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ORIGINAL ARTICLE

A comparison of gelatine surrogates for wound track assessment

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Abstract

The use of ordnance gelatine has been widespread in the field of ballistics as a simulant for soft tissue when assessing ballistic threats. However, the traditional method of preparing ordnance gelatine is time-consuming and requires precision to ensure that the final mold meets the required specifications. Furthermore, temperature control is necessary post-production, and there are limitations on its usage duration. To address these issues, manufacturers have developed pre-mixed, gelatine-like products that are stable at room temperature and require less preparation time. Nonetheless, it is uncertain whether these new products can perform in the same manner as the gold standard of ordnance gelatine. This study used five types of blocks, including ordnance gelatine (10% and 20%), Clear Ballistics (10% and 20%) and Perma-Gel (10%) and subjected them to 9 mm, 0.380 Auto fired from a universal receiver and a 5.56×45 mm ammunition fired by a certified firearms instructor. Delta-V and total energy dissipation were measured after each test using data collected from ballistic chronographs placed in front of and behind each block. High-speed video was recorded, and a cut-down analysis conducted. The findings revealed variations in energy dissipation and fissure formation within the block, with greater energy based on fissure formation observed in the ordnance gelatine. Additionally, the high-speed video showed the occurrence of secondary combustions occurring in the premixed gelatines.

Keywords Wound track · Ordnance gelatine · Surrogates · Ballistics

Introduction

Penetrating ballistic trauma has been studied extensively; both in terms of treatment of injuries and ways to quantify the damage of the tissues effected. The degree of damage is often correlated to the amount of kinetic energy dissipated into tissue. There are a variety of surrogates that have been used to investigate how kinetic energy is absorbed by the human body. Soap and clay have been explored in the past since they provide a permanent deformation cavity, however they lack the visco-elastic nature of human tissue [1] despite being able to demonstrate the cavitation caused by penetrating rounds being well established [2]. The use of animal surrogates and post-mortem human subjects (PMHS) have also been studied [3, 4]. However, for large-scale studies of penetrating munitions, non-biological surrogates are often preferred due to ethical concerns and limited access to biological specimens.

The current "gold standard" tissue simulant in ballistics is ordnance gelatine. Early studies [5] have demonstrated that ballistic ordnance gelatine reacts similarly to live tissue during penetrating ballistic impacts. Due to its transparency and with the use of high-speed cameras, a large temporary cavity can be visualized as the bullet passes through the gelatine. This cavity then collapses leaving a smaller permanent "wound" cavity similar to that seen in human tissue. Therefore, the use of this material was proposed for studying the wound profiles of various munitions based on the ability to record both the temporary and permanent cavities [5].

The ongoing use of ballistic ordnance gelatine is well-established in the ballistics community [6–9]. Procedures for the use of both 10% and 20% concentrations as well as calibration methods to maintain consistency between

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production batches are also well established [10]. However, these processes can be time consuming and require specific procedures in order to fabricate a final mold that is within specifications [5, 11]. The gelatine needs to be kept at a very precise temperature post-production which requires refrigeration [12]. In addition, there is a limited time window in which the gelatine will produce consistent results [13] and each block can only be used once and then must be discarded. Based on these limitations, room temperature stable materials that can be remolded have been produced.

Two types of reusable gelatine that have been produced include: Perma-Gel (http://www.perma-gel.com/) and Clear Ballistics (http://clearballistics.com/). These thermos plastic elastomer simulants can be melted down and remolded after testing. This allows for less time and waste during testing. In addition, they can be tested at room temperature which eliminates the need for ongoing refrigeration and time limitations once removed from refrigeration that exist for ordnance gelatine. The Perma-Gel is a synthetic, colorless, clear material that is presented as being able to simulate cold (4 °C) 10% gelatine. Clear Ballistic gelatine is produced in both 10% and 20% products.

Mabbot et al. [14] evaluated Perma-Gel by comparing the penetration depth of ball bearings at several velocities. It was reported that the depth of penetration into the Perma-gel was 30 mm less than into the standardized 10% ordnance gelatine. When compared to the 20% ordnance gelatine, the depth of penetration was 35 mm more in Perma-Gel. Previous work in our lab with two lower energy rounds has indicated that using the permanent fissures created in the gelatine after the temporary cavity collapses to assess the overall damage demonstrated differences between the newer reusable simulants and ballistic ordnance gelatine [15]. The differences in the amount of energy dissipated by the blocks, based on entrance and exit velocities, however, were not statistically significant. Whether these results will hold true for higher energy rounds has still not been explored.

The goal of the current research was to analyze various munition types and tissue simulants used for penetrating ballistic trauma. Testing was conducted to compare the three (3) tissue simulants using three (3) commercially available munitions. After testing, a comprehensive analysis was conducted on the blocks based on newly developed techniques and extensive video analysis.

Table 1 Soft tissue ballistic simulants and ammunition

Round	Ordnance		Clear ballistics		Perma-gel
	10%	20%	10%	20%	10%
5.56×45 mm	X	X	X	X	X
9 mm	X	X	X	X	X
0.380 Auto	X	X	X	X	X

Methods

A total of five (5) different soft tissue simulants were tested for the current research. Ordnance gelatine in 10% and 20% concentrations were tested as well as and Clear Ballistics 10% and 20% products and Perma-Gel 10% product which is the only product available.

A total of three (3) rounds were used to evaluate the blocks: 9 mm Luger, 124 grain Full Metal Jacket (FMJ) (Fiocchi), 0.380 Auto, 95 grain FMJ (American Eagle) and 5.56 mm x 45 mm, 55 grain FMJ (Winchester). These rounds were chosen to provide a range of muzzle energies while also being relevant to the types of rounds being deployed in the United States. The 9 mm and 0.380 Auto rounds were fired from a universal receiver, while the 5.56×45 mm was fired by a certified firearms instructor. For each condition, a total of three (3) tests were conducted (See Table 1).

High-speed video of the events was captured overhead and laterally at 35,000 fps. For the 9 mm and 0.380 Auto testing, a Phantom Miro (Vision Research) was placed overhead while a Phantom V1212 camera was positioned laterally. For the 5.56×45 mm testing, a Phantom V2640 camera was positioned laterally with a frame rate of 20,000 fps. Ballistic Precision Chronographs (Caldwell) were placed in front of and immediately after each block to determine the change in velocity (delta-V) and total energy dissipated. The muzzle to block distance was 4.97 m with the initial chronograph placed 3.45 m from muzzle. The second chronograph was placed 20 cm after the distal side of the block. Post-velocity calculations were made if the trajectory deflection of the bullet occurred.

The ordnance gelatine blocks were prepared in both 10% and 20% concentrations using 250 bloom Type A Ordnance gelatine (Kind and Knox). The 10% concentration of ordnance gelatine was mixed using 10 parts by weight (1,000 g) of gelatine with 90 parts by volume (9,000 ml) of water. The 20% concentration was prepared by mixing 20 parts by weight (2,000 g) of gelatine with 80 parts by volume (8,000 ml). The mixtures were allowed to de-gas for approximately one hour before being poured into a 15.2 cm by 15.2 cm by 40.6 cm (6 inch by 6 inch by 16 inch) molds. The molds were then placed in an environmental conditioning chamber at 10 °C (50 °F) and 4 °C (39 °F) for 30 h prior to use for the 20% and 10% batches respectively.

A calibration test was performed for each batch of gelatine to ensure the blocks were within specification. If a block failed this calibration test, it was discarded and not used. This test consisted of firing a 0.177 calibre copper-plated spherical BB at 179 +/- 4.5 m/s (590 +/- 15 fps) into one block from each batch. The muzzle to block distance was 2 m (6.5 ft). The resting position of the BB within the gelatine was required to be 8.5 ± 1 cm (2.95 ± 0.39 inch) for 10% and 4.4 ± 0.2 cm (1.5 ± 0.25 inch) for 20% batches.

Two (2) Perma-Gel (USALCO, LLC) blocks were obtained for testing. These blocks are reported to simulate 10% ordnance gelatine at 4 °C and can be stored at room temperature. The blocks were initially 44.5 cm by 29.3 cm by 12.7 cm (17.5 inch by 11.5 inch by 5 inch) but were heated to the manufacturer's melt-down specifications and then poured into molds the same size as those used with the ordnance gelatine.

Given the reported reusability of this simulant, after each test, the blocks and/or sections were placed in a roaster oven and heated to 107 °C (225 °F) per the manufacturer's instructions. Any fragments or material that remained in the block from the prior testing were strained out. Once all of the fragments were removed, the gelatine was then poured back into the molds. The molds were then placed into a conditioning chamber at 100 °C (212 °F) for 2 to 4 h to de-gas. Molds were allowed to cool for twelve (12) hours prior to testing.

Four (4) Clear Ballistics block were obtained for testing, two (2) 10% and two (2) 20%. These blocks also come preformed and are reported to simulate 10% and 20% ordnance gelatine. The material is reportedly reusable and room temperature stable. The blocks were ordered in the size of 15.2 cm by 15.2 cm by 40.6 cm (6 inch by 6 inch by 16 inch).

Once tested, the blocks and/or sections were placed in a roaster oven that was heated to 132 °C (270 °F). Per the manufacturer's instructions, the blocks were not heated above 138 °C (280 °F). The gelatine was heated until the entire block was melted, and the material was strained to remove any fragments or particles. Once the fragments were removed, the gelatine was poured back into the molds. The molds were then placed into a conditioning chamber at 129 °C (265 °F) for 2 to 4 h to de-gas. Molds were cooled for 12 h prior to testing.

Post-test measurements

To compare the different tissue simulants, several post-test measurements were made, and the high-speed video was analyzed. Dimensional measurements were made of the entire block, and photographs were taken. Next, each block was cut longitudinally, into 50 mm slices starting from the impact surface based on techniques described by Jussila [3] and Fackler [8] to estimate the kinetic energy dissipation within each slice. These individual slices were also analyzed based on techniques described by Schyma [16, 17]. Each slice was placed on a light source and photographed. The number of fissures and their lengths were determined for each section. The length of the fissures was measured using digital calipers on the physical block. The photographs were then analyzed within ImageJ (Rasband, W.S., ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA, https://imagej.nih.gov/ij/, 1997–2018.) utilizing the polygon feature to digitally connect the vertices of the fissures to develop a polygon. The polygon area and polygon perimeter of the developed polygon were then measured.

Every interval slice produced two cross-sectional images of the same damaged area. To resolve this issue, the average of the polygon areas and polygon perimeters were calculated and used as the representative polygon for that interval. In circumstances where a polygon could not be drawn due to a low number of cracks (less than 3), the polygon tool was used to surround the damaged area of the gelatine.

The overhead high-speed video was analyzed using a sectional radius (SR method) technique where a grid was created with eight (8) equally spaced horizontal sections. The grid was projected on top of the original video aligning the grid with the frame of the block. Individual stepwise frames of the video were then analyzed to determine the largest radius that was observed within the temporary cavity expansion for each section of the block. A compiled overlay of the maximal temporary cavity expansion within each section of a sample block of gelatine is shown in Fig. 1.

Post-testing analyses

Four techniques were used to estimate the kinetic energy that was dissipated into each block: Fissure Surface Area (FSA), the Wound Profile Method (WPM), the Polygon Area Method (PA), and the Sectional Radius Method (SR). The FSA method was developed by Knappworst and described by Sellier and Kneubuehl [2] and is based on determining a proportionality constant using the total energy dissipated in the block. This constant is then used to determine the amount of energy dissipated by each section of the block using the sum of the fissure lengths in the section (Eq. 1).

$$\sum r_i = C * (E'_{tr})\, i \tag{1}$$

where E'_{tr} = energy dissipated.

C = proportionality constant.

r_i = length of fissures at cross-section i of the block.

The PA technique is used to estimate the energy dissipated by each section of the block by determining the overall area of the polygon derived by connecting the vertices of generated fissures. The cumulative sum of these area values along the block can provide further insights into how the overall energy is deposited as the bullet travels through the tissue simulant [16]. Utilizing this technique, a cumulative sum of PA was generated at each 50 mm interval. This cumulative

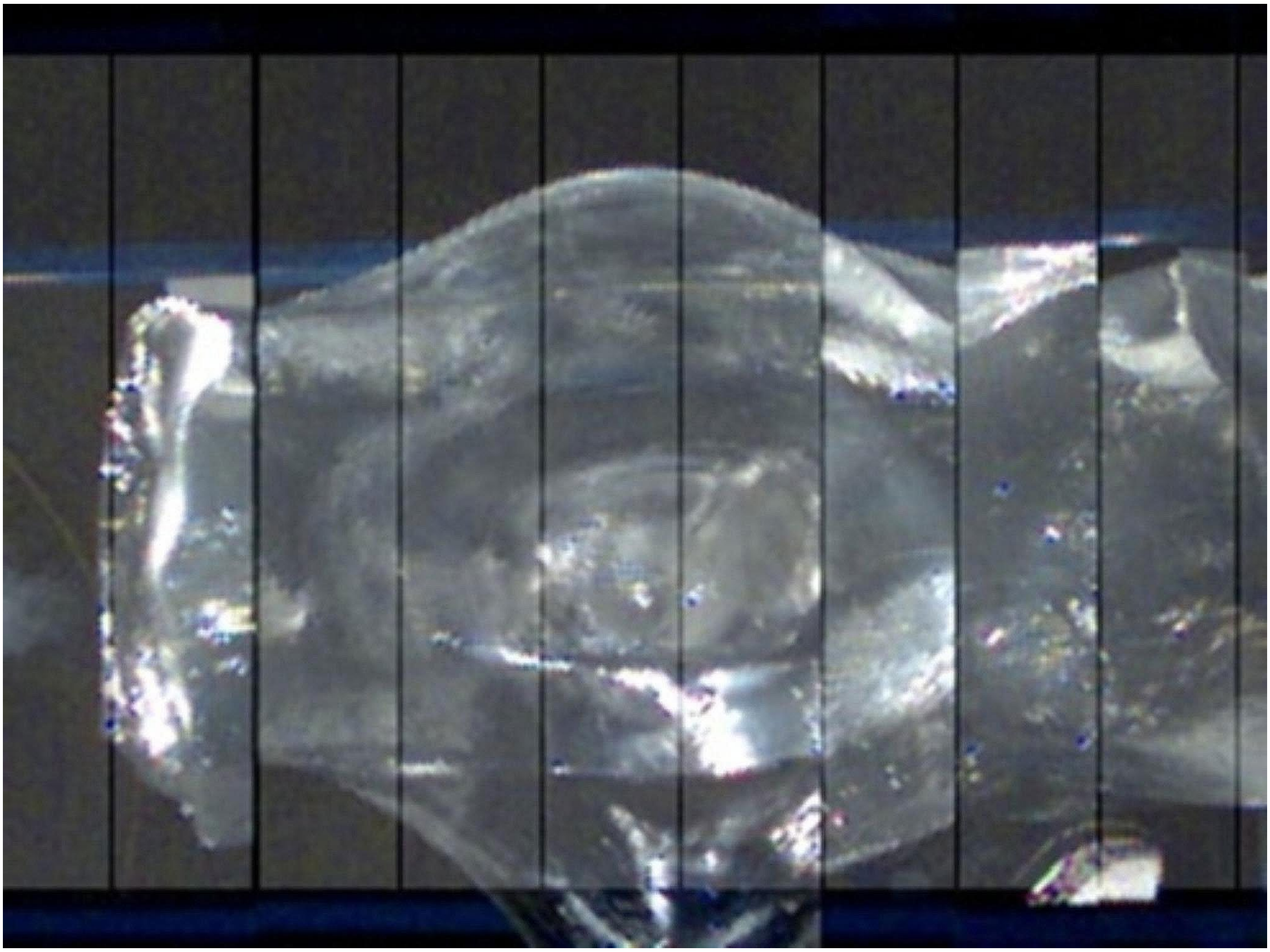

Fig. 1 Sectional overlay of maximal temporary cavity expansion of sample gelatine at distance intervals of importance

sum can then be used to develop an approximation for the energy dissipated into the block at length i using Eq. 2:

$$PA_i = \mathrm{E}\prime_{tr} * \left(\frac{\sum_0^i PA}{\sum_0^{400\,mm} PA} \right) \tag{2}$$

where $\mathrm{E}\prime_{tr}$ = Energy dissipated into block

PA = polygon area.

The WPM was reported by Fackler and Malinowski [5] and estimates the diameter of the temporary cavity by adding the two largest fissures in a section. Their average can then be used to determine the energy ratio dissipated into a specific slice i using Eq. 3.

$$RE_i = \pi * lw * ({r1_{tc}}^2 + r1_{tc} * r2_{tc} + {r2_{tc}}^2)/3 \tag{3}$$

where $\mathrm{RE_i}$ = energy ratio number for section i.

lw = length of bullet channel.

r1 = radius on impact side.

r2 = radius on exit side.

tc = temporary cavity.

As the measurements using the SR method also estimated the diameter of the temporary cavity of the slice, Eq. 3 could also used to estimate the energy ratio dissipated into the block at specific slices.

After all measurements were tabulated, comparisons were made within and between the groups using standard statistical analysis including a one-way ANOVA and basic t-test with significance set to $p < 0.05$. Each munition series was analyzed separately.

Results

The energy imparted into each block was calculated from the impact and residual velocities when available. For the cases where the bullet did not exit it was assumed that all of the impact energy was dissipated within the block. (See Tables 2, 3 and 4) The mass used for the energy calculation was as follows: 9 mm bullet – 7.96 g, 0.380 Auto – 6.18 g and 5.56×45 mm round – 3.56 g. It should be noted that none of the fissures reached the edges of the block.

9 mm ammunition

Neither the impact energy nor the dissipated energy differed significantly ($p > 0.05$) for any of the tested blocks (Table 2). The trajectory of the round did not deflect significantly in the gelatin.

Area methods

The FSA method demonstrated that for the 10% blocks, the energy released per 50 mm block section was significantly different for the first 150 mm (three sections) of the block with the ordnance gelatine dissipating significantly more energy than either Clear Ballistics or Perma-Gel ($p < 0.05$). However, the total energy dissipated past 150 mm was not statistically different (Fig. 2a), except for the Clear Ballistics at 250 mm ($p < 0.05$). There were no significant differences between the 20% ordnance gelatine and Clear Ballistics (Fig. 2a). The energy values for each segment of the synthetic materials were plotted against the same segment of ordnance gelatine with a 1 to 1 ratio line indicating a perfect correlation (Fig. 2b).

Table 2 Energy calculations for the 9 mm round

Test ID	Impact velocity (m/s)	Impact energy (J)	Residual velocity (m/s)	Residual energy (J)	Dissipated energy (J)
Clear 10_1	361	519	192	147	372
Clear 10_2	330	434	202	163	271
Clear 10_3	308	377	145	84	293
Mean	**333**	**444**	**180**	**131**	**312**
Std Dev	**27**	**71**	**30**	**42**	**53**
Clear 20_1	356	504	161	103	400
Clear 20_2	308	377	150	89	288
Clear 20_3	321	409	116	53	356
Mean	**328**	**430**	**142**	**82**	**348**
Std Dev	**25**	**66**	**24**	**26**	**57**
PermaGel_1	345	474	176	123	351
PermaGel_2	347	478	150	90	388
PermaGel_3	337	451	149	89	362
Mean	**343**	**468**	**158**	**101**	**367**
Std Dev	**5**	**15**	**15**	**20**	**19**
ORD10_1	347	479	152	92	387
ORD10_2	327	426	156	97	329
ORD10_3	327	426	155	95	330
Mean	**334**	**443**	**154**	**95**	**349**
Std Dev	**11**	**31**	**2**	**2**	**33**
ORD20_1	352	493	78	24	469
ORD20_2	307	374	49	10	365
ORD20_3	313	390	116	53	337
Mean	**324**	**419**	**81**	**29**	**390**
Std Dev	**25**	**65**	**33**	**22**	**70**

The PA method demonstrated that for the 10% blocks, the energy released per 50 mm block section was significantly different for the first 150 mm (three sections) of the block with the ordnance gelatine dissipating significantly more energy than either Clear Ballistics or Perma-Gel ($p < 0.01$). The Perma-Gel continued to be significantly different up to 250 mm ($p < 0.05$). However, the total average energy dissipated for the entire block was not statistically different (Fig. 2c). For the 20% blocks, the ordnance gelatine and Clear Ballistics was significantly different at the 250 and 300 ($p < 0.05$) mm points in the blocks. Each of the average values for the synthetic materials was plotted against the ordnance gelatine with a 1 to 1 ratio line indicating a perfect correlation (Fig. 2d).

Temporary cavity methods

The WPM demonstrated that the temporary cavity formation with the 9 mm round produced significant differences between the ordnance gelatine and the newer simulants (Fig. 3a). When compared to 10% ordnance gelatine the 10% Clear Ballistics demonstrated a smaller temporary cavity and that difference was statistically significant for all points in the block with the exception of the 200 mm and final section at 400 mm ($p < 0.05$). The 10% Perma-Gel also demonstrated a smaller temporary cavity that was statistically significant for the first 150 mm of the block in comparison to the 10% ordnance gelatine. The 20% ordnance gelatine demonstrated a larger temporary cavity than the 20% Clear Ballistics and that difference was statistically significant in the first 100 mm and at 250 mm ($p < 0.05$).

The SR method demonstrated that the temporary cavity formation with the 9 mm round produced similar results between the ordnance gelatine and the newer simulants for most the length of the block (Fig. 3b). The 10% Clear Ballistics demonstrated a statistically smaller temporary cavity in comparison to the 10% ordnance gelatine at 50 mm ($p < 0.05$), however the 10% Perma-Gel not statistically different from the others for the length of the block. The 20% ordnance demonstrated a statistically significant larger temporary cavity compared to the 20% Clear Ballistics at 300 mm ($p < 0.05$).

.380 Auto ammunition

The impact energy was not significantly different ($p > 0.05$) for each type of gelatine. The dissipated energy showed variation, as only one out of the three rounds completely penetrated through the 20% ordnance gelatine (ORD 20)

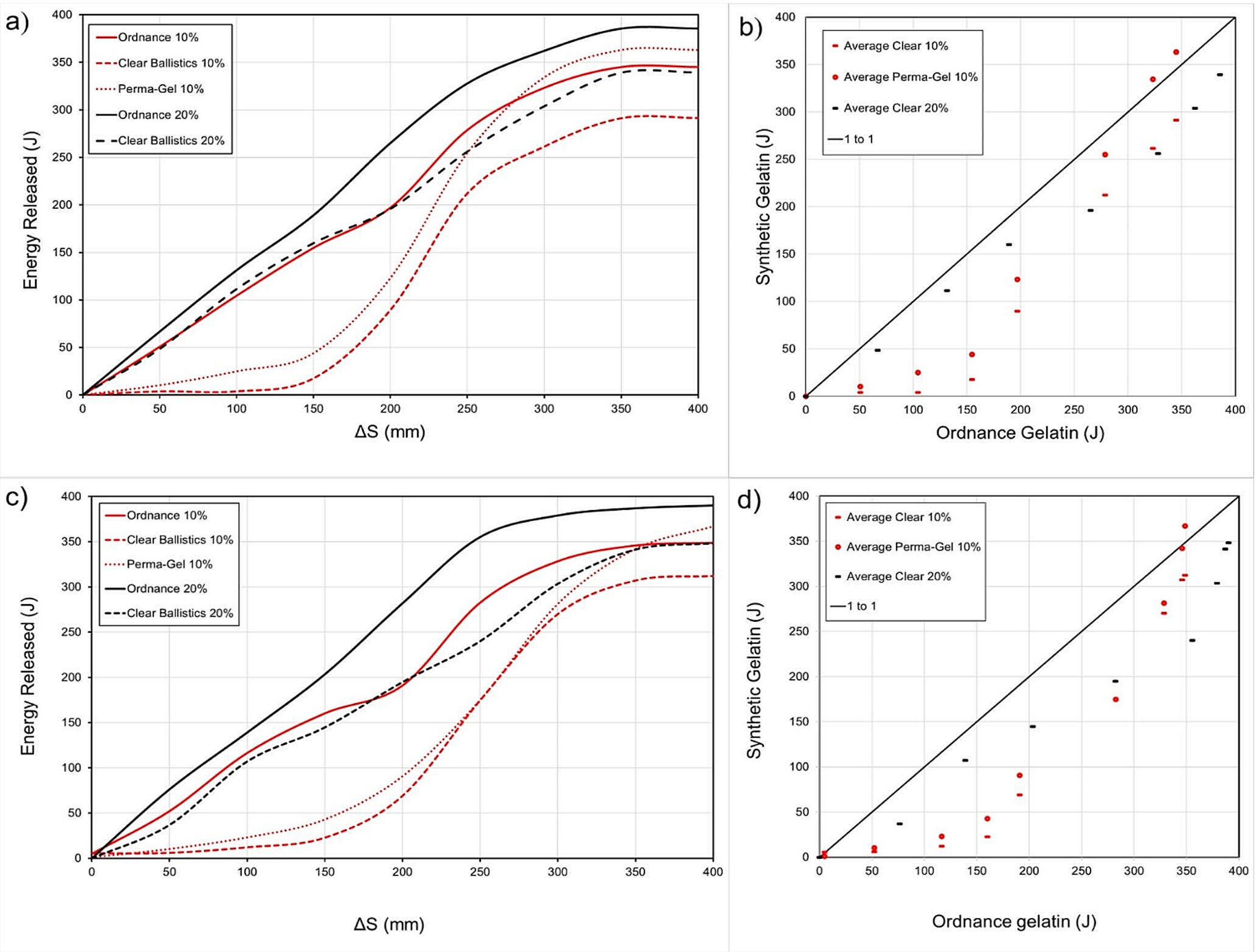

Fig. 2 9 mm ammunition **a**) energy released based on position in block using FSA method, **b**) comparison of synthetic surrogates to ordnance gelatine using FSA method, **c**) energy released based on position in block using PA method, and **d**) comparison of synthetic surrogates to ordnance gelatine using PA method

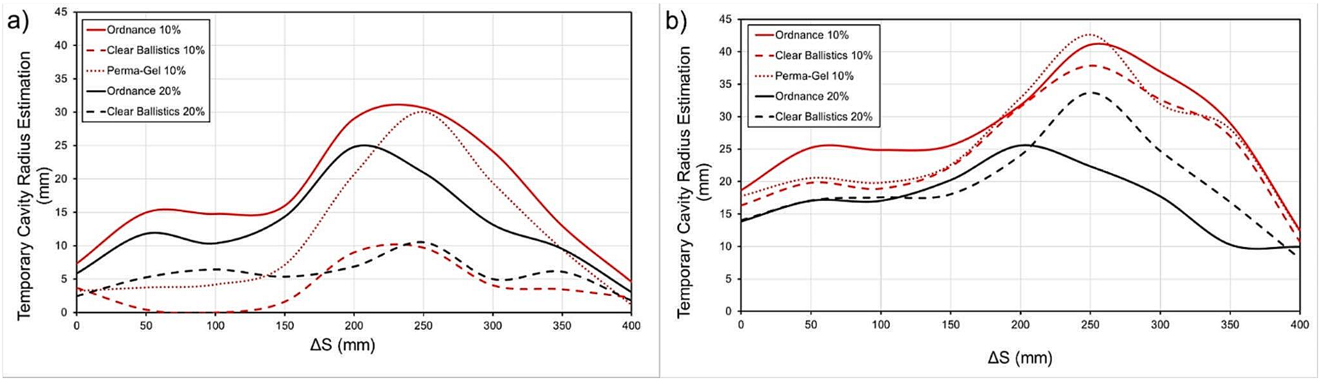

Fig. 3 Estimation of temporary cavity from 9 mm ammunition using image analysis **a**) by WPM and **b**) by SR

block, while all three rounds penetrated through the 20% Clear Ballistics (Clear 20) blocks, resulting in a statistically significant lower dissipated energy ($p < 0.05$) (Table 3).

Area methods

When looking at the energy dissipated for the 0.380 Auto round, the FSA method showed that the only statistically significant differences were between the 20% ordnance gelatine and the 20% Clear Ballistics within the first 50 mm block and the 250 mm block ($p < 0.05$). At all other points, including the total energy dissipated; there were no statistical differences in either the 10% or 20% simulants (Fig. 4a). Each of the average values for the synthetic materials was plotted against the ordnance gelatine with a 1 to 1 ratio line indicating a perfect correlation (Fig. 4b).

The PA method demonstrated a statistically significant difference for the average energy released for the first 150 mm of the block with the 10% ordnance gelatine dissipating significantly more average energy than the Perma-Gel ($p < 0.01$). The 10% Clear had significantly less energy dissipated in Sect. 200 mm ($p < 0.05$) when compared to the ordnance gelatine. However, the total average energy dissipated for the entire block was not statistically different (Fig. 4c). For the 20% blocks, the difference between ordnance gelatine and Clear Ballistics was statistically significant up to the 100 mm section ($p < 0.05$) with the 50 mm having a higher significance ($p < 0.01$). Each of the average values for the synthetic materials was plotted against the ordnance gelatine with a 1 to 1 ratio line indicating a perfect correlation (Fig. 4d).

Table 3 Energy calculations for the 0.380 Auto round

Test ID	Impact velocity (m/s)	Impact energy (J)	Residual velocity (m/s)	Residual energy (J)	Dissipated energy (J)
Clear 10_1	294	267	173	93	174
Clear 10_2	286	252	156	75	177
Clear 10_3	294	268	125	48	219
Mean	**291**	**262**	**152**	**72**	**190**
Std Dev	**5**	**9**	**24**	**22**	**25**
Clear 20_1	288	257	119	43	213
Clear 20_2	290	261	163	82	179
Clear 20_3	292	264	106	35	229
Mean	**290**	**261**	**129**	**53**	**207**
Std Dev	**2**	**4**	**30**	**25**	**26**
PermaGel_1	285	250	151	70	180
PermaGel_2	283	247	124	48	199
PermaGel_3	294	268	128	50	217
Mean	**287**	**255**	**134**	**56**	**199**
Std Dev	**6**	**11**	**14**	**12**	**19**
ORD10_1	268	222	145	65	157
ORD10_2	293	265	150	69	195
ORD10_3	295	268	141	62	207
Mean	**285**	**252**	**145**	**65**	**186**
Std Dev	**15**	**26**	**4**	**4**	**26**
ORD20_1	290	260	0	0	260
ORD20_2	288	256	0	0	256
ORD20_3	294	267	67	14	254
Mean	**291**	**261**	**22**	**5**	**257**
Std Dev	**3**	**6**	**39**	**8**	**3**

Temporary cavity methods

The WPM demonstrated that the temporary cavity formation with the 0.380 Auto round produced significant differences between the ordnance gelatine and the newer simulants (Fig. 5a). The 10% Clear Ballistics demonstrated a smaller temporary cavity that was statistically significant in comparison to the 10% ordnance gelatine for all points in the block with the exception of the final two Sects. (350 and 400 mm) ($p < 0.05$), with the 50 mm, 150 mm, 200 mm and 300 mm sections having a $p < 0.01$ significance. The 10% Perma-Gel also demonstrated a smaller temporary cavity that was statistically significant for the first 250 mm of the block in comparison to the 10% ordnance with the 50 mm, 100 mm, and 200 mm being $p < 0.05$ and the 150 mm and 250 mm being $p < 0.01$. The 20% ordnance demonstrated a statistically significant larger temporary cavity than the 20% Clear Ballistics in the 50 mm and 150 mm sections ($p < 0.05$) as well as the 100 mm and 200 mm sections ($p < 0.01$).

The SR method demonstrated that the temporary cavity formation with the 0.380 Auto round produced similar results between the ordnance gelatine, Perma-Gel and Clear Ballistics for the entire length of the block (Fig. 5b) for both 10 and 20% formulations.

5.56 × 45 mm ammunition

The impact energy was not significantly different ($p > 0.05$) for any of the surrogates. There were also no statistically significant differences between any of the surrogates in terms of energy dissipated. This is likely due to the overall design of the round (Table 4).

Area methods

When looking at the energy dissipated for the 5.56 × 45 mm round, the FSA method showed that there were no statistically significant differences between the 10% ordnance and the other 10% simulants (Clear Ballistics and Perma-Gel). This held true for the 20% simulants as well (Fig. 6a). Each of the average values for the synthetic materials was plotted against the ordnance gelatine with a 1 to 1 ratio line indicating a perfect correlation (Fig. 6b).

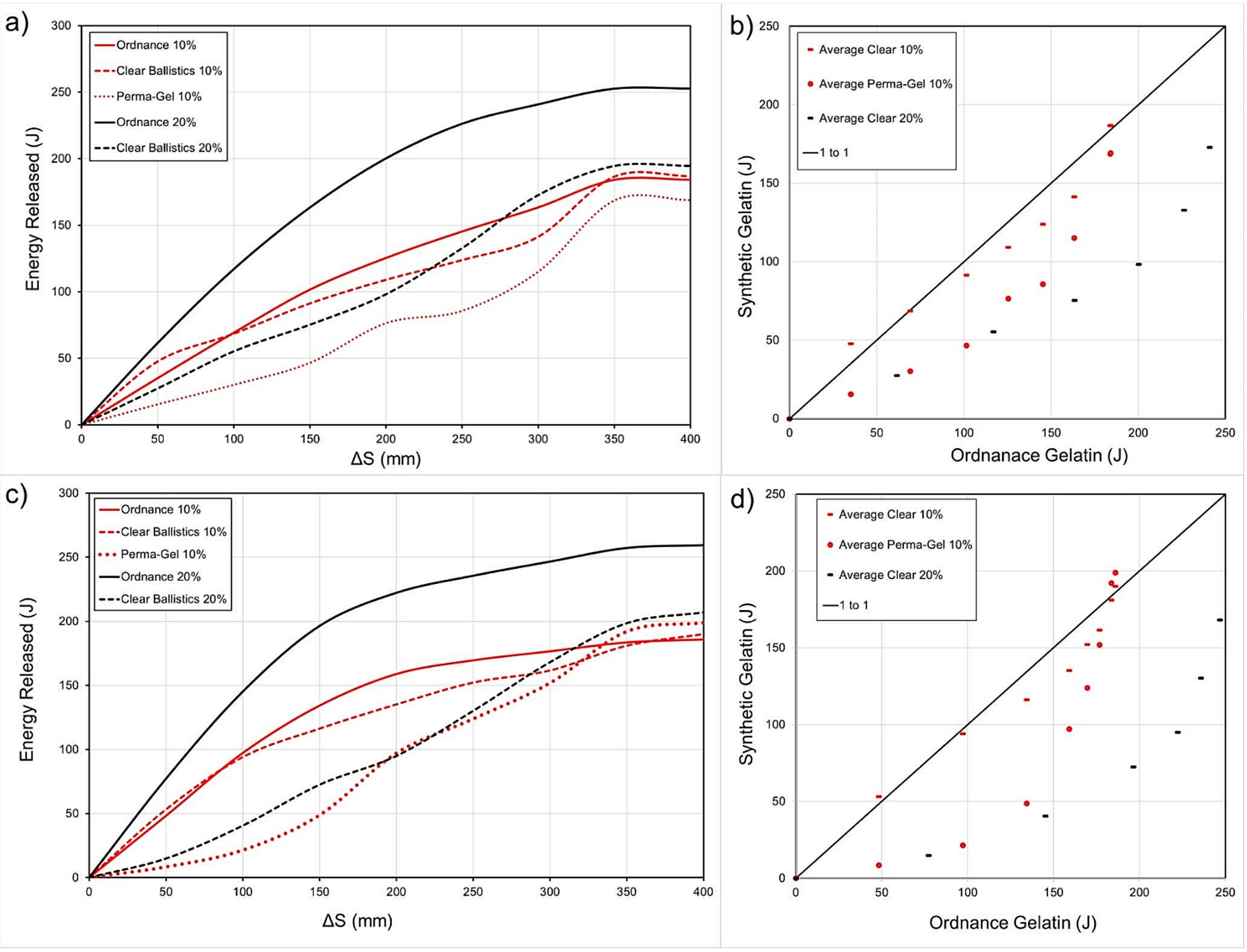

Fig. 4 0.380 Auto ammunition **a**) energy released based on position in block using FSA method, **b**) comparison of synthetic surrogates to ordnance gelatine using FSA method, **c**) energy released based on position in block using PA method, and **d**) comparison of synthetic surrogates to ordnance gelatine using PA method

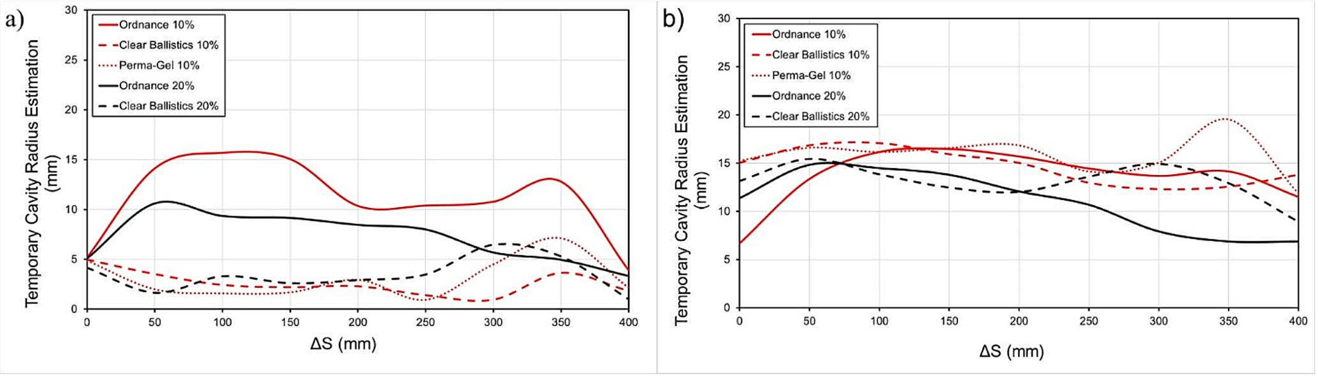

Fig. 5 Estimation of temporary cavity from 0.380 Auto ammunition using image analysis **a**) by WPM and **b**) by SR

Table 4 Energy calculations for the 5.56×45 mm round

Test ID	Impact velocity (m/s)	Impact energy (J)	Residual velocity (m/s)	Residual energy (J)	Dissipated energy (J)
Clear 10_1	957	1629	0	0	1629
Clear 10_2	956	1626	41	3	1623
Clear 10_3	932	1547	0	0	1547
Mean	**948**	**1601**	**14**	**1**	**1600**
Std Dev	**14**	**46**	**24**	**2**	**46**
Clear 20_1	942	1581	0	0	1581
Clear 20_2	930	1538	0	0	1538
Clear 20_3	915	1489	49	4	1485
Mean	**929**	**1536**	**50**	**4**	**1535**
Std Dev	**14**	**46**	**2**	**0**	**48**
PermaGel_1	927	1530	0	0	1530
PermaGel_2	941	1577	0	0	1577
PermaGel_3	948	1599	41	3	1596
Mean	**939**	**1569**	**14**	**1**	**1568**
Std Dev	**11**	**35**	**24**	**2**	**34**
ORD10_1	941	1575	0	0	1575
ORD10_2	915	1491	0	0	1491
ORD10_3	944	1587	0	0	1587
Mean	**933**	**1551**	**0**	**0**	**1551**
Std Dev	**16**	**52**	**0**	**0**	**52**
ORD20_1	915	1490	0	0	1490
ORD20_2	927	1528	0	0	1528
ORD20_3	939	1569	0	0	1569
Mean	**927**	**1529**	**0**	**0**	**1529**
Std Dev	**12**	**39**	**0**	**0**	**39**

The PA method demonstrated similar results with no significant differences (Fig. 6c). Each of the average values for the synthetic materials was plotted against the ordnance gelatine with a 1 to 1 ratio line indicating a perfect correlation (Fig. 6d).

Temporary cavity methods

The WPM demonstrated that the temporary cavity formation with the 5.56×45 mm round produced significant differences between the ordnance gelatine and the other simulants (Fig. 7a). The 10% Clear Ballistics demonstrated a smaller temporary cavity that was statistically significant in comparison to the 10% ordnance gelatine for the 50 mm, 200 mm and 250 mm locations ($p < 0.05$). The 10% Perma-Gel also demonstrated a smaller temporary cavity compared to the 10% ordnance gelatine for the same locations but had a higher significance ($p < 0.01$). The 20% ordnance gelatine demonstrated a larger temporary cavity that was statistically significant compared to the 20% Clear Ballistics in the 150 mm section ($p < 0.05$) but was similar at all other locations.

The SR method demonstrated that the temporary cavity formation with the 5.56×45 mm round produced similar results between the ordnance gelatine and Clear Ballistics for the entire length of the block (Fig. 7b) for both the 10% and 20% gelatine simulants.

Discussion

Historically, gelatine has been utilized as a tissue simulant to analyze ballistic injury. However, the current gold standard is ordnance gelatine which requires significant time and produces a substantial amount of product waste. Reusable tissue surrogates that require less preparation would be advantageous, but concerns have been raised regarding the fidelity of these simulants when compared to the gold standard. The current study extensively studied the differences between currently proposed reusable surrogates and ordnance gelatine.

When assessing the overall energy dissipation of the surrogate blocks, there was no significant difference between the novel simulants (Clear Ballistics and Perma-Gel) and the ordnance gelatines based on the simple analysis of the input and output velocities. However, the estimation of the energy dissipated, and temporary cavity estimation based on fissure lengths did reveal statistically significant differences for most of the blocks when comparing the ordnance gelatine and respective Clear Ballistics and Perma-Gel simulants. It should be noted that for at least one block of the Perma-Gel there were several sections that did not have any noticeable fissures to measure.

To further investigate the response of the blocks, video analysis was conducted. The results show that the measurement of the temporary cavity in the video did not correlate well with the size of the temporary cavity estimated using the WPM. Additionally, there was no statistically significant difference between the ordnance gelatine and the novel simulants when using the video as the analysis tool. This suggests that the novel simulants respond in a similar manner visually to the ordnance gelatine, but fissure measurement-based methods showed statistically significant differences when compared to ordnance gelatine for some calibres. It should be noted that the 5.56×45 mm testing resulted in a better one-to-one comparison when using FSA and PA than the 9 mm and 0.380 Auto testing. This suggests that this higher energy round may exceed the elastic tolerance of synthetic surrogates resulting in fractures, whereas the lower energy rounds do not exceed the tolerance and do not exhibit as many fractures in the synthetic gelatines.

For all forms of gelatine there is an inherent issue of human error when analyzing the blocks [18]. Several of the methods to determine energy dissipated, and damage involves making precise measurements of the remaining fractures in the gelatine. The partially automated technique

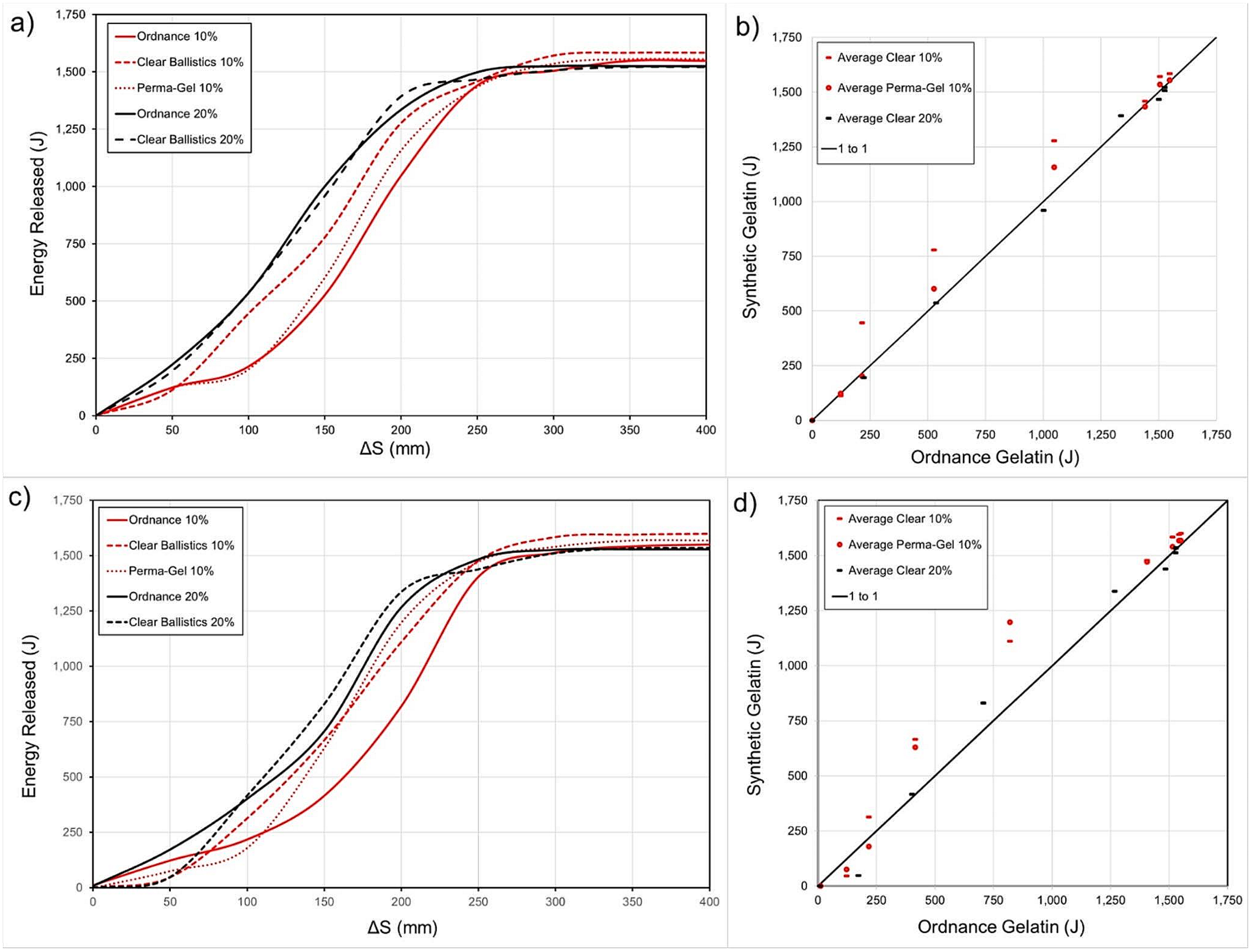

Fig. 6 5.56×45 mm ammunition condition **a**) energy released based on position in block using FSA method, **b**) comparison of synthetic surrogates to ordnance gelatine using FSA method, **c**) energy released based on position in block using PA method, and **d**) comparison of synthetic surrogates to ordnance gelatine using PA method

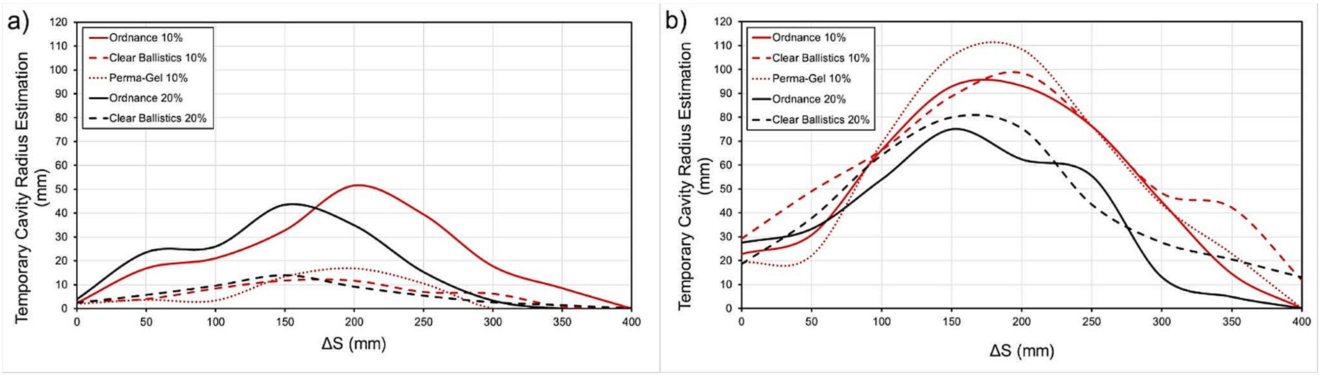

Fig. 7 Estimation of temporary cavity from 5.56×45 mm ammunition using image analysis **a**) by WPM and **b**) by SR

of PA and PP proposed by Schyma [19] does remove the burden of the final calculation of area and perimeter but requires the correct points to be chosen. This aspect of these methods can lead to errors in measurements with resulting errors in energy and injury predictions. One possibility that should be explored in the future is using some sort of imaging technique such a Computerized Tomography (CT) scan to determine the permanent damage to the blocks.

Additionally, the accuracy of methods of determining the temporary cavity can be problematic, as high-speed video equipment is costly and the FSA and WPM are time-consuming and prone to human error. Another difference with the novel simulants is the often-present flash when the temporary cavity collapses. Whether the flash is from sonoluminescence, cavitation or other mechanism is unclear. However, this phenomenon does not seem to cause additional physical damage within the block based on fissure length measurements. The event occurs after the peak temporary cavity expansion so it is unlikely to affect this variable.

The underlying question to these results is how do they compare to living human tissue. The gold standard of ordnance gelatine has been validated with animal surrogates with the recognition that the penetrated tissues are often inhomogeneous [20]. However, comparative data from human subjects is lacking and future work in this area should include the analysis of the medical imaging of penetrating events to determine wound tracks created by similar rounds.

Summary

In this study, a total of five surrogate materials for penetrating ballistic trauma were evaluated: 10% and 20% ordnance gelatine, 10% and 20% Clear Ballistics, and 10% Perma-Gel. The blocks were subjected to three common but distinct threats: 9 mm, 0.380 Auto, and 5.56×45 mm. While analysis of three blocks in each group revealed statistically significant differences in “damage” along the length of the blocks when using WPM, PA, and FSA, there were no significant differences in total energy dissipated by the entire block and temporary cavity formation (determined by high-speed video) between the surrogate types. However, further research is needed to determine how these surrogates predict injury to human tissue.

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Declarations

Research involving human participants and/or animals Not Applicable.

Informed consent Not Applicable.

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