

OPTIMAL SKIN SIMULANT FOR BALLISTIC TESTING

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Abstract

An extensive literature review, combined with practical experience of forensic testing, has identified several concerns regarding existing studies into skin simulants. These can be summarized as arising due to human skin being a highly complex, multi-layered and anisotropic material whose mechanical properties depend on many factors such as age and gender of the host. In many studies (and papers) essential information is missing. Although there is some parallelism between the studies, the reported energy density at perforation is very inconsistent (a function of the natural variation of skin properties alluded to above) and differs from 0,113 J/mm² [1] to 0,239 J/mm² [2]. Which is, in fact, a more than 100% variation. Such a variation is arguably insufficient to enable accurate replication with a single simulant material. Combined with the missing common agreement about the energy density threshold between countries, laboratories and researchers, this analysis clearly identifies the need for an adjustable and / or customizable skin simulant. To-date, the most often used simulation material for human skin in ballistic testing is 'Chrome crusted cow hide' [3]. However, this is a natural material and, consequently therefore, inevitably physically variable in nature – both inter and intra hide. Ballistic tests on 10 chrome crusted cow hides using 4,5 mm BB's gave v50% ranging from 113 m/s to 200 m/s, an uncontrolled variability for forensic experiments. Hence, the authors examined a skin analogue that could be produced in-house, enabling tailoring to match the desired properties, and with improved consistency. To this end, a thin, 4 mm thick, layer of gelatine (30 – 45 weight %,

increasing per 1 weight %) was studied. The ballistic resistance of the gelatine skin analogue was compared to the v50%'s published values in literature, with good agreement found as the gelatine concentration was varied. In comparison to the chrome crusted cow hides this suggests that this relatively simple and accessible approach has potential to provide a more consistent standard.

In the aftermath of shooting incidents in the Netherlands, the question often arises whether the weapon and / or the incident could have been lethal. Differentiation between potential effects of a given weapon can have a massive societal impact, since the punishment demanded by the public prosecutor depends on the crime committed and the lethality of the used firearm. These questions especially occur at incidents involving unstable or low velocity projectiles. For example, with air pressured rifles, converted firearms, indirect shots, etc. To assess the potential lethality of fired projectiles, validated simulation materials are needed to measure phenomena like projectile perforation, penetration depth, energy transfer, trajectory deflection, etc. of the used ammunition. Synthetic simulation materials are already in use for bones [4], skull [5] and soft (muscle) tissue [6]. However, no universally accepted (homogeneous) material has been found as a suitable skin simulant for ballistic testing [7]. This is compounded by the complexity of skin, the variation of measured intra and inter skin properties [8-10], and the variations in $v_{50\%}$ (the velocity where 50% of the shots penetrate and 50% of the shots do not) from numerous studies [11-14]. These are discussed in more detail later. While “chrome-crust cowhide” is the most widely adopted / best validated skin simulant, as a natural material, variation in properties such as thickness and tensile strength, amongst others, inevitably affect repeatability of ballistic experiments. To get repeatable and reliable measurements for empirical shooting tests, as little variation as possible in the ballistic response is desired. This is especially the case for the transition regime between penetration and non-penetration. A standardized, homogeneous material, with known mechanical properties, would reduce this variability.

To this end, the authors propose a new method of using an adjustable gelatine layer as a skin simulant. The suggested and validated method demonstrates the ability of the gelatine skin simulant to cover the whole range of human skin $v_{50\%}$ as reported in the literature. Importantly, this accessible and flexible approach holds out the potential to

give forensic scientists the possibility of tailoring a skin simulant to the desired situation, something which would be extremely useful to reconstruct shooting incidents as requested by court.

Requirement for a reproducible skin simulant

The punishment demanded by the public prosecutor or imposed by the judge depends on the crime committed. The less serious the crime, the lower the penalty. Whilst the specific legal requirements and penalties vary with region/nationality and are beyond the scope of this paper, in this study, the authors have chosen to focus on the area of Dutch law. This is to enable specific examples in the legal sphere to be highlighted as the primary author has personal knowledge of the same.

A good example is the fact that in Dutch law there is a differentiation between (attempted) murder, manslaughter and mistreatment [15]. If, for example, the weapon used lacks the energy to commit a homicide, the punishment imposed by the judge would not be based on murder or manslaughter, but on mistreatment. Differentiation between potential effects of a given weapon can therefore have a massive societal impact. In cases where firearms are used, ballistic trials offer a way to map the potential energy. In the Netherlands, the energy, impact or lethality of the used weapon is often tested by empirical shooting experiments on simulation target materials. Importantly, as such experiments are conducted not only to test the weapon, but also to reconstruct shooting incidents involving human casualties, accurate simulation materials are needed to capture the likely effects of the resultant impact for both ethical and practical reasons. For example, precise simulation of penetration depth into the impacted tissue and the assessment of damage / associated rates of projectile energy loss.

However, living systems are extremely complex in construction – e.g. the multi-layered (and often anisotropic [16]) nature of tissue and the dermal layers. There are several different layers / elements which comprise a typical tissue. These include connective tissue (e.g. adipose tissue), muscle tissue, nervous tissue and epithelial tissue (e.g. dermal layers) [17, 18]. The dermal layer (skin) is a multi-layered thin membrane. This

membrane covers the surface of the body and is often considered of little importance in ballistic testing, with much more attention given to the bulk gelatine tissue simulant [19, 20]. As a consequence of this complex nature, prediction of the ballistic effect on living targets is extremely challenging. At higher velocities the effect of skin may be less vital, but while typically a thin layer, skin has the potential to influence failure modes – particularly in bone – during and after ballistic impact, for example, preventing ejection of bone fragments away from the impact point. A wide variety of synthetic simulation materials are already in use for analogues of bone and bulk tissue (for example, Synbone® and ballistic gelatine [3, 6, 7, 21-24]). However, to-date only a very limited number of materials have been considered for simulation of the physical properties of epidermis (skin) [25]. The challenge is exacerbated by the natural variation in the properties of skin, both inter and intra people. As an example of just one factor, Southwood in 1955 stated that human skin thickness varied considerably [26]. Similarly, Fenton et al. [7] summarized different research papers, stating that the mean thickness of human skin varied from 0,3 mm to 2,6 mm. Such variations must inevitably affect the response to ballistic impact. Furthermore, like many materials, tissues are known to have a high degree of strain-rate sensitivity [27], a factor which is much less well understood [7]. Whilst it is possible to be able to match the reported quasi-static properties of skin to a synthetic material, matching at higher strain-rates might be challenging. Combined with the relatively unknown anisotropic failure characteristics [16], it's unlikely that a single skin simulant material would be sufficient to simulate dynamic behaviour under impact. Hence, skin simulants utilised in blunt impact studies may not be suitable for ballistic impact studies.

Requirement for an adjustable skin simulant

Based on the literature summarised in the earlier paragraphs, it is apparent that human skin is a very complex material. The mechanical properties of human skin are dependent on many factors including age, gender, health conditions, hydration, Langer's lines, anatomical region, testing method and testing orientation (due to skin being highly anisotropic).

However, in many articles key information is missing, e.g., specimen size, method, instrumentation, test speed, environmental conditions, thickness (with or without dermis and underlying tissue), orientation (in-plane directions). These omissions are likely a function of the fact that very many discussions in the literature are aimed at solving a particular (forensics) problem, rather than providing a more general solution to the issue of tissue analogue reproducibility.

If the complexities and missing key information are taken into account, it should not come as a surprise that the reported energy density (the energy per unit area) needed to penetrate human skin is very inconsistent throughout the literature, see Table 1. As an example, Sellier found the lowest value of 0,113 J/mm² based on the measurements of Sperrazza and Kokinas [28]; whereas the highest value 0,239 J/mm² was found by Bir et al. [21]. Interestingly Jussila [3], Misliwetz [14] and DiMaio [13] are somewhat in the middle with 0,16 to 0,21 J/mm² (unsurprisingly for Jussila [3] as his work was in-part based on averages of the literature to-date at the time the work was produced). These differences make it very complex to find one suitable skin simulant – clearly identifying the need for a more rigorous approach / solution.

Table 1 Threshold velocities obtained for literature review, calculated back to a 4,5 mm steel sphere.

Velocity [m/s]	Kinetic Energy Density [J/mm ²]	Reference	Comment
95	0,10	NATO standard [29]	Lowest limit
100	0,11	Sellier [1]	
110	0,13	Mattoo [12]	
120	0,16	Jussila et al. [3]	Average value of skin on chest 30 y/o man
130	0,18	DiMaio et al. [13]	Averaged value
140	0,21	Misliwetz [14]	
150	0,24	Bir et al. [21]	

Current situation

Ballistic testing is inherently expensive and hazardous in nature. Combined with the availability of material and ethical considerations, this has led to a significant drive to maximise the value (effectiveness) of ballistic tests when they are undertaken. Further, there is a challenge in employing real-world tissue-based targets, often necessitating the use of simulant materials. However, only a very limited number of materials have been considered for a ballistic impact simulant of human skin. As mentioned before, the most often used simulation material for human skin is 'Chrome crusted cow hide' [3].

However, the variability in mechanical and ballistic properties of this natural material both inter and intra hide directly affects the repeatability of resultant experiments, a challenge (with natural materials) clearly highlighted by Breeze et al. [30] in their work using goat's skin. [3]

Consequently, in order to ensure accurate and repeatable ballistic tests, there is a clear need to find or develop a more consistent (in terms of the factors mentioned earlier) skin analogue. In addition, whether by having a material whose properties can be (reliably) altered, or a range of materials, the ability to match the properties of the simulant to the expected, potential, or court required properties of skin on the victim may have further / future forensic advantages. In order to solve this clear need, the authors present a novel solution to overcome these shortcomings in the currently used skin analogues.

2 Method and Materials

2.1 Chrome crusted cow hides

Chrome crusted cow hides were used to enable a baseline assessment of the most widely used material. Jussila [3] found this to be the best of the skin simulants that he evaluated. He attributed this optimum behaviour to the experimentally determined v50% when compared to the v50% of human skin he had chosen as his benchmark. In addition, he cited the consistency of the average tensile strength across samples of $20,89 \pm 4,11 \text{ N/mm}^2$. However, in contrast, Fenton et al. [7] stated that skin (both human and animal) is extremely variable in its properties, due to the inherent difference in age, sex, location, orientation and so on – with an inevitable influence in ballistic response. A total of 10 different leather hides were bought to enable both intra and inter studies of the ballistic properties. The hides are all chrome tanned upholstery “crust” cowhide with a nominal thickness of 1,0 mm. The hides were cut into 40x15 cm rectangles to fit the gelatine blocks and attached to the gelatine by using cling film. The latter was selected as it was very thin and had minimal impact (checked by experiment) on ballistic performance.

2.2 Preparing the gelatine

The disadvantages of the currently preferred material is clearly highlighted in the earlier discussion. Of particular note were issues around the consistency, reinforced by ballistic experiments on the 10 cow hides as reported later. The need for a different (type of) material was consequently immediately obvious. To this end, the approach of using a castable material was considered. Gelatine is widely used as a soft tissue simulant [31, 32], but in a thin and higher percentage (concentration) layer it has – to the authors knowledge – never reportedly been investigated as a potential (tailorable) skin simulant. One of the key advantages of such an approach over conventional more variable materials such as rubbers is the adjustability of the mechanical and ballistic properties

by changing the percentage weight of gelatine – for example, potentially providing a route to simulate skin of different ages.

Further, gelatine is already routinely used in many ballistic ranges and therefore the material / facilities required – as well as the manufacturing expertise – will already be in place. This is important as it has the potential to facilitate uptake of the technique presented here within the wider forensics / ballistic community.

Gelatine blocks used to simulate human tissue usually consist of 10 [32, 33] or 20 weight % [23, 34, 35] concentration gelatine. To investigate its use as a simulant of human skin, in this study, sheets were cast in higher percentages. Initially starting at 30 weight % concentration gelatine, this was increased in intervals of 1%. After 45 weight % the gelatine became too viscous to pour, identifying an upper bound in terms of the practical concentrations to be considered for future work.

The steps needed to prepare the tissue simulant gelatine differ slightly between papers [31, 33, 36] but the fundamental process is quite similar. They generally follow the common steps of dispersion, swelling, dissolution, moulding and setting to make the gelatine. The method as published by the gelatine manufacturer Gelita [37], is shown in Figure 1.

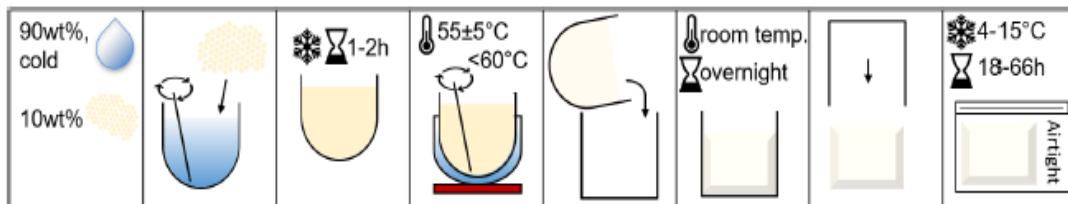


Figure 1 Method of preparing gelatine, according to the manufacturer, from ref [38].

Fackler and Malinowski [33] were amongst the first authors to describe their manufacturing method in 1987. They used cold water in the dispersion step and suggested keeping the temperature, when dissolution was occurring, to below 40 °C to avoid thermal degradation. Jussila [31] on the other hand, described using half heated water and half cold water in the dispersion step and heated the mixture up to 45 °C.

This approach may have been adopted to let the gelatine dissolve easier in the water. In contrast, Coupland, Rothschild and Thali [36] and GELITA AG [37] used cold water again, but instead suggested heating the mixture to a maximum of $55 \pm 5^\circ\text{C}$ (based on the fact that they noted that thermal degradation began occurring only at 60°C or above). With this work, to accommodate the higher percentages of gelatine anticipated as being required for the skin simulant (to ensure sufficient stiffness, etc), the basic method had to be slightly adjusted. This was necessary as the higher percentages of gelatine couldn't be fully dissolved in cold water. Hence the method was adapted to include a 2 minute delay between adding the gelatine to the water and stirring which was found to aid gelatine dissolution. Once the gelatine mixture was poured into the moulds, they were immediately wrapped in plastic to prevent water evaporation, only being unwrapped immediately prior to ballistic testing. Hence, the refined method followed for the production of all the gelatine sheets was consequently as seen in the flow chart in Figure 2 below.



Figure 2 Flow chart illustrating the production process for gelatine sheets employed by the authors.

2.3 Preparation of the gelatine moulds

Moulds were designed and manufactured to enable the reliable and reproducible production of cast gelatine sheets. In addition to the weight percent gelatine, the thickness of the gelatine was considered to likely have an influence on the ballistic performance of the sheets. Hence the mould was designed to enable different sheet thicknesses in the range 1 to 5 mm to be produced. However, due to practical considerations (e.g. the viscosity of the gelatine made it hard to cast in the thinner moulds), the authors focused on 4 mm thick sheets in this study, a thickness that could be reliably manufactured and was robust enough for handling. The mould, as shown in Figure 3, consists of a thin, flat frame. The frame is sandwiched between two flat plates and screwed tight on the sides. The mould was designed to enable vertical pouring of the gelatine so as to let any air bubbles in the mix float to the top (a sheet edge) and not be trapped along the sheet surface (impact face). By using the flat plates in between the frames, multiple sheets could be simultaneously cast, potentially with varying thickness, as can be seen in Figure 3(C).

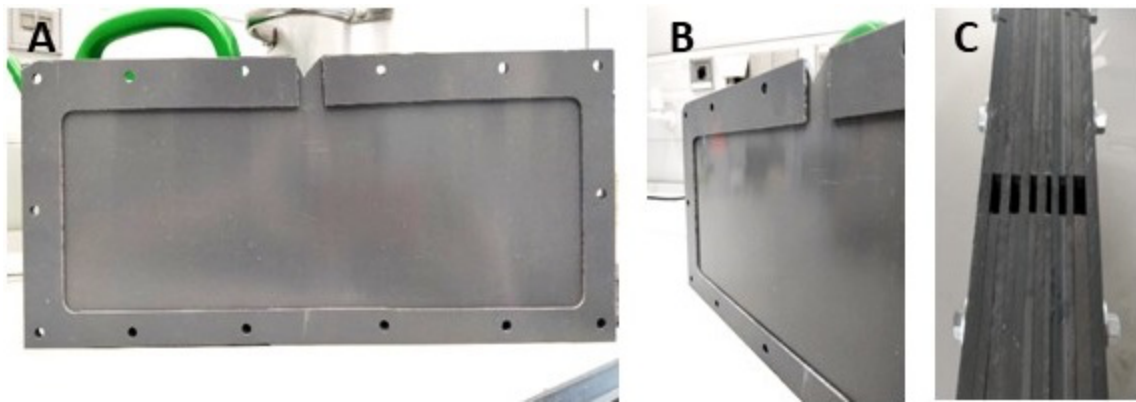


Figure 3 Manufactured moulds for the gelatine skin simulant.

2.4 Shooting protocol

The shooting experiments were performed at the shooting range of the Netherlands Forensic Institute (NFI). This is an indoor shooting range equipped with a bench rest and velocity meters. Figure 4 gives an overview of the experimental arrangement. The top image shows a systematic overview, while the bottom one shows the set-up in practice. This set-up is very simple and based on earlier ballistic experiments, amongst others [2, 3, 14].

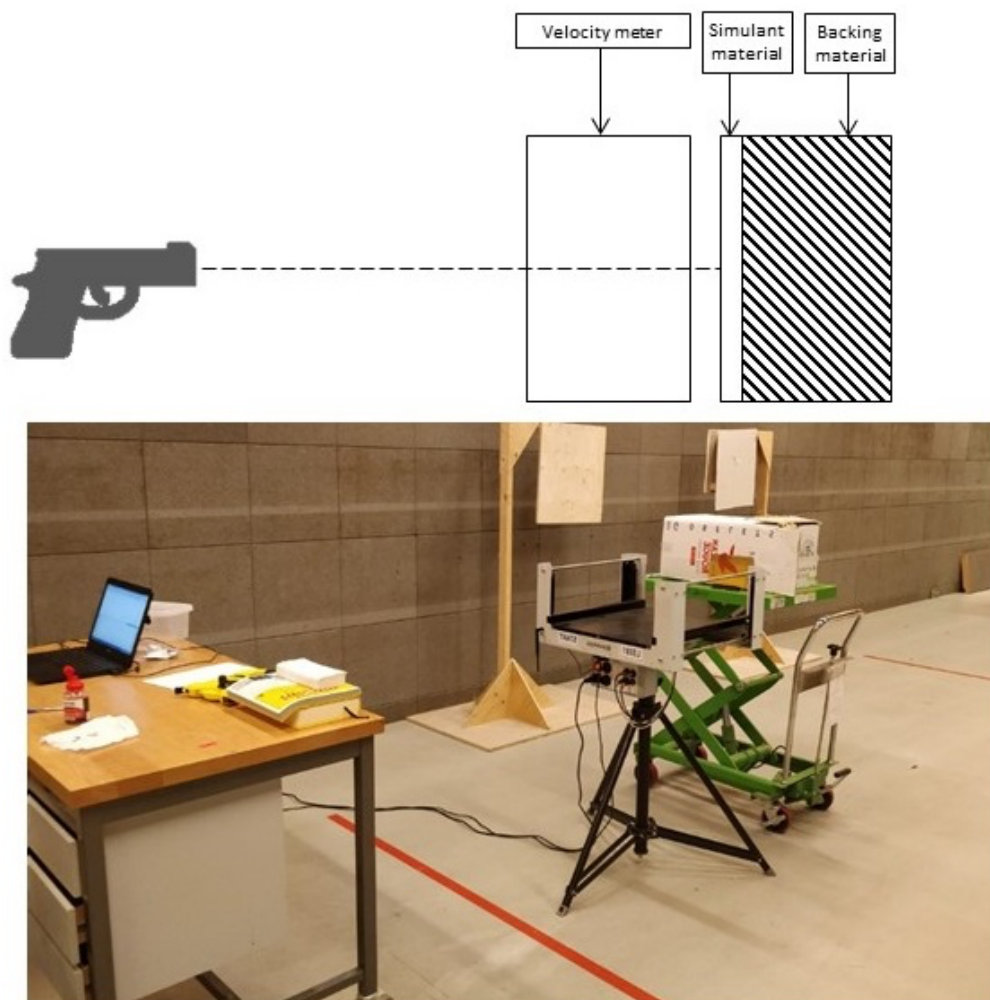


Figure 4 Overview of the shooting set-up at the Netherlands Forensic Institute shooting range: (top) schematic illustration; (bottom) picture of set-up in-situ.

A Crossman model 397PA air pressured rifle with a 4,5 mm barrel was used to perform the shots. Key factors contributing to the choice of this type of rifle were:

- The low average velocity (adjustable between 30 and 180 m/s);
- The relative ease to change the velocity (velocity could be adjusted with the number of pump strokes);
- The 4,5 mm barrel, chosen because previous research has also been done and described in this caliber [3, 13, 14], enhancing the utility in terms of potential for wider comparison of data to be generated in this research.

For projectiles, Crossman 4,5 mm copper coated steel ball bearings (BBs) [39] were used. These were chosen over lead to reduce the projectile deformation on impact. The brand and this specific type of BBs was chosen because the quality (from visual observation) was more consistent than that of 5+ other different brands and models considered by the author. The weight of the Crossman Copperhead BBs was also more consistent than the 5 others. Table 2 shows the average weight and standard deviation of the BBs.

Table 2 Properties of used projectiles.

Brand	Number	Average weight [gram]	Standard deviation
Crossman Copperhead	50	0,345	0,002

The projectile velocity was measured 0,5 m prior to impacting the target. An optical velocity measurement system, Prototypa LS-01L Intelligent light gates, was used to measure the velocity. This optical velocity measurement system has an accuracy of 0,2% [40].

The selected simulant materials were attached to a block of gelatine, just prior to the ballistic tests, and held in place using cling film. The gelatine block was prepared according to the method from Jussila [31]. Type A ballistic grade (250 bloom, 10 weight %) was used, procured from Gelita. The mixture was allowed to cool for 1 hour before being poured into a 40x15x15 cm mould (16"x6"x6"). After air cooling to 20 °C the block was placed in a fridge at 4 °C for 24 hours before use.

For each test on the cow hides and skin simulants, a total of 50 no. 4,5 mm copper coated steel BBs were shot. The use of 50 individual shots per experiment ensured good statistics, that patterns could be clearly discerned and that any outlying results were immediately apparent. The 50 shots were distributed over the 40x15cm surface of the gelatine block. Care was taken to ensure there were gaps between each impact area and no double trajectories were observed. The temperature of the block was measured before and after the shooting, using a thermocouple applied 5 centimetres into the block on the side where the skin simulant was applied. All the tests were conducted with a measured temperature between +3.5° and +4.5 °C, with the simulant/block being returned to the fridge as necessary. Whilst acknowledging the temperature measurement was not taken in the skin simulant layer, an assumption has been made that the thin skin layer would be a very similar temperature even though warming starts on the outside layers. This factor is important, as the temperature has a significant effect on the mechanical properties of the gelatine, as pointed out in the study by Cronin and Falzon [32]. The initial projectile velocity was around 100-120 m/s, using the average penetration velocity from the literature (for ballistic gelatine) as reference. For each shot, the velocity was measured, along with whether or not the bullet had penetrated into the gelatine, the latter determined by visual observation post firing.

2.5 Analytical approach

A common method of analysing the effectiveness of ballistic skin simulants (simulant with a gelatine backing) is to measure the impact velocity and the penetration depth. Analysis is then by a linear regression line to plot the impact velocity and the penetration depth. The linear regression has an equation of the form $Y = a + bX$. Translated back to this particular research, Y represents the v50%, X the Gelatine weight percentage and a and b are the models' parameters; e.g.

$$v50\% = a + b \cdot \text{Gelatine weight \%} \quad (1-1)$$

The linear regression line is practical, it is very easy to plot with just a few shots. However, this approach assumes that both materials (the tested skin simulant and the gelatine backing) are behaving the same at different velocities – e.g., that deformation and failure modes are consistent across the velocity range of interest. This assumption, that the whole interaction between the bullet, skin- and tissue simulant is linearly correlated with the velocity seems simplistic. This is especially the case since Ottenio [16] pointed out that the mechanical properties of human skin (like most if not all materials) are subject to modification with strain rate (corresponding to impact velocity). Therefore, it was felt important to consider that there might be some heteroscedasticity. The regression line may lead to extrapolating at the extremities of the data set, where one would expect some kind of ‘boundary’ effect. Hence, in this research a different approach is used, similar to Bir et al. [2, 21].

While the research presented in this study also involved shooting at a skin simulant with gelatine backing material and measuring the impact velocity, only bullet penetration or non-penetration was considered. In this case the velocity is the independent variable, or covariate and the penetration or non-penetration is a binary / dichotomous dependent variable [41]. A logistic regression can be used to model the probability of an event happening – in this case penetration / non penetration (the dependent variable), which is based on the velocity (the independent variable). The formula for the logistic regression is as follows [42]:

$$\pi (x) = \frac{e^{(\beta_0 + \beta_1 x)}}{1 + e^{(\beta_0 + \beta_1 x)}} \quad (1-2)$$

Which can be rewritten for this series of tests as (where P is the probability of penetration and V is the velocity):

$$P (V) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 V)}} \quad (1-3)$$

For each weight percentage of gelatine, 50 shots were conducted at each velocity. The penetration / non-penetration and velocity data for each shot was recorded in Microsoft

Excel and imported into SPSS Statistics 26 (IBM Corp.). In order to implement the analytical approach, the binary logistic regression option in SPSS, using the logistic regression formula above, was employed to analyze the data and determine how velocity affects the probability of a bullet penetrating the skin simulant under consideration.

3 Results: Chrome crusted cow hides

Analysis of the shooting tests on the 10 hides resulted in Figure 5. The variation in v50% per hide is clearly shown in this graph. Again, this variation is arguably quite shocking, not least since the chrome tanned upholstery “crust” cowhide considered here is supposed to be one of the best natural skin simulants. As stated before, in order to ensure accurate and repeatable (and consequently evidentially useful) ballistic tests a more consistent and effective skin analogue is consequently desired.

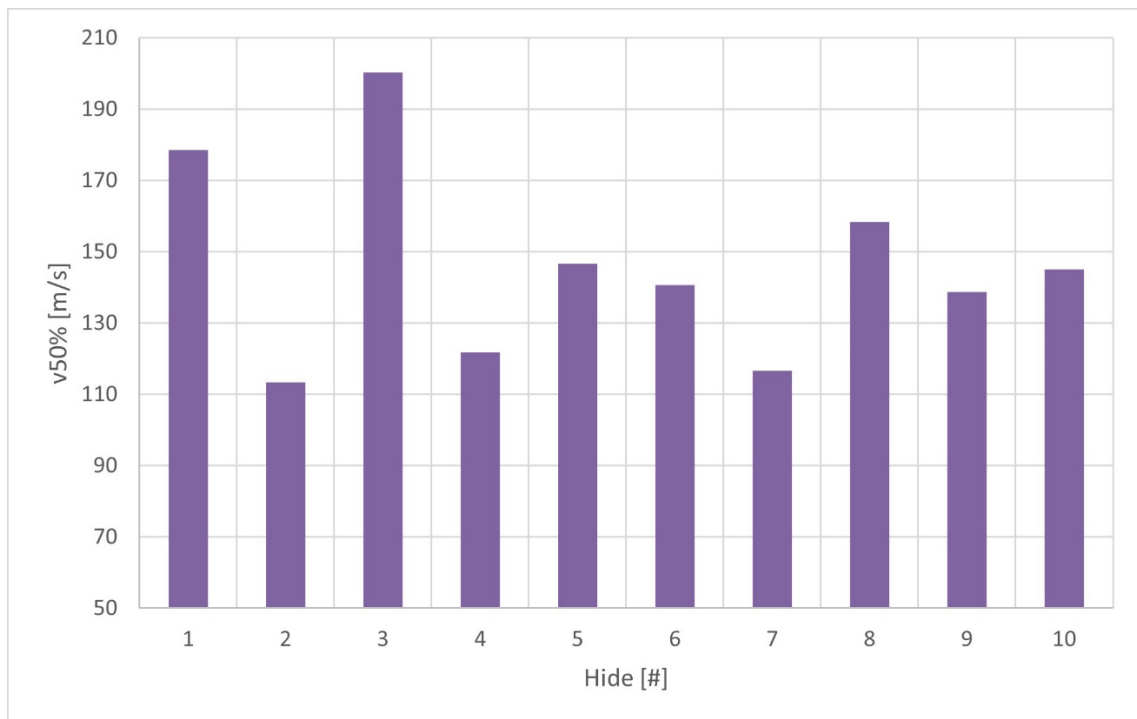


Figure 5 v50% penetration velocity leather hides.

Building on the data above, the logistic regression plots in Figure 6 below also clearly indicate the spread of the v50% in the hides. The gradient of the plots is an indication of the consistency of the material. The steeper the curve, the more consistent the material is / the lower the level of scatter in the underlying data. Ideally therefore, the gradient of the plots should be vertical. This means that materials (hides) with a lower gradient are more inconsistent. The averaged gradient of the leather hides was 0.021 (SD = 0.055). Figure 5 and Figure 6 combined illustrate the essential problem of using leather as a skin simulant, both the inter and intra variation are shocking for a material that is often used as a skin simulant.

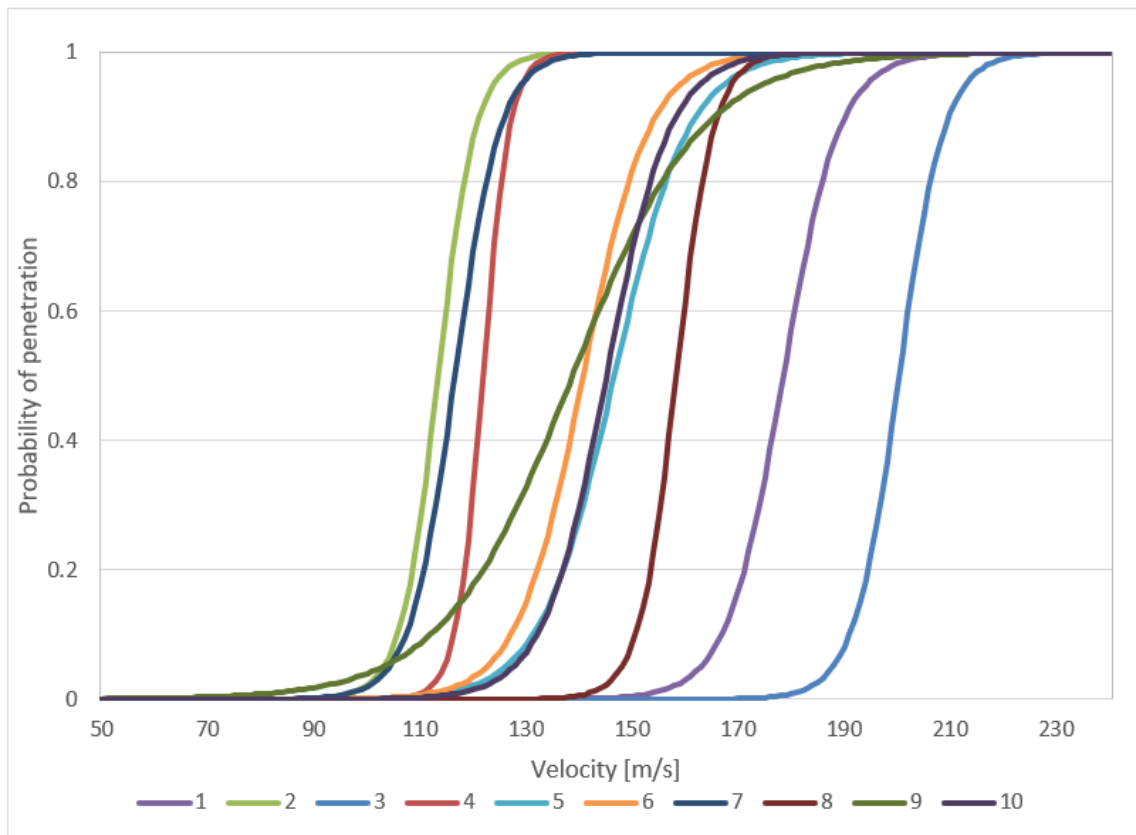


Figure 6 Results of logistic regression of 10 leather hides v50%, each colour represents a different hide. Given the velocity (on the x-axis), the probability is given (on the y-axis) that a 4,5 mm sphere perforates the skin simulant.

4 Results: Gelatine

The gelatine v50% logistic regression plots in Figure 7 display the results for a 4 mm thick sheet in a range of weight percentages (of gelatine), starting at 30% and increasing to 45%. A horizontal translation per percentage may therefore be expected. However, on closer inspection it's apparent that the data in the figure isn't as linear as the corresponding interval of 1 weight % increase in the gelatine concentration between tested sheets. As an example, the lines of 40% and 41% are almost overlapping – hinting at the challenges associated with creating higher concentration mixes. This is something which is also seen in the gradient of the 42, 43 and 45% plots. In turn, the plots of these higher weight percentages tend to be less steep - and therefore more inconsistent - than the lower weight percentages.

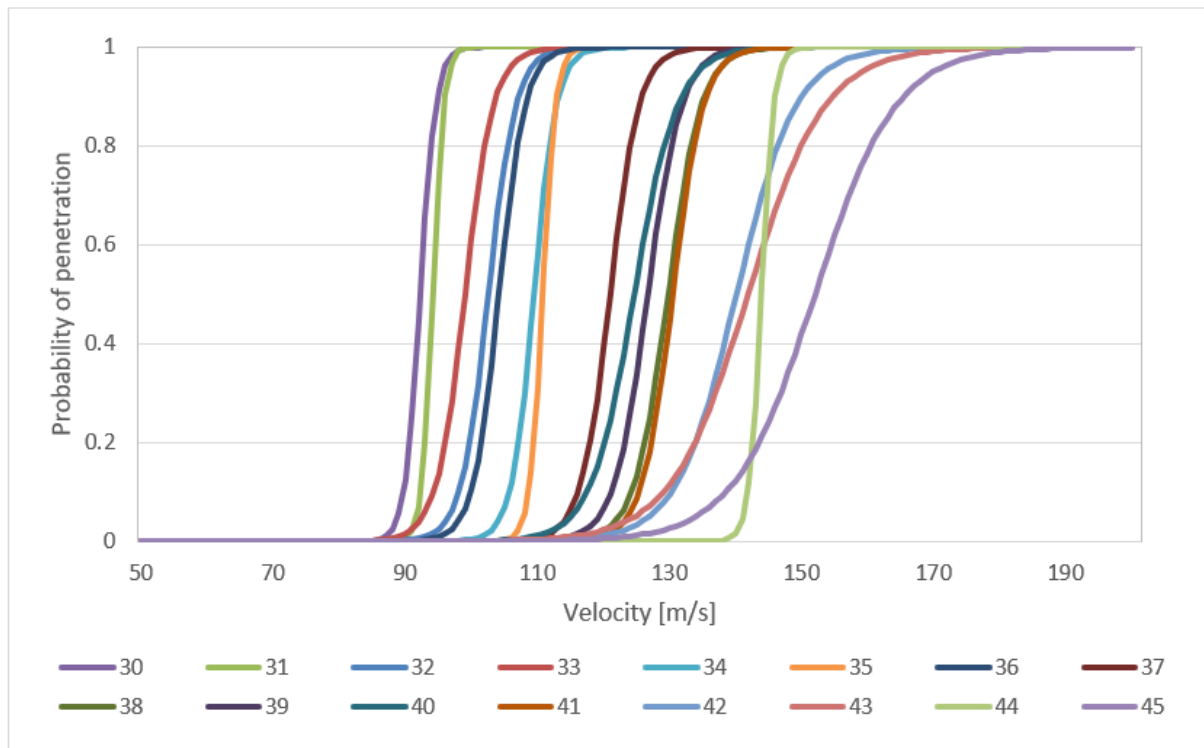


Figure 7 Results of logistic regression of gelatine skin simulants v50%, increasing per weight %. Given the velocity (on the x-axis), the probability is given (on the y-axis) that a 4,5 mm sphere perforates the skin simulant.

The inconsistencies in the properties (i.e., thickness and v50%) of natural chrome crusted cow hide shown in Section 3 could be reduced by careful control of the gelatine sheet production. In addition to repeatable thickness control, the variability in terms of ballistic (v50%) performance of the gelatine is also lower compared to leather. While precautions should be taken to guarantee a consistent percentage of gelatine in the water, the gelatine proved to be much more consistent than the leather. The calculated (average) gradient of the gelatine skin simulants was 0.137 (SD = 0.078), more than double the equivalent gradient of the leather hides. This faster rise is clearly indicative of a much more consistent response with fewer outlying data points from ballistic testing.

Figure 8 shows the v50% of each gelatine percentage with a best fit applied and the corresponding R^2 value has been calculated. A strong correlation (0,97) was found, giving confidence that the v50% can be predicted based on the percentage of gelatine even at higher gelatine concentrations. Importantly, despite the challenges associated with preparing higher concentrations, the data points are not diverging with increasing values of the gelatine weight %, indicating homoscedasticity. The lowest tested weight

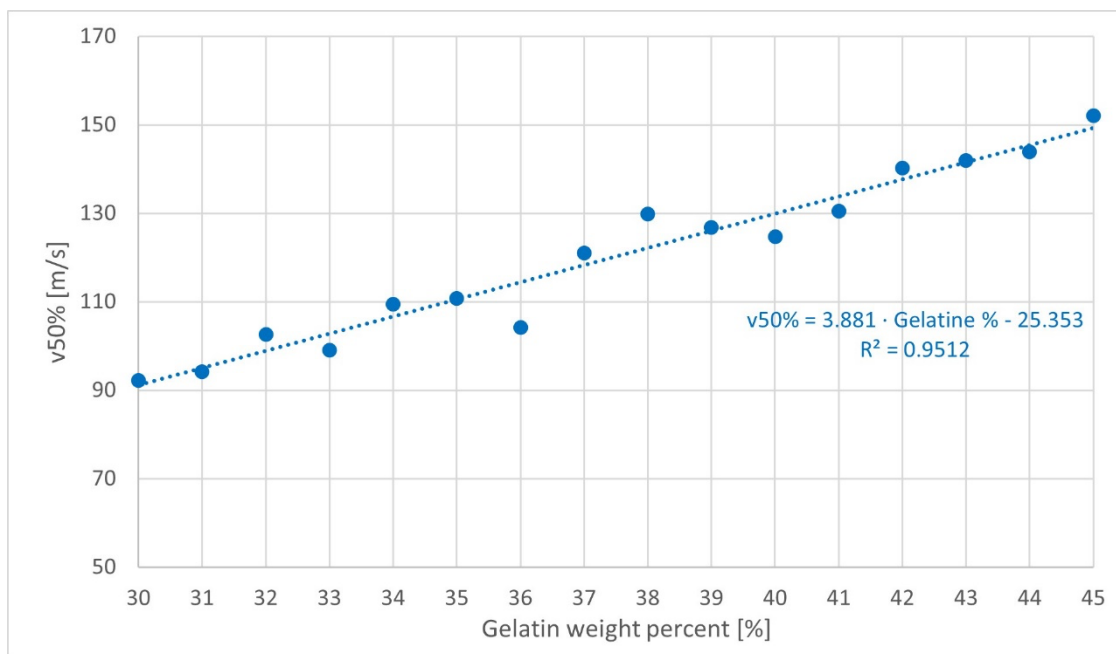


Figure 8 Gelatine v50% vs Gelatine weight %

percentage (30%), has a v50% velocity of approximately 92 m/s while the highest tested weight percentage (45%), has a v50% velocity of approximately 152 m/s.

5 Summary

This study has shown that the properties of chrome crusted cow hides vary considerably which presents concerns for the validity of penetration experiments. Whilst further studies using different projectile types are needed, the proposed use of gelatine sheets offers a repeatable and controllable skin simulant for 4,5 mm steel ball bearing projectiles. The benefits of the proposed approach are expanded in detail below, in short it offers the investigator/researcher the flexibility to tailor the simulant to match the range of reported v50% values for human skin. It is acknowledged that the approach entails extra production work to make a different % gelatine mix to prepare the skin simulant layer. However, while there is no off the shelf material(s) with the required ballistic response, and response repeatability, this additional process does not seem excessive.

Overall, the specific benefits of employing gelatine as a skin analogue are:

- Adaptability (v50%)

As stated there is no agreed standard of skin penetration threshold velocity between forensic laboratories, experts and countries. The reported threshold velocity differs immensely from 95 m/s to 145 m/s. This research has shown that gelatine sheets can be produced with a v50% to match any value in this velocity range, as shown in Figure 9 below.

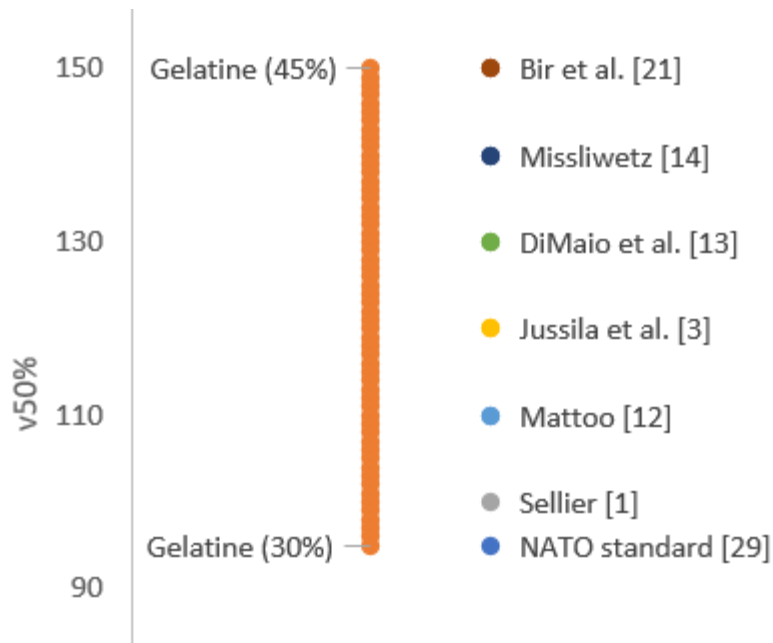


Figure 9 Overview of the suggested weight percentage gelatine in accordance with the v50% as described in the concerning literature.

- Reliability

In order to be used in court, simulation materials need to be reliable, consistent and validated. Despite some practical challenges in casting higher concentrations, the gelatine demonstrated a good repeatability over the whole range of concentrations. It showed a very strong correlation between the v50% and the gelatine weight % ($R^2 = 0,95$) from 30 weight % until 45 weight %, providing confidence in its potential utility as a forensic tool.

- Availability

The gelatine had significant advantages in terms of availability, familiarity in terms of understanding and likely existing infrastructure in forensic laboratories. It can, with minimal capital investment, be made to the desired thickness enabling, in conjunction with % gelatine, the properties to be tailored as required.

- Adaptability (Shape and thickness)

Apart from the adaptability in v50% as mentioned before, another benefit of the gelatine is the possibility to alter / cast to shape. E.g. it can be cast around a simulant skull. It's been shown that thicknesses of 2 mm can be made with lower percentages of gelatine while thickness above 4 mm seemed to represent an upper threshold influencing ballistic properties. This range of thicknesses is deemed to be viable for a skin simulant.

While there are surely challenges of using a higher (than normal) percentage gelatine mixtures to form a sheet to act as a skin simulant, the results of the ballistic testing considered here, combined with the novel castable approach of various gelatine percentages, have shown this method to be very effective and repeatable. The method covers the whole range of human skin v50% as reported in the literature in a reproducible way, proved by comparison of the gradients of the simulation materials (0.021 (SD= 0.055) for the cow hides and 0.137 (SD = 0.078) for the gelatine). This approach therefore for the first time gives forensic scientists the possibility of tailoring a skin simulant to the desired situation, or as requested by court. Additionally, the steeper gradient of the logistic regression curves for the gelatine expresses more confidence than the leather as a skin simulant.

In summary, the gelatine weight % suggested for the matching v50% velocity is reported in Table 3 for a 4 mm thick gelatine sheet, clearly showing the potential and adaptability of this technique.

Table 3 Skin simulant production suggestions for 4 mm thick gelatine sheets to match the skin threshold velocities reported in the scientific literature.

Velocity [m/s]	Kinetic Energy Density [J/mm ²]	Reference	Sheet composition - gelatine weight percentage [%]
95	0,10	NATO standard [29]	31
100	0,11	Sellier [1]	32
105	0,12		34
110	0,13	Mattoo [12]	35
115	0,14		36
120	0,16	Jussila et al. [3]	37
125	0,17		39
130	0,18	DiMaio et al. [13]	40
135	0,20		41
140	0,21	Missliwetz [14]	43
145	0,23		44
150	0,24	Bir et al. [21]	45

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2023-05

Elsevier

<https://doi.org/10.1016/j.forsciint.2023.111653>

Hes RAG, Painter JD, Appleby-Thomas GJ. (2023) Optimal skin simulant for ballistic testing, Forensic Science International, Volume 346, May 2023, Article number 111653