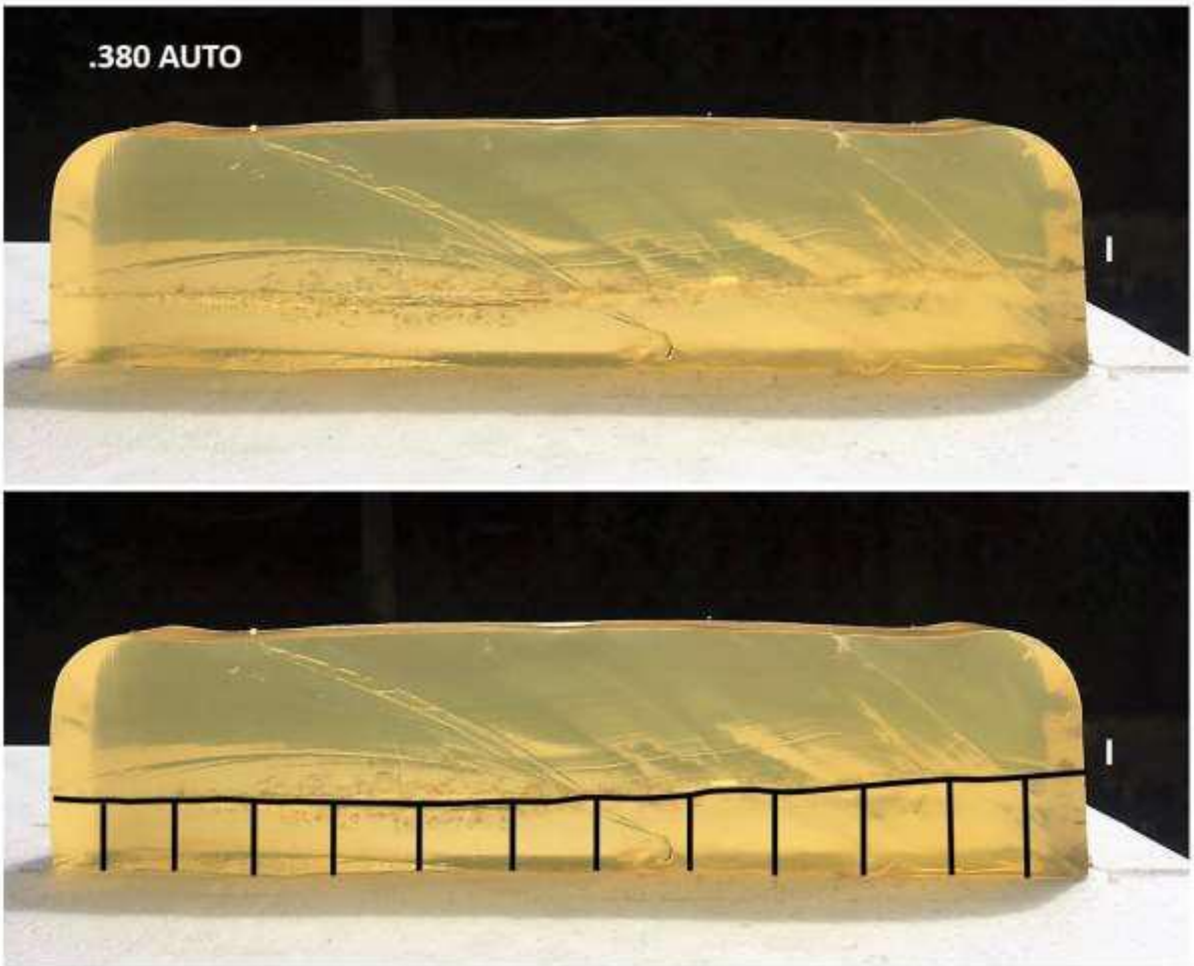

Figure 3. Permanent cavity in the gelatin block after transfixation of .380 AUTO caliber projectile. Note the black lines showing the trajectory characterization.

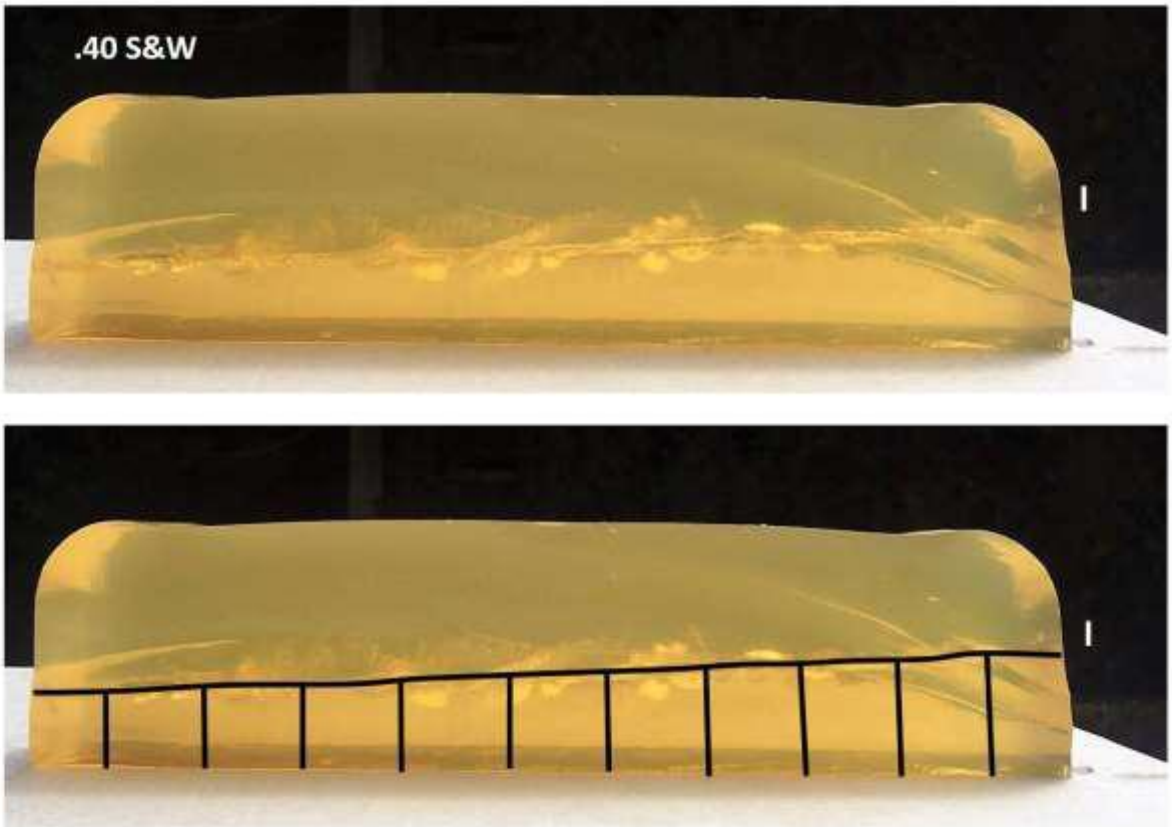

Figure 4. Permanent cavity in the gelatin block after transfixation of .40 S&W caliber projectile. Note the black lines showing the trajectory characterization.

The computational simulation was performed to evaluate the temporary cavity after the impact. It is possible to observe the differences in the destruction caused by the projectiles in the entrance and exit wounds. The .40 S&W caliber resulted in a greater wound compared to the .380 AUTO caliber. The temporary cavity was also greater in the .40 simulation, but the cavity shape was similar in both calibers.

The total deformation was evaluated in the temporary cavity in the gelatin block (Figure 5). For more accurate results, the color scale of deformation values was configured to analyze the interior of the cavity. Considering the interval of values of deformation, the simulation of caliber .380 AUTO impact ranged from 1,5 cm to 3 cm. The caliber .40 S&W impact ranged from 2 cm to 4 cm. Thus, the total deformation was greater in the .40 caliber simulation. It was noted a significative difference in the area size (Figure 6) of temporary cavities between the two calibers, which the caliber .40 S&W has the largest area (Table 4).

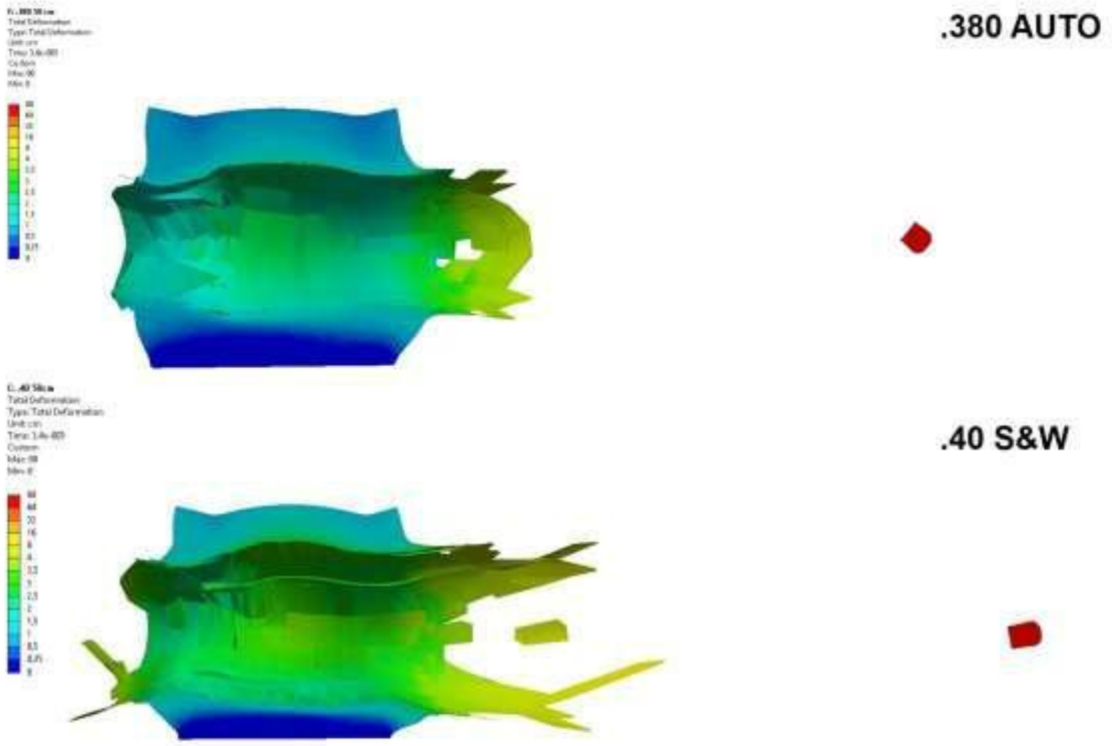

Figure 5. Results of finite element analysis showing the total deformation (characterized by the color scale) and the temporary cavities.

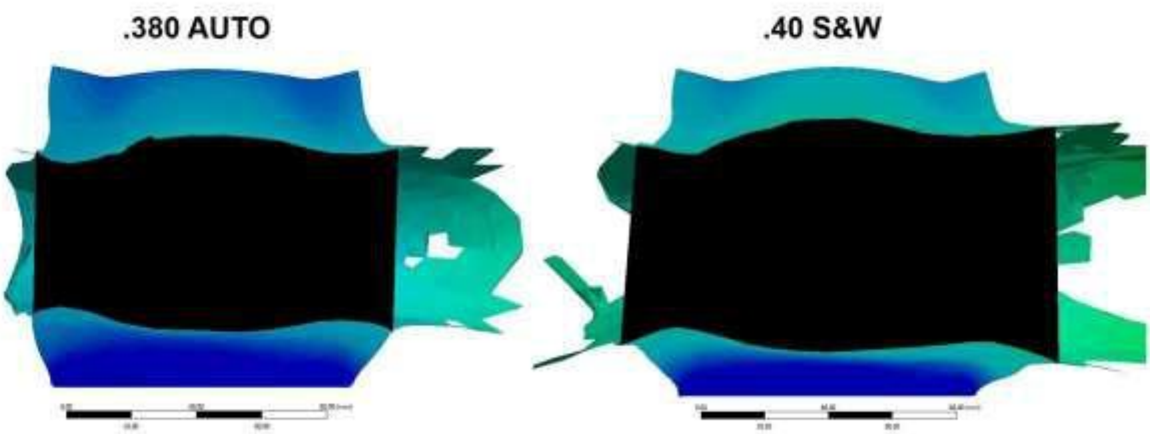

Figure 6. Area calculation of the temporary cavities (black area) showing the difference of the size of cavities.

Table 4. Temporary cavities areas created by different projectiles.

Projectile	.380	.40
Area	62.43 cm^2	93.28 cm^2

Discussion

On a ballistic gelatin test, after reaching the maximum volume, due to the viscoelastic restorative mechanical properties, it is expected which the cavity created by the ballistic impact contracts forming the permanent cavities. The permanent cavities showed trajectory's differences in the ballistic gelatin between projectiles. The .40 caliber showed a more rectilinear pathway when compared to .380. In this phase, it was also possible to visualize the effects of the rotational movement of the projectile in the experimental ballistic test, mainly in the shot made by the .40. Two different permanent cavities do not originate from equal temporary cavities, so this result indicates the reproducibility in the experimental test of these differences also in the initial stage of cavity formation.

By analyzing the differences in the cavity's areas created after the ballistic impact by the different projectiles, it can be understood that such differences agree with the specific kinetic and morphological characteristics of each one. The destructive effects of the projectile are measured by the rate of energy loss and the energy absorbed, which causes damage to the soft tissues of the human body that was simulated by gelatin. Our results indicated that the .40 S & W caliber had the greatest energy loss and created the greatest tissue destruction, which is consistent with the literature(9,10).

Experimental gelatin ballistic tests were simulated by the method of the elements previously by Yoon(7), but this study evaluated the behavior of the 9mm caliber in a long distance shoot simulation, revealing a greater degree of agreement at the moment of the formation of the temporary cavities in ballistic gelatin. At this stage, the behavior was qualitatively similar between experiment and computational simulation. However, despite the similar behavior, there was a difference in the time of transfixation of the projectile in the ballistic gelatin block between the MEF and the real experiment, suggesting the need to perform a larger number of tests in order to improve its mechanical properties.

Matoso(9) demonstrated the correlation of different injury morphology with the amount of kinetic energy at the moment of impact, in which the .40 caliber projectile, has a higher speed, caused a more rounded wound, while the lower-velocity .380 caliber caused an irregular triangular wound. Following this reasoning, in this present study, the entrance holes had no definite shape, because ballistic gelatin presented different mechanical properties, but the entrance holes were different, and it is suggested that the speed was also important in this aspect.

In addition, the bigger cavity originating from the .40 caliber may be associated with the large contact surface of the projectile, which has a flat tip. On the other hand, the 380-caliber projectile, due to its smaller size, ogival shape, and lower velocity, presented a greater loss of kinetic energy, which implies a lower penetration power of the projectile(9,11).

Although the experimental test and the computer simulation did not present the same moment of the projectile effect in the ballistic gelatin block (experimental presented the permanent cavity and computational presented the temporary cavity) both analyses were important to determine that the different calibers resulted in different cavities. It was possible to conclude that the caliber .40 S&W caused more destructive effects and morphological differences after impact on the gelatin block. For the future, the FEM presented a promising tool to perform ballistic tests, considering the advantage of a non-destructive method.

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3 CONCLUSÃO

Através da associação dos resultados obtidos na simulação computacional pelo MEF com os dados qualitativos experimentais, foi possível concluir que ambos os calibres apresentaram divergências em relação ao formato e à área das cavidades temporárias e em relação ao trajeto dos projéteis na cavidade permanente. Tal comportamento dá suporte para futuros estudos que validem o MEF como uma ferramenta na reprodução dos disparos por projéteis de arma de fogo em gelatina balística.

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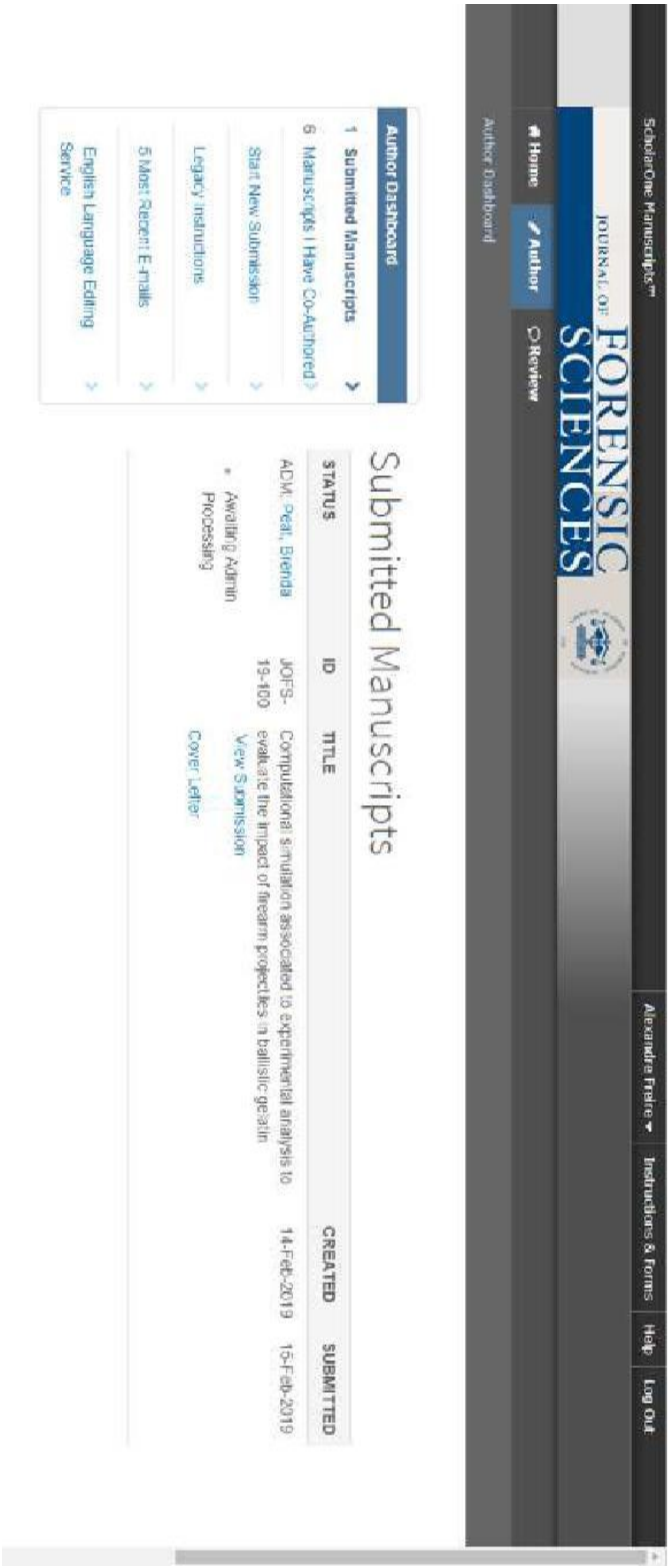
ANEXO 1- Comprovante de envio no Periódico



ANEXO 2- Comprovante do software anti-plágio

COMPARAÇÃO ENTRE ANÁLISE EXPERIMENTAL E SIMULAÇÃO COMPUTACIONAL DO IMPACTO DE PROJÉTEIS DE ARMA DE FOGO EM GELATINA BALÍSTICA

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