applied sciences

Review

Soft Tissue Simulants for Survivability Assessment—A Sustainability Focussed Review

James Read, Rachael Hazael and Richard Critchley *

Cranfield Forensic Institute, Cranfield University, Defence Academy of the United Kingdom, Shrivenham SN6 8LA, UK; james.read@cranfield.ac.uk (J.R.); rachael.hazael@cranfield.ac.uk (R.H.)
* Correspondence: r.critchley@cranfield.ac.uk

Abstract: Traditionally, human cadavers and porcine tissue have been used as means to replicate elements of the human body; however, because of the differences in biomechanical properties from the porcine limbs/organs and the potential for degradation of mechanical properties caused by ageing, they do not provide accurate material for either lethality or survivability assessment. In the 21st century and with more ethical ways of working being employed, the use of soft tissue analogues to undertake ballistic testing has become routinely accepted. However, gaps in the literature exist that have identified a difference in material characterisation. Procedurally, every researcher manufactures the gelatine differently, which, when combined with a lack of calibration procedures, can cause inconsistencies in output data, and additional concerns exist surrounding the repeatability of re-mouldable simulants, such as Perma-Gel®. Further, limited information is available on the environmental impact of '1 shot' items, such as ballistic gelatine, which has become a well-known and widely accepted material for survivability assessment. This review identifies key inconsistencies within the literature, the risk associated with survivability assessment, and potential solutions to the issues identified within, with outcomes showing that the current methodologies for survivability assessment do not align with the wider UK government ambition of being Net Zero by 2050 unless changes are made.

Keywords: tissue analogue; ballistic gelatine; sustainability; ballistic testing; Perma-Gel; environment

Citation: Read, J.; Hazael, R.; Critchley, R. Soft Tissue Simulants for Survivability Assessment—A Sustainability Focussed Review. *Appl. Sci.* **2022**, *12*, 4954. https://doi.org/10.3390/app12104954

Academic Editor: Giuseppe Lazzara

Received: 25 March 2022
Accepted: 4 May 2022
Published: 13 May 2022

1. Survivability Assessment

Survivability assessment can be defined as the method by which the penetration performance of a protective material is measured [1]. The key metric here is how effective the material is at dissipating energy throughout its molecular matrix, thereby protecting the material's integrity and providing enhanced protection [2] to the user from both ballistic and non-ballistic threats.

Because of protective materials' applications, they are subjected to a rigorous qualification process that describes how the materials should be tested and the pass criteria for both ballistic- and-stab resistant materials [3]. This assessment is traditionally conducted by applying tensile load to the material sample until failure occurs [4]. Thereby providing a comprehensive understanding of the material's limitations and the applicability for its intended purpose.

This alone cannot be relied upon to portray a full perspective of what is happening on impact. To accurately assess a projectile's influence on the human body, the specialist field of wound ballistics is used. Wound ballistics primarily concerns itself with three types of projectiles (handgun bullets, bullets from long-range weapons, and fragmentation), their differences in behaviour within the target, and wound channel formation [5].

Upon impact with the front face of the simulant, the projectile decelerates, which, as it continues inside the medium, exhibits radial energy, creating the 'Temporary Cavity' [6]. This reaction can also be seen to 'pulse' when the energy exerted inside the body and the entry and exit of air into the wound causes expansion and contraction of the tissue before collapsing because of the human anatomy's internal elasticity [5]. Simulants such as gelatine have been reported to be most desirable for this research because their elasticity is similar to that of the human torso [5], but because of this elasticity, the cavity collapses immediately [7], which, without the use of high-speed video footage, would be rendered useless because of the inability for the human eye to witness a millisecond reaction.

The permanent cavity is more simplistic; this is the pathway the projectile has created, which can vary in size and routing depending on factors such as tissue density, muscle content, and bone location [5] as well as projectile size, yaw, tumbling, and the angle of entry [8]. The permanent cavity is traditionally clearly identified post impact [9], but the analysis of the temporary cavity can better identify the amount of force generated upon projectile impact and the dissipation of that energy throughout the surrounding tissues/organs.

It is evident, therefore, that to accurately examine the performance of both current and novel protective materials and projectile performance, a broad range of simulants can be employed to assess their development potential. How can we differentiate between the simulants on offer and identify their strengths and weaknesses?

2. Simulants

Traditionally, human cadavers and animals have been used to assess wounding and behind-armour effects [10], but they do not provide an accurate enough material when an assessment of penetration or perforation is required [11]. With more ethical considerations at the forefront of any research project in the modern day, simulants have become the go-to material for many researchers. The cost and availability benefits are notable, whilst the ability to replicate and validate existing experiments is the main benefit compared with animal anatomy, which differs with the individual animal [5]. Whilst these top-level advantages provide some justification for using simulants, there are also drawbacks that should be examined.

An overview of the most common types of simulants used in a survivability context and found on the open market are reviewed below.

2.1. Ballistic Gelatine

Ballistic gelatine is a widely accepted material for survivability assessment and wound ballistic research. Two types are readily available: Type A, which is derived from acid-treated collagen found in pig skin, and Type B, which is derived from alkali-treated beef skin [12]. As the human anatomy is more closely aligned to that of porcine anatomy [10,13], the most widely used gelatine is Type A. Type A material consists of an acid-treated collagen protein found in animal products [10] and is manufactured in 10 and 20% mass constructs before being conditioned at specific temperatures before use. Both 10 and 20% constructs' ability to replicate the human body is measured by their strength and stiffness properties, which are referred to as the 'bloom number'. Ballistic gelatine is available in 50–300 bloom constructs [10]; however, the Type A bloom number must reside between 250 and 300 to provide accurate results in wound ballistic research [14]. To provide the bloom number, a 112 g sample of 6.67 w/w gelatine is manufactured to standardised time and temperature systems before undergoing a compressive test resulting in the bloom figure [15].

It has been reported that the concentration and temperature during preparation can also influence the performance ability [11] but should be controlled using calibration.

Currently calibrated using the US Fackler method [16], the 10% construct (Figure 1) is reported to be the most beneficial for uses in which penetrating impact analyses are required [17]. Manufactured with 90 parts water and 10 parts gelatine, the material can be affected by water quality, temperature, and post-manufacture conditioning [15], leading to inconsistencies in output data. However, with variables that can be controlled in lab environments, this material has historically shown its viability in wound ballistic research.

By contrast, the 20% construct is uncalibrated [17] and is often referred to as 'NATO' gelatine [15], which is manufactured with 80 parts water and 20 parts gelatine powder [5]. It has been reported that 20% gelatine is superior to 10% gelatine when examining deflection and force data, with outputs showing reactions closer to those of human responses [18]; however, this evidence is singular, and the claim that performance is only viable for these measurements cannot be found elsewhere. Similar to the 10% construct, this material also exhibits issues with water quality, temperature, and post-manufacture conditioning, but because of the uncalibrated manufacturing technique [14], researchers can vary their manufacturing method, increasing the difficulty in experiment repeatability.

Regardless of which construct of ballistic gelatine is used, the shelf life remains poor [14,15]. Polymer-based gels, such as the brain tissue simulants Sylgard and Styrene-Ethylene-Butylene-Styrene (SEBS), which is a thermoplastic elastomer [19], have been developed to provide a suitable alternative with similar performance properties to those of ballistic gelatine to measure behind-armour blunt trauma and back-face deformation. This may eliminate storage requirements and alleviate shelf-life issues; however, the existing issue of manufacturing variable control remains of concern for survivability.

Figure 1. 10% ballistic gelatine [17].

2.2. Perma-Gel®

Although 10 and 20% constructs are valid means by which to assess multiple technologies within both the defence and civilian research fields, Perma-Gel® (shown in Figure 2) provides re-meltable and re-castable properties that reduce both project costs and environmental impacts yet has been reported to exhibit similar performance properties to both types of gelatine [20,21]. Perma-Gel can be categorised as a transparent synthetic thermoplastic material that is manufactured using gellants, mineral oil, and butylated hydroxytoluene [21]. Previous research has also shown that this material's response to impact is similar to that of other co-polymers of similar compositions [22]. Other advantages include increased shelf life in comparison to gelatine; no pre-conditioning being required, cutting project time; and its transparency and ability to analyse various wound ballistics perimeters, such as temporary and permanent cavities [5,6]. It has been reported that, once remelted and reformed, the material behaves differently and can affect Depth of Penetration values [14]. Although this has been reported, no work appears to have further explored why this phenomenon occurs. Furthermore, there have been reports that the material may only be suitable for reuse between 10–15 times, and the more the material is remelted and reused, a yellow tint appears to form within the blocks, which may interfere with output data [15]. A. Mabbot's work provided insight into Perma-Gel® and confirmed that either information on these data is unverified or that gaps exist in the literature [15].

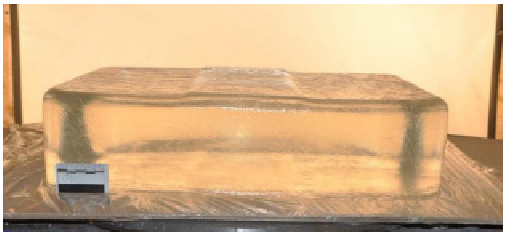

Figure 2. Perma-Gel block [15].

2.3. Ballistic Soap

Ballistic soap (shown in Figure 3) has been reported to produce the same desirable characteristics as gelatine (density, isotropy, and homogeneity) [23]; however, it lacks the elasticity properties required for survivability assessment. This material is typically manufactured using the hydrolysis of fats with a strong base to form sodium or potassium salts of carboxylic acid. This, paired with the remaining glycerine by-product, generates long aliphatic hydrocarbon chains that govern the behaviour of ballistic soap [24]. Upon the impact of a bullet, ballistic soap exhibits plastic-like behaviour and is thus more suited to capturing information on the maximum sizes of the temporary cavity rather than exploring the permanent cavity pathway. This can be carried out using X-ray or by cutting into the block to reveal the wound profile [5]. It is thus only viable to use this material for partial experimental data capture, as all-encompassing use would result in invalid conclusions because of the inability to analyse the full extent of the damage caused by the bullet impact and inaccurate results.

Unlike gelatine, ballistic soap has a much longer storage life (a number of years as opposed to days) [11]; this is predominantly due to the complex glycerine manufacturing process, which means the material is purchased by the researcher as opposed to being made on site. Prior to any data capture, the material should undergo baseline testing to ensure that viable performance is shown and that a comparison can be made with previous/future blocks. However, as these are not reusable materials, nor are they transparent, the opportunity to realise cost savings and use high-speed video footage to analyse results is limited.

Figure 3. Ballistic soap [25].

2.4. Roma Plastilina® Clay No. 1

Traditionally used to measure behind-armour blunt trauma (BABT), Roma Plastilina No. 1 modelling clay consists of minerals, oils, and waxes [26,27]. It is placed within a 420 × 350 × 100 mm steel tray with one large face exposed, ensuring that no air gaps exist [3]. The exposed face is made smooth by scraping the material to align with the edges of the steel tray, thereby creating a defect-free face.

Because of the complexity in manufacture, ROMA Plastilina No. 1 is traditionally bought from a supplier before being moulded, as stated above, and conditioned within laboratory conditions [27].

Prior to exposure to experimental conditions, the moulded blocks must be calibrated to ensure that the material aligns with both the National Institute of Justice [28] and CAST standards [29] depending on the customer base and test location. This begins with the material being conditioned to 30 °C for at least 3 h prior to calibration. The material is then led flat, and a minimum of 3 drop tests from 1.5 m ± 0.5 (2 m for NIJ) are conducted using a 1.043 kg spherical steel ball 63.5 mm in diameter [28,29]. To pass, the material must not decompress more than 15 mm ± 1.5 mm for CAST and 20 mm ± 3 mm for NIJ, which is measured using a vernier calliper from the top of the tray [30].

Once calibrated, experimentation must be conducted at a controlled temperature [31], ensuring that the output data remain consistent and no premature ageing of the material occurs [32]. Additionally, the material is considered to be out of calibration within 45 min [33].

The protective material is located centrally to the front face of the Plastilina and secured to minimise movement; this is highlighted in Figure 4. Once testing has been completed, the protective material is removed from the front face of the Plastilina, and any depth of indentation is measured using a vernier calliper or another agreed-upon method [17]. It should be noted that, because of the construction of Roma Clay, the mixture equates to roughly twice the density of human tissue and is thus used as a worst-case testing material [31].

Figure 4. Roma Plastilina No. 1 used as a backing material for survivability assessment [17].

Survivability assessment can be achieved using a magnitude of materials [34]. Regardless of which gelatine or alternative synthetic material is used, excessive water is used and waste is generated during experimental regimes, which, in a world that is aiming to reduce its impact on climate change, is unacceptable, and a shift in approach is required. To further elaborate on the advantages and disadvantages of the previously discussed materials, see Table 1.

Table 1. Survivability Simulant Summary [10,15].

Simulant Name	Reported Advantages	Reported Disadvantages
Gelatine	Removes ethical concerns Accepted as human tissue simulant History of extensive testing Demonstrates temporary and permanent cavity mechanics Elasticity similar to human tissue Transparency	Lacks biomechanical properties of organs and tissues Only represents human torso/porcine thigh Radial cracks occur during bullet penetration Affected by bacterial contamination, decomposition, and short storage life (2–3 days prior to use) Different blooms used Varying concentrations Not re-useable Temperature-dependant—must be kept refrigerated No standard manufacturing procedure
Perma-Gel®	Reported to be re-useable (8–15 times) No pre-conditioning required Clear and odourless material Captures permanent cavity Displays temporary cavity formation	Limited data to confirm claims on performance and re-useability Only comes in one block size Difficulties with disposal (synthetic polymer)
Ballistic Soap	Long storage life No pre-conditioning required Captures max size of temporary cavity (viewed in place)	Not re-useable Purchase only—not made in-house because of manufacturing complexity Opaque nature—limited opportunity to review high-speed video Non-elastic nature
Roma Plastilina®	History of extensive testing No pre-conditioning required Moulding to shapes is easy	Opaque nature—limited opportunity to review high-speed video Non-elastic nature Purchase only—not made in-house because of manufacturing complexity

3. Sustainability

Traditionally, the term 'sustainability' is used in multiple contexts. To ensure clarity and consistency throughout this paper, this research focuses on three distinct areas. The term sustainability has been defined as a reduction in water usage and the carbon footprint associated with the manufacture, supply chain, and use of materials, but it is primarily defined as a reduction in waste generation from survivability assessment. To ensure that this is brought to the forefront of this research, the author will explore the Reduce, Re-Use, and Recycle principle [35] and its applicability to a selection of soft tissue analogues.

With the future target of reducing environmental impact through a reduction in global emissions by 2050 [36], it is vital that the way in which both defence and civilian operations and research is conducted is altered to align with the aforementioned target. This is already being considered within Defence Equipment and Support (DE&S), with corporate documentation providing outline guidance to align the procurement and operations for defence material with the Net Zero target [37]. To ensure that all sectors align with the government's ambitions, the amount of waste being generated must be clearly understood.

3.1. Waste Generation

3.1.1. Ballistic Gelatine

It is apparent from the review of literature above that gelatine has always been used as a '1 shot' item, and with any form of re-useable simulant suffering from degradation issues, the current survivability assessment methodology does not align with the targets listed above.

To demonstrate the impact of using excessive water and generating excessive waste, a calculation of water consumption and waste generated by an experimental scenario has been conducted.

For this calculation, the Fackler method has been used to ensure alignment with current standards of manufacture and uses moulds of 25 × 25 × 50 cm [16]. Experimentally, the author considered a total of five variables and three repeats for statistical analysis, using a 10% by mass construct (1000 g of gelatine and 9 L water) [38]. By using and rearranging an equation for density (Equation (1)), the outputs required are presented in Table 2.

$$\rho = \frac{m}{v} \tag{1}$$

Equation (1)—Density Formula
where:
ρ = Density (g/cm^3)
m = Mass (g)
v = Volume (cm^3)

Table 2. Gelatine waste generation from survivability assessment scenario.

Water Usage	9 L × 15 = 135 L
Gelatine Powder Usage	1 Kg × 15 = 15 Kg
Block Totals	27.03 kg per block × 15 = **405.45 kg** Density = Volume divided by Mass Volume of 16 × 6 × 6″ block (9438.9 cm^3) divided by block weight 17.2 ibs (8.16 kg − 8160 g) [39] = 0.865 g/cm^3 density. Mass = Density × Volume 0.865 g/cm^3 × (50 × 25 × 25 = 31,250) = 27,031.25 g = **27.03 Kg**

3.1.2. Perma-Gel

Like the above, the dimensions from the Fackler method were used [16] in the absence of NATO calibration procedures. An experimental procedure with five variables and three repeats was used. A density of 0.87 g/cc was reported for Perma-Gel in previous studies [21]. Assuming that Perma-Gel can be used 10–15 times [15], a best-case scenario of 15 was used to calculate the waste in Table 3.

Table 3. Perma-Gel waste generation from survivability assessment scenario.

Per Block	Mass = Volume × Density 31,250 cm^3 × 0.87 g/cm^3 = 27,187.5 g = 27.19 kg
Block Totals	27.19 × 1 = **27.19 kg**

3.1.3. Roma Plastilina Clay No. 1

In accordance with the CAST standard [3], steel trays measuring 420 mm × 350 mm × 100 mm (length × width × height) are filled with Roma Plastilina No. 1 [40]. To aid calculation, an experimental procure was simulated in which a maximum of 6 shots were fired at various locations on the front face of the Roma Plastilina [3]. In accordance with the above two calculations, five variables and three repeats were assumed, equating to 15 firings required. Assuming that the material was defect-free and calibrated correctly, the calculation at Table 4 was made using a material density of 1.53 g/cm^3 [41].

Table 4. Roma Plastilina No.1 Waste Generation from Survivability Assessment Scenario.

Per Tray Roma Clay Usage	Mass = Volume × Density (42 × 35 × 10 = 14,700 cm^3 volume) × 1.53 g/cm^3 density = 22,491 g = 22.491 kg = 27 bars
Total Experiment Waste Totals	3 × 22.491 kg = **67.473 kg**

It is clear from the above simulation that traditional survivability testing generates excessive waste from one-shot items. However, the waste implications cannot be considered in isolation. The cost both commercially and in relation to safety must also be considered.

Although the cost of ballistic gelatine can vary depending on the quality and construct [42,43], the overall consumable cost can be viewed as minimal compared with the safety cost, which is evidently higher. The Health and Safety Executive (HSE) reports the societal cost of a person incurring a fatal injury to be £1.745 M [44,45], which reinforces the need to establish reliable survivability information from testing. With no calibration procedure for the NATO 20% gelatine construct [14] and limited information available for Perma-Gel, it is clear that repeatability within differing labs can contribute to inconsistencies in output data, leading to incomplete or incorrect conclusions surrounding the protective material's performance. This high-risk approach to survivability testing is not a viable way of working and, if continued, could increase the risk of fatality.

Action is thus required to reduce the environmental impact and further advance technology to meet both the sustainability requirements and the demands of the government to reduce casualties on operations [46].

To ensure that the Ministry of Defence (MoD) is consistent with its goals to reduce its environmental impact whilst maximising technological innovation, the use of an Environmental Management System is required to ensure compliance with laws and policy.

3.2. Environmental Management Systems

Within the United Kingdom (UK), the Ministry of Defence is mandated to apply environmental policy and procedures to projects currently in use or within the acquisition cycle by the Secretary of State for Defence [47] using an Environmental Management System. This is carried out using the 'Project Orientated Environmental Management System' (POEMS). POEMS allows project teams to ensure that they are compliant with environmental laws and policy, which helps to ensure that the reputational profile of the MoD is upheld through improving environmental performance and minimising the impact on the environment. This concept was established by utilising the international standards ISO 14001 [48] and ISO 14040 [49], with the latter being of most interest to this research.

The ability of researchers to conduct a Life Cycle Assessment (LCA) before the use or acquisition of material through ethical procurement can ensure that an accurate assessment of the material's environmental impacts from 'cradle to grave' are taken into consideration [50,51]. This approach similarly aligns with the US Department of Defense's Military Standards 882—Standard Practice for System Safety [50].

A review of the literature and advanced training suggested that although alignment with the principle of environmental management is true, POEMS does not currently mandate that projects include sustainability within their assessment at the time of this writing. When specifically looking at survivability assessment, there are numerous potential alternative materials and novel approaches that could be considered to ensure that a sustainable approach is enacted, with the authors' top choices discussed in the following sections.

3.3. Alternative Solutions—What Can Be Done?

3.3.1. Modelling and Simulation

The use of digital tests and evaluations could be beneficial to both generating a comprehensive database consisting of material responses to assist in providing additional data sets and reducing the amount of waste and water usage. This would require verification and validation prior to wider use to ensure that results are accurate. This is traditionally carried out using Hugoniot equations of state to generate data for hydrocodes, which power the model [52]. In recent years, a shift has been made towards including digital modelling for material qualification [53] and the use of digital twins to replicate equipment, which can allow for cheaper and faster results [54].

Although this sounds like a good idea in theory, there are multiple factors to consider, including the quality of the model, its fidelity, and the model's outputs aligning with current UK standards, which is paramount in the technical space to provide an acceptable means of compliance. This is further complicated by the energy required to power such models, which may be excessive, and therefore, what you reduce in waste and water usage, you use in electricity. This could be alleviated with the use of green energy alternatives. The generation of electricity from windfarms, solar, or tidal (dependant on location) could be used to reduce the infrastructure's reliance on traditional energy sources.

Initially, to generate a database of material responses, experimental studies will be required to explore soft tissue analogue responses to impacts of various geometries, sizes, and weights at varying velocities. This is a gigantic task that will take a significant amount of time. Noting the Net Zero target of 2050, further alternatives should be sought to allow time for this solution to mature.

3.3.2. Use and Supply of Foodstuff Gelatine

Alternative materials for survivability assessment should be sought to reduce environmental impact, as demonstrated in Tables 2–4. One such solution is the viability of commercial gelatine used in food to be used with suitable alterations to the material's composition. Commercial grade gelatine is a by-product of the meat processing industry, and the quality of the gelatine produced relies on the protein extraction method employed during manufacture [55,56]. The manufacturing of gelatine has already improved, with the ability to extract the required high-quality by-products for gelatine, high-purity fats to generate biofuels, which further reduce CO_2 emissions and minerals for fertilisation applications and anti-corrosive treatments for steels [55]. This move towards a more sustainable manufacturing method, paired with the ability to clean and recycle the wastewater generated during production before returning the water to nature, is extremely advantageous. In addition, any excess proteins or other organic materials are broken down using bacteria to generate biogas, which helps power resources requiring heat and electricity [55]. This is of massive importance when it has been reported that over 300,000 metric tonnes of gelatine are produced worldwide annually for sectors such as pharmaceutical/medical/cosmetic, food/confectionery, and technical industries [57].

The literature suggests that although a high volume of gelatine is used during survivability assessment, the environmental impacts are minimised through the manufacturing phase. However, this does not consider the supply chain or the disposal of used material. The more '1 shot' items are required during experimentation, the higher the supply chain impact on the environment, with more weight added to transportation methods or increased frequency of delivery, increasing the supplier's carbon output.

It has been reported that the UK domestic freight industry generated 33.7 million tonnes of CO_2 in 2004, with 92% of these emissions caused by road transport [58]. As road transportation is the most common, the following text will focus on road haulage impact.

In recent years, improvements to the fuel efficiency of road haulage vehicles have increased the usage rates and durations for which they are used. This maturation in technology has not kept pace with the ability to reduce emissions, which continues to have negative impacts on the environment [59]. As previously mentioned, the target remains to be Net Zero by 2050 [36], and when taking this timeframe into consideration, companies will be required to explore numerous avenues to meet the government's ambition [59,60]. Once such technology at the forefront of innovation is electrification [61]. This brings the benefit of increased reliability and low operating and maintenance costs [62]; further, they are able to access inner-city regions that have been designated as 'ultra-low emission/clean air zone' status [63].

However, this solution also has drawbacks. Among them are the limited range of electric vehicles, the currently limited infrastructure to charge a vehicle, and the demand that will be placed on the electric grid [62] as the road haulage industry moves towards adopting this technology. Increased demand on the electricity grid means that more electricity is generated, which increases the use of energy sources such as coal, oil, nuclear power, and natural gas, which generate waste products that are harmful to the environment [64]. More eco-friendly alternatives, such as wind, solar, tidal, and biogas, are being explored as replacements for the conventual methods of production [65] but will require significant investment to meet the needs of the road haulage industry.

Although it is important to highlight that there are areas of concern and wider technological improvements ongoing to improve sustainability within the manufacturing process and transportation/supply chain, greater detail on these areas is outside the scope of this research and, as such, they are not discussed in the remaining text.

3.3.3. Existing Material Alteration

To aid in the reduction of the overall cost and environmental impact of road haulage and supply chain emissions, alterations to Roma Clay [33] and Perma-Gel® may be more suitable if a method to discourage degradation [15] can be developed. This would lead to material that can be stored and used for longer durations whilst maintaining its mechanical properties after the re-melt and re-casting post impact, allowing for repeat firings to be undertaken. A recent study has shown that modification to the composition of traditional ballistic gelatine can increase the ability to review post-impact data in a more bio-representative manner [66]. Such methodology could contribute to achieving the ambition to slow degradation and increase the material's ability to re-preform, although as previously reported, the number of times the material can be re-used appears to depend on a variety of both controlled and uncontrollable factors [14,15].

One potential method for slowing degradation could be through chemical crosslinking [67]. Chemical crosslinking is the process of creating a covalent bond to join two polymer chains together, which increases the mechanical properties, stability, and durability of a material [68–70]. Results from other experiments using hydrogels have shown great promise using this technique [68–71], but from an examination of the literature, no such application to survivability has been explored, and therefore, this idea has been hypothesised.

4. Conclusions

To align with the Net Zero 2050 target, significant changes to the way survivability assessment is undertaken require exploration. This literature review has shown that although the US has derived a calibrated methodology for survivability assessment using 10% ballistic gelatine, the current 'NATO' standard of 20% remains uncalibrated. The reasoning for this within the literature is scarce and, as previously evidenced with a review of the current material set, shows signs of inconsistencies during manufacture and unknowns in both degradation and performance metrics; output data efficiency is limited. This approach increases risk; with reported operational combat fatality numbers shown to be consistent throughout a recent 9-year period and a cost per fatality reaching £1.745 M [44,45], such test methodologies require evaluation to minimise risk to both the user and the taxpayer.

Not only does survivability experimentation need to be considered from a performance standpoint, but sustainability also requires more outlook. During a simulated survivability scenario, both excessive water use and excessive waste generation have been evidenced, which increases both cost and environmental concern in any testing regime. Whilst ballistic gelatine was shown to produce the most waste, Perma-Gel was shown to be of most benefit when evaluating against the definitions of sustainability used within this thesis. However, the literature has reported inconstancies in the understanding of both degradation and the number of remelt/remould opportunities available before affecting performance. To mitigate this, various physical and hypothesised mitigations have been researched alongside potential alternative solutions for survivability assessment, with advantages detailed alongside mitigations for areas of concern.

A review of the literature shows that although some work is ongoing to mature these approaches, the methods remain at a low technology readiness level. This immaturity, paired with limited funding opportunities, provides evidence that this area will take time to mature, and with an increased number of anomalies in the understanding of material performance, higher risk will continue to be taken when understanding output data. It is clear from this literature review that continued work in this area is required to mature a variety of solutions that will better help researchers understand the materials being tested and align with the wider government ambition.

Author Contributions: Conceptualization, J.R., R.C. and R.H.; methodology, J.R.; software, J.R.; validation, J.R., R.C. and R.H.; formal analysis, J.R.; investigation, J.R.; resources, J.R.; data curation, J.R.; writing—original draft preparation, J.R.; writing—review and editing, J.R.; visualization, J.R.; supervision, R.C. and R.H.; project administration, J.R.; funding acquisition, J.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by Cranfield Forensics Institute, The Defence Ordnance Safety Group, and Defence Equipment and Support.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tichler, C. *Portable Ballistic Protection for UK*; Publication No. 47/11; Home Office: London, UK, 2011; pp. 1–32. Available online: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/115680/cast4711.pdf (accessed on 5 October 2021).
2. Fiberline. KEVLAR®PARA-ARAMID. Available online: https://www.fiber-line.com/uploads/pdf%20US/fl.us.datasheet-kevlar-para-aramid.pdf (accessed on 20 February 2022).
3. Payne, T.; O'Rourke, S.; Malbon, C. *Body Armour Standard (2017)*; CAST Publication Number: 012/17; Home Office: London, UK, 2017; pp. 1–92. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/634517/Home_Office_Body_Armour_Standard.pdf (accessed on 5 October 2021).
4. British Standards Institute. Protective Clothing and Equipment for Use in Violent Situations and in Training—Blunt Trauma Torso, Shoulder, Abdomen and Genital Protectors. Requirements and Test Methods. 2003. Available online: https://shop.bsigroup.com/products/protective-clothing-and-equipment-for-use-in-violent-situations-and-in-training-blunt-trauma-torso-shoulder-abdomen-and-genital-protectors-requirements-and-test-methods/standard (accessed on 20 February 2022).
5. Coupland, R.M.; Rothchild, M.A.; Thali, M.J.; Kneubuehl, B.P. *Wound Ballistics: Basics and Applications*; Springer: London, UK, 2011; pp. 87–137.
6. Amato, J.J.; Rich, N.M.; Lawson, N.S.; Gruber, R.P.; Billy, L.J. Temporary Cavity Effects in High Blood Vessel Injury by High Velocity Missiles. 1970, pp. 1–15. Available online: https://apps.dtic.mil/sti/pdfs/AD0713504.pdf (accessed on 6 October 2021).
7. Schyma, C.; Madea, B. Evaluation of the temporary cavity in ordnance gelatine. *Forensic Sci. Int.* **2012**, *214*, 82–87. [CrossRef] [PubMed]
8. Fackler, M.; Brown, A.J.; Johnson, D. Wound Ballistics Review—2000 Number 3. *J. Int. Wound Ballist. Assoc.* **1995**, *4*, 1–25. Available online: http://thinlineweapons.com/IWBA/2000-Vol4No3.pdf (accessed on 8 October 2021).
9. Ordog, G.J.; Wasserberger, J.; Balasubramanium, S. Wound ballistics: Theory and practice. *Ann. Emerg. Med.* **1984**, *13*, 1113–1122. [CrossRef]
10. Humphrey, C.L. Characterisation of Soft Tissue and Skeletal Bullet Wound Trauma and Three-Dimensional Anatomical Modelling. 2018, pp. 23–32. Available online: https://digital.library.adelaide.edu.au/dspace/handle/2440/112985?mode=full (accessed on 9 October 2021).
11. Sellier, K.; Kneubuehl, B. *Wound Ballistics and the Scientific Background*; Elsevier: Amsterdam, The Netherlands, 1994; pp. 1–479.
12. Hanani, Z.A.N. Gelatin. In *Encyclopedia of Food and Health*; Academic Press: Cambridge, MA, USA, 2016; pp. 191–195. [CrossRef]
13. Maiden, N. Historical overview of wound ballistics research. *Forensic Sci. Med. Pathol.* **2009**, *5*, 85–89. [CrossRef]
14. Carr, D.J.; Stevenson, T.; Mahoney, P.F. The use of gelatine in wound ballistics research. *Int. J. Leg. Med.* **2018**, *132*, 1659–1664. [CrossRef] [PubMed]
15. Mabbott, A. The Overmatching of UK Police Body Armour. Ph.D. Thesis, Cranfield University, Cranfield, UK, 2015; pp. 35–75. Available online: https://dspace.lib.cranfield.ac.uk/bitstream/handle/1826/10515/Mabbott2015.pdf?sequence=1&isAllowed=y (accessed on 12 October 2021).
16. Nicholas, N.C.; Welsch, J.R. *Institute for Non-Lethal Defense Technologies Report: Ballistic Gelatin*; Applied Research Laboratory—Pennsylvania State University: Pennsylvania, PA, USA, 2004; pp. 1–28. Available online: https://www.researchgate.net/publication/235099580_Institute_for_Non-Lethal_Defense_Technologies_Report_Ballistic_Gelatin (accessed on 15 October 2021).
17. Read, J.; Critchley, R.; Hazael, R.; Peare, A. Penetration Performance of Protective Materials from Crossbow Attack. Research Thesis, Cranfield University, Cranfield, UK, 2021; pp. 1–78.

18. Maiden, N.R. *The Assessment of Bullet Wound Trauma Dynamics and the Potential Role of Anatomical Models*; The University of Adelaide: Adelaide, Australia, 2014; pp. 8–204. Available online: https://digital.library.adelaide.edu.au/dspace/bitstream/2440/99527/2/02whole.pdf (accessed on 2 November 2021).
19. Koene, L.; Papy, A. Towards a better, science-based, evaluation of kinetic non-lethal weapons. *Int. J. Intell. Def. Support Syst.* **2011**, *4*, 169–186. [CrossRef]
20. Mabbott, A.; Carr, D.J.; Champion, S.; Malbon, C. Comparison of porcine thorax to gelatine blocks for wound ballistics studies. *Int. J. Leg. Med.* **2016**, *130*, 1353–1362. [CrossRef] [PubMed]
21. Appleby-Thomas, G.J.; Wood, D.C.; Hameed, A.; Painter, J.; Le-Seelleur, V.; Fitzmaurice, B.C. Investigation of the high-strain rate (shock and ballistic) response of the elastomeric tissue simulant Perma-Gel®. *Int. J. Impact Eng.* **2016**, *94*, 74–82. [CrossRef]
22. Pervin, F.; Chen, W.W. Mechanically Similar Gel Simulants for Brain Tissues. In *Conference Proceedings of the Society for Experimental Mechanics Series*; Springer: New York, NY, USA, 2011; Volume 1, pp. 9–13. [CrossRef]
23. Pirlot, M.; Dyckmans, G.; Bastin, I. Soap and gelatine for simulating human body tissue: An experimental and numerical evaluation. In Proceedings of the 19th International Symposium of Ballistics, Interlaken, Switzerland, 7–11 May 2001; Abal, R., Ed.; Royal Military Academy: Brussels, Belgium, 2001; pp. 1–9. Available online: https://www.researchgate.net/profile/Marc-Pirlot/publication/266459600_SOAP_AND_GELATINE_FOR_SIMULATING_HUMAN_BODY_TISSUE_AN_EXPERIMENTAL_AND_NUMERICAL_EVALUATION/links/54dc60bc0cf23fe133b141e0/SOAP-AND-GELATINE-FOR-SIMULATING-HUMAN-BODY-TISSUE-AN-EXPERIMENTAL-AND-NUMERICAL-EVALUATION.pdf (accessed on 18 November 2021).
24. Shepherd, C.J.; Appleby-Thomas, G.J.; Wilgeroth, J.M.; Hazell, P.J.; Allsop, D.F. On the response of ballistic soap to one-dimensional shock loading. *Int. J. Impact Eng.* **2011**, *38*, 981–988. [CrossRef]
25. Defensible Ballistics. Ballistic Soap (Large Block)—Defensible Ballistics. 2022. Available online: https://www.defensible.co.uk/products/p/ballistic-soap-large-block (accessed on 3 March 2022).
26. ArtMolds. Roma Plastilina No. 1 Material Safety Data Sheet. Available online: https://www.artmolds.com/pub/customfile/MSDS_ROMA_1.pdf (accessed on 3 March 2022).
27. Hernandez, C.; Buchely, M.F.; Maranon, A. Dynamic characterization of Roma Plastilina No. 1 from Drop Test and inverse analysis. *Int. J. Mech. Sci.* **2015**, *100*, 158–168. [CrossRef]
28. National Institute of Justice. Ballistic Resistance of Personal Body Armor, NIJ Standard-0101.04 | National Institute of Justice. NIJ Standard-0101.04 United States of America: National Institute of Justice-USA. September 2000; pp. 1–65. Available online: https://nij.ojp.gov/library/publications/ballistic-resistance-personal-body-armor-nij-standard-010104 (accessed on 10 December 2021).
29. Croft, J.; Longhurst, D. HOSDB Body Armour Standards for UK Police (2007). Part 2: Ballistic Resistance. 39/07/B Home Office. 2007, pp. 1–36. Available online: https://www.bodyarmornews.com/wp-content/uploads/2013/10/HOSDB__2007_-_part_2.pdf (accessed on 6 October 2021).
30. Suppitaksakul, C. A measuring set for visualization of ballistic impact on soft armor. In Proceedings of the 2010 7th International Symposium on Communication Systems, Networks and Digital Signal Processing, CSNDSP 2010, Newcastle Upon Tyne, UK, 21–23 July 2010; IEEE Computer Society: Washington, DC, USA, 2010; pp. 359–363. [CrossRef]
31. EnvironMolds. Technical Bulletin: Roma Plastilina No.1 Ballistic Clay. 2008. Available online: https://www.artmolds.com/pdf/RomaPlastilinaNo1TechBulletin.pdf (accessed on 4 March 2022).
32. Tao, R.; Rice, K.D.; Djakeu, A.S.; Mrozek, R.A.; Cole, S.T.; Freeney, R.M.; Forster, A.M. Rheological Characterization of Next-Generation Ballistic Witness Materials for Body Armor Testing. *Polymers* **2019**, *11*, 447. [CrossRef] [PubMed]
33. Mrozek, R.; Edwards, T.; Bain, E.; Cole, S.; Napadensky, E.; Freeney, R. Developing an Alternative to Roma Plastilina #1 as a Ballistic Backing Material for the Ballistic Testing of Body Armor. In *Conference Proceedings of the Society for Experimental Mechanics Series*; Springer: Cham, Switzerland, 2019; pp. 297–299. [CrossRef]
34. Malbon, C.; Carr, D. *Comparison of Backing Materials Used in the Testing of Ballistic Protective Body Armour*; Cranfield Online Research Data (CORD): Cranfield, UK, 2018; p. 1. Available online: https://doi.org/10.17862/CRANFIELD.RD.7347245.V1 (accessed on 8 March 2022).
35. Abdul-Rahman, F. Reduce, Reuse, Recycle: Alternatives for Waste Management Guide G-314. January 2014, pp. 1–8. Available online: http://aces.nmsu.edu/pubs/_g/G304.pdf (accessed on 10 March 2022).
36. HM UK Government. *Net Zero Strategy: Build back Greener*; HM Government: London, UK, 2021; pp. 1–368. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf (accessed on 11 March 2022).
37. Defence Equipment & Support. Our New Environmental Strategy—Defence Equipment & Support. 2021, pp. 1–19. Available online: https://des.mod.uk/our-new-environmental-strategy/ (accessed on 11 March 2022).
38. Jussila, J. Preparing ballistic gelatine—Review and proposal for a standard method. *Forensic Sci. Int.* **2004**, *141*, 91–98. [CrossRef] [PubMed]
39. Clear Ballistics. 10% Ballistic Gelatin FBI Block. 2020. Available online: https://www.clearballistics.com/shop/10-ballistic-gelatin-fbi-block/ (accessed on 3 March 2022).
40. Sculpture House. ROMA Plastilina—Gray-Green—No.1—2ibs. 2022. Available online: https://www.sculpturehouse.com/p-1157-roma-plastilina-gray-green-soft-case.aspx (accessed on 6 March 2022).

41. Carton, E.; Roebroeks, G.H.J.J.; Broos, H.; Halls, V. Characterization of Dynamic Properties of Ballistic Clay. In Proceedings of the Personal Armour Systems Symposium, Nurnberg, The Netherlands, 17–21 September 2012; 2014; pp. 1–10. Available online: https://www.researchgate.net/publication/306359099_Characterization_of_dynamic_properties_of_ballistic_clay (accessed on 10 March 2022).
42. Ballistic Dummy Labs. Ballistic Blocks. 2022. Available online: https://ballisticdummylab.com/collections/ballistic-blocks-1 (accessed on 3 March 2022).
43. Defensible Ballistics. Ballistic Gel. 2022. Available online: https://www.defensible.co.uk/products/ballistic-gel (accessed on 3 March 2022).
44. Health and Safety Executive. Economics of Health and Safety—Appraisal Values or "Unit Costs". 2022. Available online: https://www.hse.gov.uk/economics/eauappraisal.htm (accessed on 17 March 2022).
45. Health and Safety Executive. Costs to Britain of Workplace Fatalities, Self-Reported Injuries and Ill Health, 2018/19. 2020. Available online: https://www.hse.gov.uk/statistics/pdf/cost-to-britain.pdf (accessed on 17 March 2022).
46. Ministry of Defence. Deaths in the UK Regular armed Forces: Annual Summary and Trends over Time 1 January 2010 to 31 December 2019. March 2020; pp. 1–28. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/875096/20200226_UK_Deaths_National_Statistic_2020-O.pdf (accessed on 3 February 2022).
47. Defence Safety Authority. DSA01.1 Defence Policy for Health, Safety and Environmental Protection. DSA 01.1 Ministry of Defence. August 2016; pp. 1–36. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/548060/DSA01_Defence_Policy_for_Health_Safety_and_Environmental_Protection-20160804.pdf#:~{}:text=DSA01.1 (accessed on 3 February 2022).
48. *ISO 14001:2015*; Environmental Management Systems—Requirements with Guidance for Use. International Standards Organisation: Geneva, Switzerland, 2015; pp. 1–35. Available online: https://www.iso.org/standard/60857.html (accessed on 3 February 2022).
49. *ISO 14040:2006*; Environmental Management—Life Cycle Assessment—Principles and Framework. International Standards Organisation: Geneva, Switzerland, 2006; pp. 1–20. Available online: https://www.iso.org/standard/37456.html (accessed on 3 February 2022).
50. Galante, E.; Temple, T.; Ladyman, M.; Gill, P.P. The UK Ministry of Defence Project Orientated Environmental Management System (POEMS). *Propellants Explos. Pyrotech.* **2016**, *42*, 36–43. [CrossRef]
51. *ISO 14044:2006*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. International Standards Organisation: Geneva, Switzerland, 2006; pp. 1–46. Available online: https://www.iso.org/standard/38498.html (accessed on 4 February 2022).
52. Shepherd, C.J.; Appleby-Thomas, G.J.; Hazell, P.J.; Allsop, D.F. *The Dynamic Behaviour of Ballistic Gelatin*; Cranfield University: Swindon, UK, 2009; pp. 1–4. Available online: https://dspace.lib.cranfield.ac.uk/bitstream/handle/1826/5321/Shepherd%20et%20al.%20SCCM2009_pre-published.pdf?sequence=1 (accessed on 4 February 2022).
53. Radosinski, L.; Labus, K.; Zemojtel, P.; Wojciechowski, J.W. Development and Validation of a Virtual Gelatin Model Using Molecular Modeling Computational Tools. *Molecules* **2019**, *24*, 3365. [CrossRef] [PubMed]
54. Batty, M. Digital twins. *Environ. Plan. B Urban Anal. City Sci.* **2018**, *45*, 817–820. [CrossRef]
55. Gelatine Manufacturers of Europe. Social Responsibility. 2021. Available online: https://www.gelatine.org/en/socialresponsibility.html#c1375 (accessed on 15 March 2022).
56. Alipal, J.; Mohd Pu'Ad, N.A.S.; Lee, T.C.; Nayan, N.H.M.; Sahari, N.; Basri, H.; Idris, M.; Abdullah, H. A review of gelatin: Properties, sources, process, applications, and commercialisation. *Mater. Today Proc.* **2021**, *42*, 240–250. [CrossRef]
57. Haug, I.J.; Draget, K.I. 6—Gelatin. In *Handbook of Hydrocolloids*, 2nd ed.; Woodhead Publishing: Sawston, UK, 2009; pp. 142–163. [CrossRef]
58. Mckinnon, A. *CO_2 Emissions from Freight Transport in the UK: Report Prepared for the Climate Change Working Group of the Commission for Integrated Transport 2007*; Heriot-Watt University: Edinburgh, UK, 2007; pp. 1–58. [CrossRef]
59. Delgado, O.; Rodríguez, F.; Muncrief, R. *Fuel Efficiency Technology in European Heavy-Duty Vehicles: Baseline and Potential for the 2020–2030 Time Frame*; International Council on Clean Transportation Europe: Berlin, Germany, 2017; pp. 1–76. Available online: https://theicct.org/sites/default/files/publications/EU-HDV-Tech-Potential_ICCT-white-paper_14072017_vF.pdf (accessed on 9 February 2022).
60. Mckinnon, A. *A Logistical Perspective on the Fuel Efficiency of Road Freight Transport*; Heriot-Watt University: Edinburgh, UK, 1999; pp. 1–28. Available online: https://www.researchgate.net/publication/253972398 (accessed on 9 February 2022).
61. Liimatainen, H.; van Vliet, O.; Aplyn, D. The potential of electric trucks—An international commodity-level analysis. *Appl. Energy* **2019**, *236*, 804–814. [CrossRef]
62. Feng, W.; Figliozzi, M.A. Conventional vs. Electric Commercial Vehicle Fleets: A Case Study of Economic and Technological Factors Affecting the Competitiveness of Electric Commercial Vehicles in the USA. *Procedia-Soc. Behav. Sci.* **2012**, *39*, 702–711. [CrossRef]
63. Mayor of London. The Mayor's Ultra Low Emission Zone for London | London City Hall. 2021. Available online: https://www.london.gov.uk/what-we-do/environment/pollution-and-air-quality/mayors-ultra-low-emission-zone-london (accessed on 15 March 2022).
64. Just Energy. Electricity 101. 2020. Available online: https://justenergy.com/learning-center/electricity/ (accessed on 15 March 2022).

65. Panwar, N.L.; Kaushik, S.C.; Kothari, S. Role of renewable energy sources in environmental protection: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1513–1524. [CrossRef]
66. Zecheru, T.; Dena, A.; Cîrmaci, M.; Său, C.; Zaharia, C.; Lăzăroaie, C. Potential Use in Forensics of a Novel Hybrid Gelatin—Dynamic Impact Assessment. *J. Forensic Sci.* **2018**, *63*, 758–765. [CrossRef]
67. Difference Between. Difference Between Physical and Chemical Cross Linking|Compare the Difference Between Similar Terms. 2021. Available online: https://www.differencebetween.com/difference-between-physical-and-chemical-cross-linking/ (accessed on 17 March 2022).
68. Ermis, M.; Calamak, S.; Kocal, G.C.; Guven, S.; Durmus, N.G.; Rizvi, I.; Hasan, T.; Hasirci, N.; Hasirci, V.; Demirci, U. Hydrogels as a New Platform to Recapitulate the Tumor Microenvironment. In *Handbook of Nanomaterials for Cancer Theranostics*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 463–494. [CrossRef]
69. Vasile, C. Polymeric Nanomaterials: Recent Developments, Properties and Medical Applications. In *Advanced Drug Delivery Reviews*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 1–66. [CrossRef]
70. Hennink, W.E.; van Nostrum, C.F. Novel crosslinking methods to design hydrogels. *Adv. Drug Deliv. Rev.* **2012**, *64*, 223–236. [CrossRef]
71. Mooradian, D.L. Allografts and xenografts in soft tissue repair: Current use and future trends. In *Extracellular Matrix-derived Implants in Clinical Medicine*; Woodhead Publishing: Cambridge, UK, 2016; pp. 41–62. [CrossRef]