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Anthony Bracq, Rémi Delille, Christophe Maréchal, Benjamin Bourel, Franck Lauro, et al.. On the use of a SEBS polymer gel block as a new ballistic target to assess blunt ballistic impacts: Application to a wide range of LLKE projectiles. International Journal of Impact Engineering, 2021, 153, pp.103874. 10.1016/j.ijimpeng.2021.103874 . hal-03446694

HAL Id: hal-03446694

<https://uphf.hal.science/hal-03446694>

Submitted on 24 Apr 2023

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On the use of a SEBS polymer gel block as a new ballistic target to assess blunt ballistic impacts: application to a wide range of LLKE projectiles.

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Abstract

The objective of the present paper is to determine the ability of a transparent polymeric gel, used as a reference material with a mechanical response comparable to that of a human body, to assess less-lethal kinetic energy (LLKE) projectiles. To do this, a consistent measurement method of the dynamic deformation of the gel impacted by a projectile is first of all presented. It relies on high-speed images and image processing routines. Several metrics from the measured gel wall displacement profile are used to investigate experiments. Secondly, repeated impact conditions on various gel blocks confirm that, the proposed material meets the requirements of mechanical consistency, batch-to-batch reproducibility and easy handling. Thirdly, 138 ballistic experiments covering kinetic energies from 10 J up to 300 J are performed, involving commercially available LLKE projectiles of various stiffness. The important dataset is used to perform a statistical analysis through Spearman's correlation matrix between metrics and projectile parameters. It mainly reveals the need to use a ballistic target to determine the wounding potential of a given projectile rather than kinetic energy density or momentum density. Robust power law mathematical fits describe the relations between three metrics (maximum gel displacement, displacement - rate of displacement-based metric and maximum displaced volume) and kinetic energy density depending on LLKE projectiles' stiffness. Fourthly, three case reports available in literature and involving LLKE projectiles have been replicated on a gel block. An experimental procedure is proposed based on numerous case reports to give design guidelines in terms of projectile mass, velocity and stiffness. Finally,

this original study demonstrates the gel material capabilities to assess LLKE weapons before their field deployment.

However, further investigations need to be pursued to propose a relevant injury predictive tool and associated risk curves to law enforcement agencies and regulatory bodies.

Keywords: Non-penetrating ballistic impact, Less-lethal projectile, Experimental testing, Image processing,

Statistical analysis, Blunt trauma

1. Introduction

Over the past few centuries, ballistic impacts have been studied to improve ammunition efficiency and precision. Accordingly, innovative personal protective systems have been designed to protect the human body. For decades, biomechanical interactions have been studied to understand and mitigate ballistic trauma. Severe injuries may arise from non penetrating or blunt ballistic impacts. Behind Armour Blunt Trauma (BABT) is the term used to define trauma due to the dynamic deformation of the body armour. Since the 1970's, modern conflicts in Western civilisations have resulted in the use of Less-Lethal Kinetic Energy projectiles (LLKE) especially for riot control purposes. [Tailor-made kinetic energy projectiles are also employed to simulate BABT on animals \[1\]](#). Such non penetrating ballistic impacts may also lead to serious physiological and physical injuries, as reported by many authors [2, 3, 4, 5, 6].

In view of these observations, authorities' concerns have led to clinical studies on Post-Mortem Human Subjects (PMHS) and anaesthetised animals. These aim to quantify the injury potential of LLKE projectiles by gaining a comprehensive understanding of ballistic blunt trauma [7, 8, 9]. One of the major outcomes of the clinical study of Bir and Viano [8] is the use of the viscous criterion (i.e. thoracic wall displacement rate dependent model) as an explanatory variable to predict the risk of rib and sternum fractures [8, 10]. Nevertheless, conclusions only rely on

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15 plastic baton rounds impacting PMHS' sternum at a maximum kinetic energy of 112 J. In spite of these encouraging
16 results, cadaver and animal testing remains challenging and raises ethical issues. One of the main drawbacks is the
17 difficulty of testing multiple projectiles over a wide range of kinetic energies.

18 To address this matter, homogeneous soft materials have been created to mimic human body tissue. 10 and 20
19 wt% ballistic gelatin are two standard materials mainly utilised to gain insight into penetrating and blunt impacts
20 and effects on the human body [11, 12, 13, 14]. Hanlon and Gillich [15] also provide elements in favour of ballistic
21 gelatins properties for use in describing the backface dynamics of body armour. Nonetheless, numerous studies
22 have highlighted several practical issues using ballistic gelatins. This material exhibits prohibitive properties such
23 as a precipitate ageing time, a poor thermal stability, a significant humidity sensitivity and a low transparency [16,
24 17, 18]. Therefore, synthetic tissue simulant materials have been recently developed. Ballistic gelatins from Clear
25 Ballistics and styrene-ethylene-butylene-styrene (SEBS) polymer-based materials are examples of stable, reusable
26 and transparent synthetic targets [19, 20, 21, 22, 23, 24]. Moreover, Mrozek et al. [25] have highlighted the versatility
27 of SEBS polymer gel. Its mechanical properties can be tuned by adjusting polymer concentration.

28 Researchers have also proposed hybrid experimental-numerical methods to assess ballistic impacts and the wound-
29 ing potential of projectiles [26, 27]. Dynamic impact tests of compliant LLKE projectiles on a rigid wall have been
30 used to simulate ballistic impacts on human body finite element models (FEM) [27, 28, 29]. Nonetheless, such in-
31 vestigations are time consuming and intricate. Moreover, outcomes depend upon FEM and material laws describing
32 body parts' behaviour. Experimental investigations are thus mandatory to evaluate projectiles and provide guidelines
33 for their design at a latter stage. Tawell [30] has reported momentum and kinetic energy based threshold values above
34 which "serious injury is highly likely to occur". Indicated values of $5000 \text{ kg}\cdot\text{s}^{-1}\cdot\text{m}^{-1}$ (impulse by unit area) and 200
35 J are not representative of previous case reports [8, 4]. An impulse of $2100 \text{ kg}\cdot\text{s}^{-1}\cdot\text{m}^{-1}$ and a kinetic energy of 112

36 J were sufficient to cause serious injuries to the human torso. Additionally, Kapeles and Bir [31] have outlined the
37 limitations of a kinetic energy based injury criterion when dealing with compliant LLKE projectiles. To the authors'
38 knowledge, no research provides sufficient data and a reliable experimental procedure to assess LLKE projectiles
39 before their field deployment.

40 Consequently, the objective of the present paper is to propose a consistent experimental target to both evaluate
41 blunt impacts and introduce novel mass-velocity guidelines for LLKE projectiles. As illustrated by Fig. 1, the
42 scientific procedure consists in using transparent SEBS polymer gel blocks as ballistic targets. Multiple impact shots
43 using various LLKE projectiles will constitute a database of experimental measurements which are mandatory to
44 perform a statistical and biomechanical analysis. In the first instance, materials and methods involved in this study are
45 described, from ballistic experiments to statistical analyses. In a second phase, the robustness of the proposed ballistic
46 target is shown based upon repeated experiments on several manufactured gel blocks. Then, a substantial number of
47 test results are used to identify relevant experimental metrics to analyse an impact. Finally, impact conditions detailed
48 in case reports are replicated on gel blocks. This highlights the potential of gathering case studies when giving design
49 guidelines according to the projectile's stiffness.

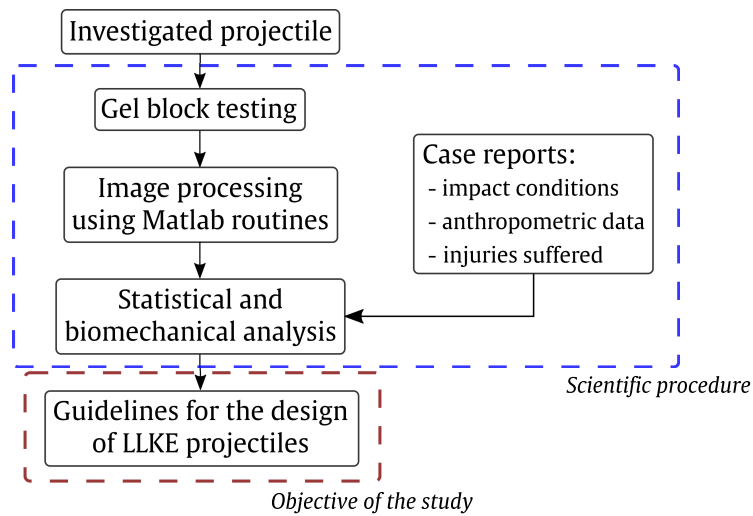


Figure 1: Flow chart representing the scientific procedure and the objective of the study involving ballistic experiments, statistical and biomechanical analysis.

2. Materials and methods

2.1. Projectiles involved in the study

In order to assess the influence of LLKE projectiles and related mechanical properties as well as shooting parameters on a ballistic target, four homogeneous LLKE projectiles and four hybrid LLKE projectiles are used during experiments (see Tables 1 and 2). Homogeneous projectiles of 37 mm in diameter (PBR and S-PBR) are made of plastic. Hemispherical projectiles (HEM) of 40 mm in diameter are designed by the French Ministry of the Interior based on high-density polyethylene material. Foam is also used to manufacture Flash-Ball® projectiles. Then, hybrid projectiles of 40 mm in diameter are made of a compliant nose and a rigid rear part. Rubber and foam materials of different densities are used to tune the mechanical properties of projectiles. The shooting parameters of these commercially available projectiles are chosen to cover a wide range of kinetic energies (from 10 J up to 300 J). More precisely, Tables 1 and 2 indicate the geometry, the mean mass and the kinetic energy distribution of each projectile. 138 impact experiments are thus performed to obtain reliable statistical analyses. Among these projectiles are two

62 solid rubber projectiles (PBR and S-PBR) used in the clinical study of Bir and Viano [8] and Bir et al. [7] and two
 63 soft projectiles (Flash-Ball[®] and eXact iMPact[™]) used in two real world incidents depicted by Wahl et al. [5] and
 64 Kobayashi and Mellen [4] respectively.

Table 1: Description of homogeneous less-lethal kinetic energy projectiles and impact conditions applied to the ballistic target.

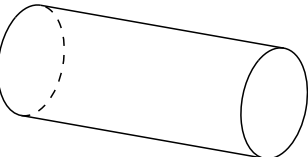
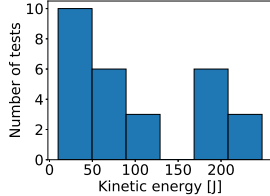
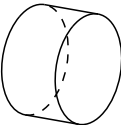
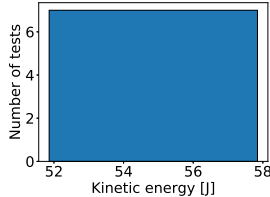
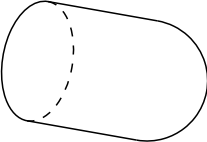
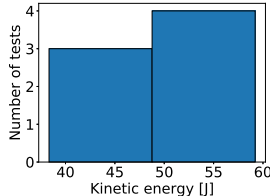
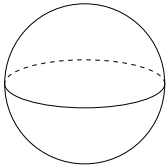
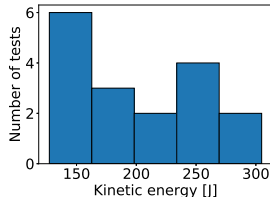
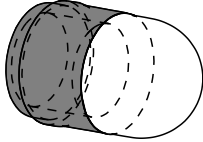
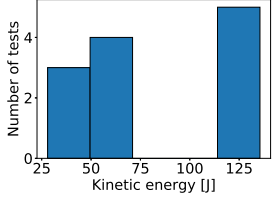
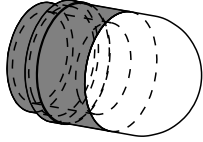
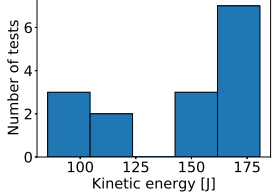
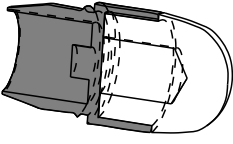
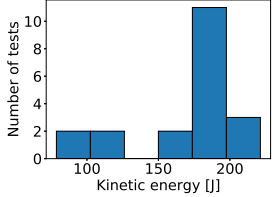
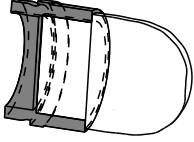
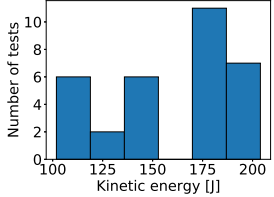
Projectile	Name (Manufacturer)	Diameter [mm]	Length [mm]	Mass [g]	Kinetic energy distribution
	PBR Pains-Wessex Schermully	37	100	140	
	S-PBR SIMAD S.p.A	37	22	30	
	HEM French Ministry of the Interior	40	65	59	
	Flash-Ball (Verney-Carron)	44	44	28	

Table 2: Description of hybrid less-lethal kinetic energy projectiles and impact conditions applied to the ballistic target.

Projectile	Name (Manufacturer)	Diameter [mm]	Length [mm]	Mass [g]	Kinetic energy distribution
	eXact iImpact (Defense Technology)	40	62	29	
	B&T (Brgger & Thomet)	40	62	32	
	ALX2015 (Alsetex)	40	78	62	
	CTS4557 (Combined Tactical Systems)	40	62	60	

65 2.2. Polymer gel block and ballistic experiments

66 All ballistic experiments described in this study are carried out using polymeric gel SEBS blocks as ballistic
67 targets. In order to constitute a SEBS gel block, SEBS copolymer powder provided by Kraton Polymers LLC (Kraton
68 G1652, a linear styrene-ethylene/butylene copolymer with a styrene/rubber ratio of 30/70%) is mixed with mineral oil
69 PRIMOL 352 produced by ESSO S.A.L. A SEBS powder/mineral oil ratio of 30/70% is chosen. More information
70 about the material processing of SEBS gel samples can be found in the research studies of Bracq et al. [23, 32].

71 A 25 cm gel block cube is used during ballistic impacts in order to minimise the influence of edge effects on
72 the gel wall displacement in both vertical and horizontal directions. Figure 2 describes the experimental set-up used

73 for the analysis of ballistic impacts. A pneumatic launcher is used together with a 100 mm light gate with an exit
74 beam at 15 cm from the target to measure the impact velocity. The gel block and the barrel are placed in such a
75 way to strike the centre of the gel block. As the barrel nozzle exit is located 15 cm from the gel block surface, the
76 obliquity is equal or very close to 0, which is checked using the high-speed video record. Gel transparency along with
77 a backlighting device and a high-speed camera capture the ballistic event and, specifically, the gel wall displacement
78 profile over time. Images are recorded at 20,000 up to 46,000 frames per second. Image resolution and camera
79 positioning give a calibration factor ranging from 0.35 to 0.45 mm/pixel. Light rulers are fixed to the gel surface,
80 leading to the conversion into physical dimensions of the 2D gel wall displacement profile. Special care is taken to
81 adjust the measurements by applying Thales' theorem (geometrical corrections) and Snell's law (effect of the refractive
82 index of the gel). The corrected gel wall displacement at the centre of the block is obtained by using the gel block
83 thickness and the distance between the camera lens and the gel block surface as well as a gel refractive index $n=1.44$.
84 Specific routines coded through a graphical user interface (GUI) within the MATLAB environment (MathWorks ©)
85 are developed to compute the 2D gel wall displacement profile for each frame using gray level thresholding. This
86 technique is validated against the gel wall displacement measured by a quasi-static press equipped with a hemispheric
87 plunger. An average error of 0.6 mm is computed between the machine traverse and the image processing routine
88 for a wide range of target displacements. The next part of this paper gives a complete overview of the experimental
89 metrics resulting from a ballistic impact analysis.

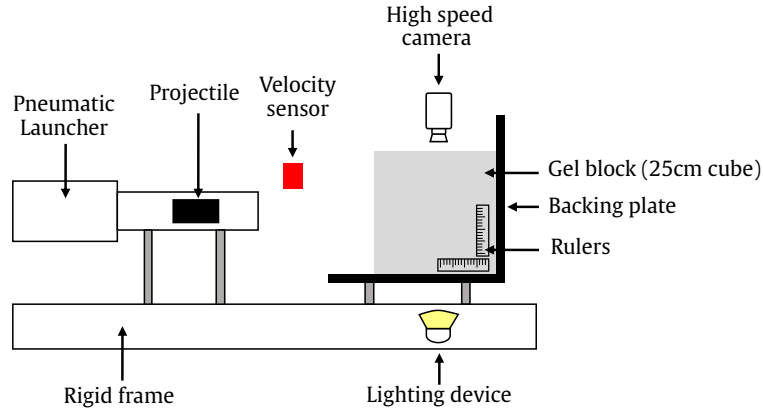


Figure 2: Schematic of the experimental set-up used for the analysis of ballistic impacts [24].

90 Fig. 3a is a photograph of the maximum gel wall displacement during an impact of a rigid hemispherical projectile
 91 (HEM) at an initial speed of 43 m/s. The red line displayed in Fig. 3a coincides with the contour of the displaced
 92 gel wall identified by the image processing routine. On the left side of Fig. 3a, the velocity sensor placed at the
 93 barrel nozzle exit may be observed. Capturing the contour for each time frame leads to the main measurements
 94 presented in Fig. 3b. It corresponds to the 2D gel wall displacement profile over time. Based on this key result,
 95 various measurements can be deduced. The maximum gel wall displaced time history is obtained, but with specific
 96 considerations (see Fig. 4a). In fact, as the early stages of the gel wall displacement (less than 5 up to 10 mm) cannot
 97 be detected by the camera due to optical issues, the time of impact is unknown. To overcome this problem, the solution
 98 describing an underdamped harmonic oscillator (UHO) system is used to fit the gel wall displacement during the main
 99 rising time and predict the time of impact. The choice of this mathematical model defined in Eq. 1 is validated by
 100 evaluating the R-squared coefficient of determination. In this example, its value is 1.000 supporting the choice of the
 101 model.

$$f(x) = ae^{-bx} \sin(cx + d) \quad (1)$$

102 where a , b , c and d are parameters to identify using curve fitting algorithms. It estimates the temporal shift to
103 apply in order to obtain a null displacement at time zero.

104 Literature has also highlighted the fact that the risk of trauma correlates better with the rate of body wall deflection
105 rather than with the deflection itself [10]. Therefore, a pseudo viscous-criterion known as energy transfer parameter
106 (ETP), expressed in m/s, is deduced from the gel wall displacement data and corresponding UHO fit (see blue markers
107 and red line in Fig. 4a) [33]. The mathematical equation of this new metric is analogous to the viscous criterion and
108 is defined by Eq. 2 [34]. More precisely, the ETP time history applied to this impact is related to both the gel wall
109 displacement and the rate of displacement. Fig. 4b shows the time evolution of this metric.

$$ETP(t) = \frac{1.3}{255.5} \left(x(t) \frac{dx(t)}{dt} \right) \quad (2)$$

110 where 1.3 is used as a pre-factor and 255.5 is related to the mean thorax depth in mm [34]. Moreover, assuming
111 axisymmetric cross-sections, the 2D gel wall displaced profile displayed in Fig. 3b may be exploited to compute the
112 displaced volume, expressed in cm^3 for each time step and its derivative, the volume growth rate (VGR), expressed in
113 dm^3/s . The volume is estimated according to Eq. 3 where n is the number of tracked points or the number of rows
114 in the image. S_i is the projected area for each point i and x_i its depth. Equations 4 and 5 define the variables y_i^* and
115 dy_i respectively, used to compute S_i . Eq. 3 is graphically represented in Fig. 5. Fig 4c depicts the displaced volume
116 and a modified UHO fit (see Eq. 6) with the R-squared value. This equation takes complex non linearity into account
117 while maintaining the limit conditions: at time zero, the volume displaced should be zero. Fig 4d shows the computed
118 volume growth rate using raw data and fitted model as a function of time. The maximum values of the aforementioned
119 measurements represent ballistic metrics and may be used to compare and assess ballistic impacts. They are defined

120 by X_{max} , ETP_{max} , VOL_{max} and VGR_{max} , related to the gel wall displacement, the ETP , the displaced volume and the
 121 volume growth rate respectively. ETP_{max} and VGR_{max} values relate to fitted curves minimising data scattering. The
 122 time period to reach the maximal gel wall displacement, $t_{X_{max}}$, expressed in ms, can serve as an additional metric to
 123 analyse ballistic experiments.

$$V = \sum_{i=0}^n S_i x_i \quad (3)$$

$$S_i = \pi d y_i \left(y_i^* - \frac{dy_i}{2} \right)$$

124 where,

$$y_i^* = |y_i - y_{\max_{i=1, \dots, n}} \{x_i\}| \quad (4)$$

125 and,

$$dy_i = |y_i - y_{i+1}| \quad (5)$$

$$f(x) = ae^{-bx} \tanh(cx)^d \quad (6)$$

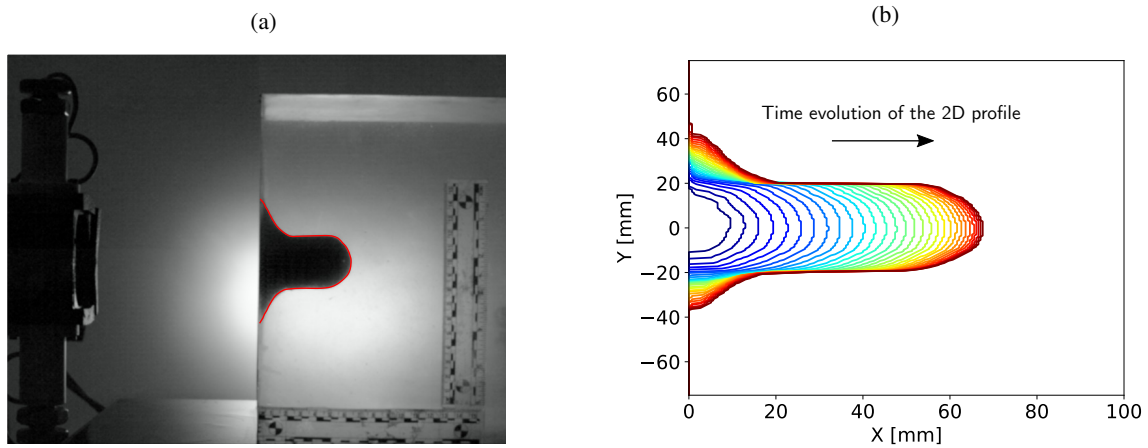


Figure 3: A photograph of the gel wall displacement taken by a high-speed camera during the impact of a rigid projectile at an initial velocity of 43 m/s (a) and corresponding 2D gel wall displacement profile curves as a function of time (b).

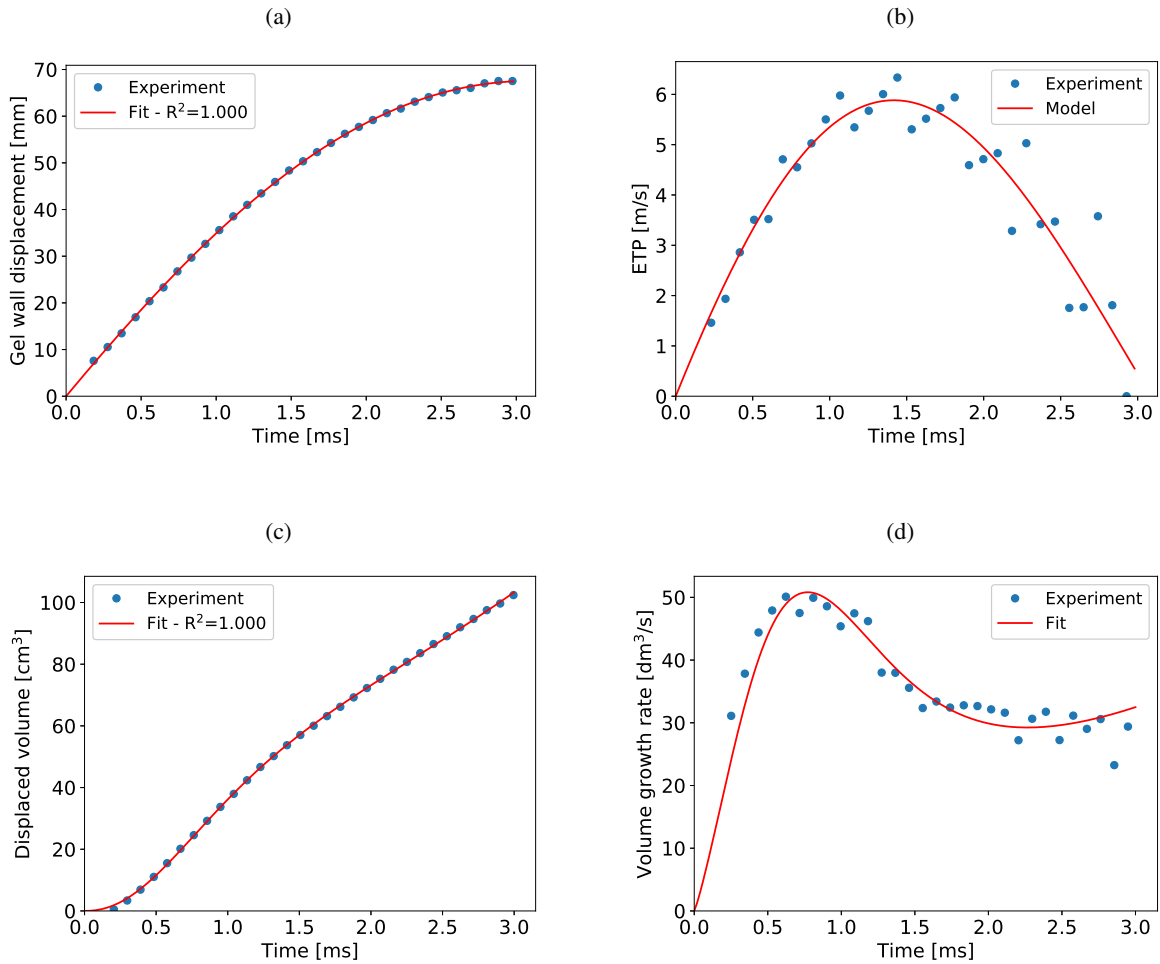


Figure 4: Experimental curves computed from the 2D gel wall displacement profile time history: the maximum gel wall displacement (a), the energy transfer parameter (b), the displaced volume and the volume growth rate (d) over time.

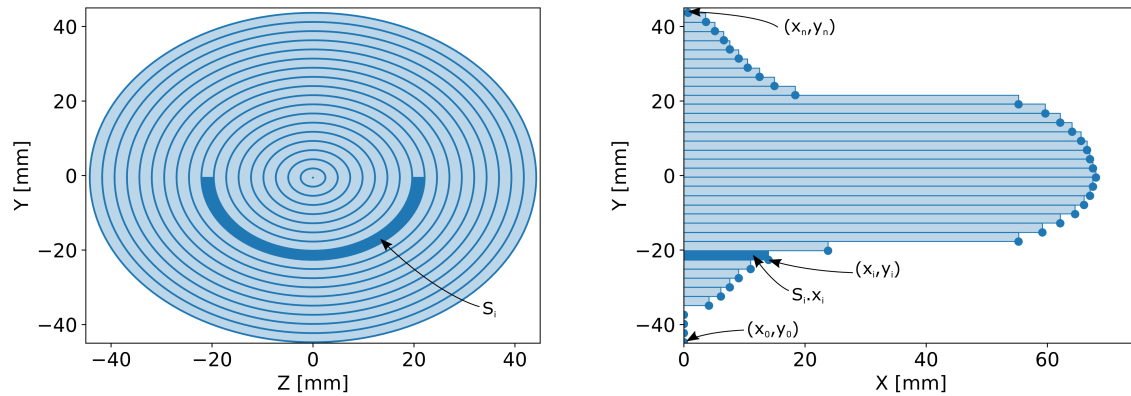


Figure 5: Graphical representation of how displaced volume is computed (note: only one point out of four is displayed for easier visualisation).

126 **2.3. Statistical analysis**

127 The statistical analyses performed in this paper serve two purposes. The first one is to assess the proposed ballistic
 128 target. The gel block has to fulfil various essential requisites in order to be adopted by law enforcement agencies,
 129 research laboratories, regulatory bodies and weapon manufacturers. Besides being easy to handle, the ballistic target
 130 has to demonstrate a mechanical consistency and ensure a batch-to-batch reproducibility. In other words, it means that
 131 repeated impact tests on a unique gel block have to present consistent results and carrying out comparable experiments
 132 on various blocks should not affect the results. To address this matter, equivalent impact conditions described in Table
 133 3 and involving hemispherical rigid projectiles (HEM) have been applied to four SEBS gel blocks produced using the
 134 same preparation method. In addition, mean and standard deviation (written in parentheses) values of the projectile
 135 mass, velocity, kinetic energy and momentum are indicated for each gel block based on a specific number of tests (see
 136 Table 3). Among these four blocks, three were produced in 2018 and one in 2014. The influence of ageing on the
 137 gel mechanical response is determined by performing impact tests, shown in Table 3, in November 2018. A one-way
 138 ANOVA analysis is performed where each block is compared to one another. The null hypothesis H_0 states that there
 139 is no difference in means of tested gel blocks.

Table 3: Description of the projectile and impact conditions applied to the ballistic target to assess its mechanical consistency and its batch-to-batch reproducibility.

Projectile	Gel block	Number of tests	Mass [g]	Velocity [m/s]	Kinetic energy [J]	Momentum [kg.m/s]
HEM	B1-2014	4	58.93 (0.10)	43.70 (0.88)	56.28 (2.28)	2.58 (0.05)
	B2-2018	5	59.26 (0.09)	43.86 (1.38)	57.04 (3.56)	2.60 (0.08)
	B3-2018	4	59.10 (0.11)	43.63 (1.50)	56.29 (3.96)	2.58 (0.09)
	B4-2018	7	58.36 (0.18)	45.34 (1.38)	60.04 (3.72)	2.65 (0.08)

140 The second purpose is to identify and quantify the potential correlations between the experimental metrics related
141 to the gel and the physical metrics linked to the impact conditions, as for instance the impact velocity or the kinetic
142 energy. 138 impact conditions, described in Tables 1 and 2, have been applied to four gel blocks covering a wide
143 range of kinetic energies and projectile types. Experiments are randomly performed on each block and the gel block
144 surface is inspected after each test. A 5 mm crack is the threshold length above which another gel block side is used as
145 the target surface. In the case of extreme degradation, the block is simply re-melted. Spearman's correlation matrix
146 is established based on these 138 data sets using MATLAB correlation functions (MathWorks ©). The significance
147 and the degree of correlation are evaluated between each metric by virtue of the p -value and Spearman's correlation
148 coefficient ρ respectively. In this study, the alpha risk is fixed at 0.05 for hypothesis tests. The null hypothesis is
149 defined by the absence of a linear or non-linear monotonic relationship between the two metrics studied.

150 The following part of this article aims to present and discuss the extensive results of this research underlining
151 the main benefits of this ballistic target to assess non-penetrating impacts and, above all, less-lethal kinetic energy
152 projectiles.

153 3. Results and discussion

154 3.1. Assessment of the proposed ballistic target

155 The first main result of this study relies on the assessment of the mechanical consistency and reproducibility of the
156 proposed polymer-based material as ballistic targets. According to Table 3, at least four equivalent shots have been
157 performed on each manufactured gel block. To discuss the reliability of the image processing method and the ballistic
158 target, box plots have been drawn based on maximum gel wall displacement and displaced volume data according
159 to the gel block number (see Fig. 6). It quantifies the scattering of experiments inter- and intra-gel blocks. Each
160 individual block reveals a low dispersion, regarding the maximal gel wall displacement metric, with a maximal span
161 around the mean of ± 3 mm. Average data is plotted using blue crosses. Fig. 6a also highlights the very good batch-
162 to-batch consistency due to the fact that for four different gel blocks, the average maximal gel wall displacement is
163 between 70.5 and 71.2 mm. Using gel wall displacement data from 20 tests for a one-way ANOVA analysis, the
164 null hypothesis cannot be rejected. It means there is statistically no significant difference between the blocks with a
165 *F*-statistical value of 0.63 and a *p*-value equal to 0.89. Consequently, considering the time frame 2014-2018 and the
166 use of four gel blocks, ageing appears to have no significant effect on the gel block response when subjected to direct
167 impacts. Fig. 6b shows a more important discrepancy in the maximum displaced volume inter- and intra-gel blocks.
168 This mainly arises from variations, which may occur between experiments in horizontal and vertical directions, and are
169 magnified by computing the displaced volume. Hence, the maximum displaced volume metric outlines a reasonable
170 scattering between gel blocks with a mean volume ranging between 120 and 128 cm³. As the ballistic target and
171 proposed image processing methodology demonstrate an important robustness, the analysis of 138 impact conditions
172 applied to gel blocks is possible. It aims to demonstrate the requirement of using a convenient ballistic target when
173 investigating different types of LLKE projectiles.

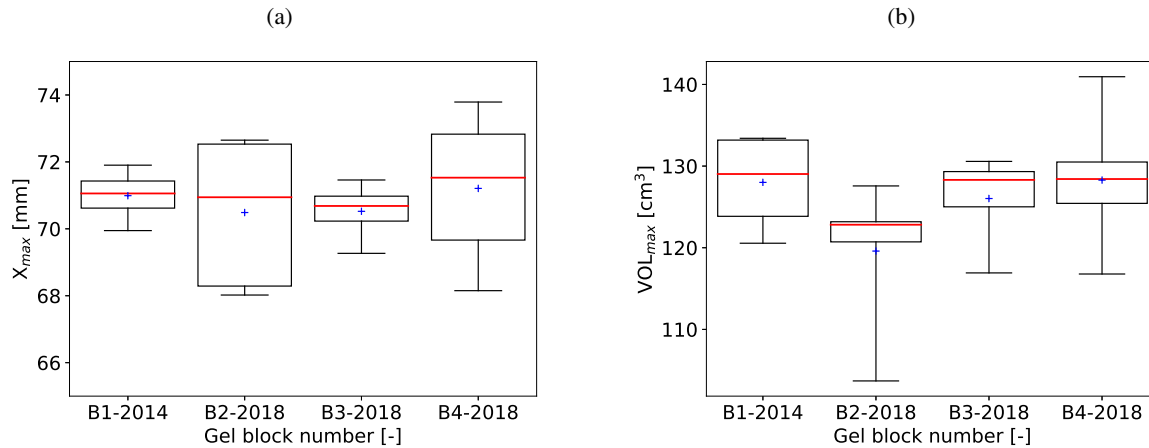


Figure 6: Scatter plots of the maximum gel wall displacement (a) and the maximum displaced volume (b) as a function of the gel block number used during impact experiments.

174 3.2. Identification of relevant experimental metrics

175 The second main objective of this study is to determine the effect of impact conditions, i.e. projectile nature, mass,
 176 velocity, kinetic energy density (KED) and momentum density (MD), on the target material response. The gel block
 177 is supposed to capture how a given projectile may interact with the human body. To deal with this matter, 138 ballistic
 178 tests (see Table 1) covering 30 distinct impact conditions are applied to gel blocks. The high number of tests ensure
 179 repeatability and give confidence in statistical analyses. As impacting the ballistic target at a desired velocity is well
 180 mastered by the experimental set-up described in Fig. 2, the scattering around the mean velocity is low for the entire
 181 dataset. Experimental metrics measured using the image processing routine present a minor dispersion, especially
 182 as regards the maximal gel wall displacement (X_{max}), rising time ($t_{X_{max}}$) and energy transfer parameter (ETP_{max}). As
 183 mentioned previously, the maximum displaced volume has a higher scattering around the mean and the same goes for
 184 the maximum volume growth rate parameter (VGR_{max}).

185 The large dataset presented in Table 1 is used to compute Spearman's correlation matrix between impact conditions
 186 parameters and gel block metrics. The correlations obtained and statistical significance values are presented in Fig.

187 7. The strong monotonic relationship between variables is quantified by Spearman's correlation coefficient ρ using a
 188 colour scale from -1 to 1. Whereas the alpha risk is fixed to 0.05 indicated with "***", more restrictive alpha risks set at
 189 0.01 and 0.001 are illustrated with "***" and "****" respectively. Correlation coefficient values located inside the black
 190 rectangle drawn in Fig. 7 are of interest. Robust relations are determined for a ρ value greater than 0.8 and a p -value
 191 less than 0.001. Thus, correlations exist between gel block metrics and impact conditions metrics. To go further, each
 192 suitable correlation is plotted highlighting eight LLKE projectiles and their respective power fitting functions (see Fig.
 193 8). Among simple mathematical models, the power law remains the best model to describe the correlations according
 194 to the R-squared coefficient of determination.

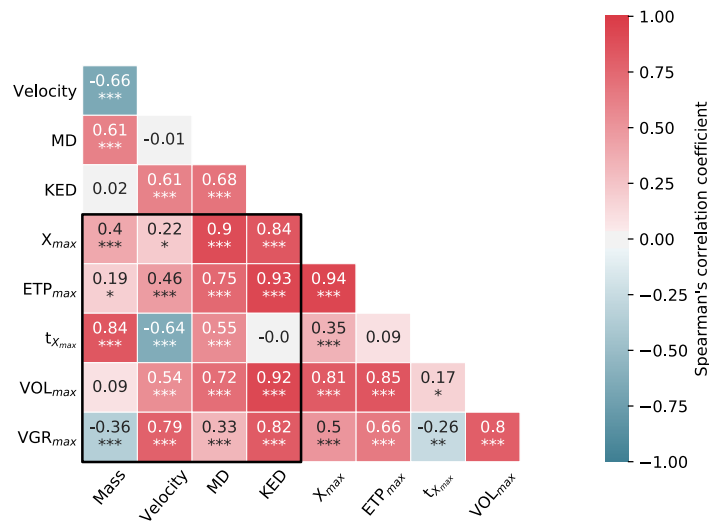
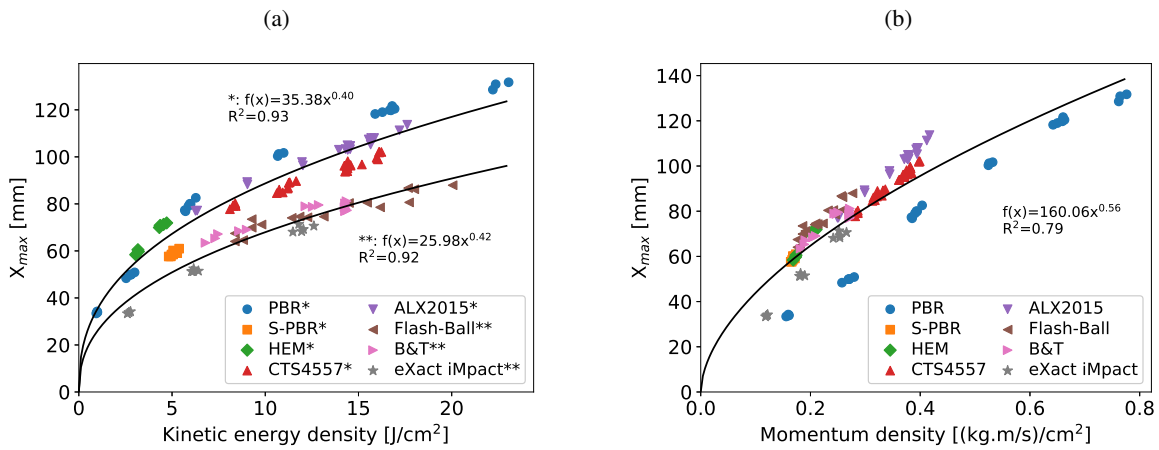


Figure 7: Spearman's correlation coefficient between experimental metrics linked to the gel and impact conditions parameters, represented by a colour scale. The statistical significance between these parameters is indicated using: * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$. A statistical analysis based on N=138 data points.

195 Fig. 8a and 8b aim to show the relations between X_{max} and the kinetic energy as well as the momentum
 196 density. The kinetic energy is often used to describe impact conditions. However, the kinetic energy needs to be nor-
 197 malised with respect to the projectiles' cross-section area to compare impacts. Depending on the projectile's stiffness,
 198 the projectile kinetic energy is not entirely dissipated by the gel block deformation, which can be characterised by

199 X_{max} . Fig. 8a displays two separate data groups related to stiff (*) and soft (***) projectiles, their respective power
200 fitting functions and R-squared coefficient of determinations. This plot highlights the fact that using kinetic energy
201 density to describe an impact condition is not relevant. In fact, a given kinetic energy density can cause a completely
202 different outcome to the target and the same applies to a human body. Fig. 8a also emphasises that CTS4557 and
203 ALX2015 hybrid LLKE projectiles follow the trend curve of plastic projectiles. This may be explained by a stiff
204 rubber nose used to design these projectiles. Therefore, they behave just like rigid projectiles where the projectile
205 kinetic energy is solely dissipated by the gel block deformation. These conclusions illustrate the importance of using
206 a ballistic target to assess ballistic impacts and projectiles. Fig. 8b shows the correlation between momentum density
207 and X_{max} regardless of the nature of the projectile. A single power fitting function is sufficient to describe this relation.
208 However, data related to high mass PBR projectile deviates from the trend curve. The latter remains trustworthy for
209 projectiles mass ranging between 30 and 60 g. This observation should alert researchers when using momentum den-
210 sity values for projectile design perspectives. An increasing monotonic relationship exists between $t_{X_{max}}$ metric and
211 the projectile mass, irrespective of the projectile nature and its impact velocity (see Fig. 8c). Even though a power
212 function accurately describes this correlation, it does not allow further impact analysis. For a given mass, a similar
213 t_{max} value can be obtained, while a large discrepancy in X_{max} may appear. Therefore, t_{max} is not a relevant metric
214 to examine ballistic impacts, neither is the projectile mass. The conclusions drawn for the correlation between X_{max}
215 and kinetic energy density apply to the ETP_{max} metric. Two distinct power fitting models are identified for stiff and
216 soft LLKE projectiles (see Fig. 8d). Knowing ETP_{max} metric is comparable to the viscous criterion, widely used
217 in biomechanical analyses, this measurement and these correlations with R-squared values above 0.9 are of interest.
218 Fig. 8e outlines a unique strong relationship between VOL_{max} and kinetic energy density, regardless of the projectile's
219 stiffness. This outcome may be explained by the effect of vertical expansion of the gel wall in VOL_{max} values. As

220 indicated previously through Fig. 8a, for a given kinetic energy density, soft projectiles have lower X_{max} values than
 221 stiff ones. However, deformable projectiles due to their soft material nature are subjected to a transverse deformation
 222 when impacting the gel block. Hence, the gel wall has a larger vertical expansion using deformable projectiles, which
 223 plays a significant role in the calculation of VOL_{max} values. Even though VOL_{max} metric presents a larger scattering
 224 for a given impact condition (see Fig. 6b), this variable still remains an interesting measurement to globally describe
 225 a ballistic impact. A correlation between VGR_{max} metric and the projectile kinetic energy density is therefore de-
 226 termined which can be captured by a power fitting function (see Fig. 8f). As reflected in Fig. 4d, the VGR_{max} is
 227 obtained at the early stages of ballistic impacts when the gel wall velocity is close to the incident projectile velocity. It
 228 is thus consistent to find that the maximum rate in volume change correlates with the projectile kinetic energy density
 229 irrespective of the projectile's stiffness. Experimental data remains scattered and a low R-squared value of 0.63 is
 230 computed. Consequently, VGR_{max} and this relation cannot be considered in future experimental analyses and in the
 231 identification of suitable shooting parameters.



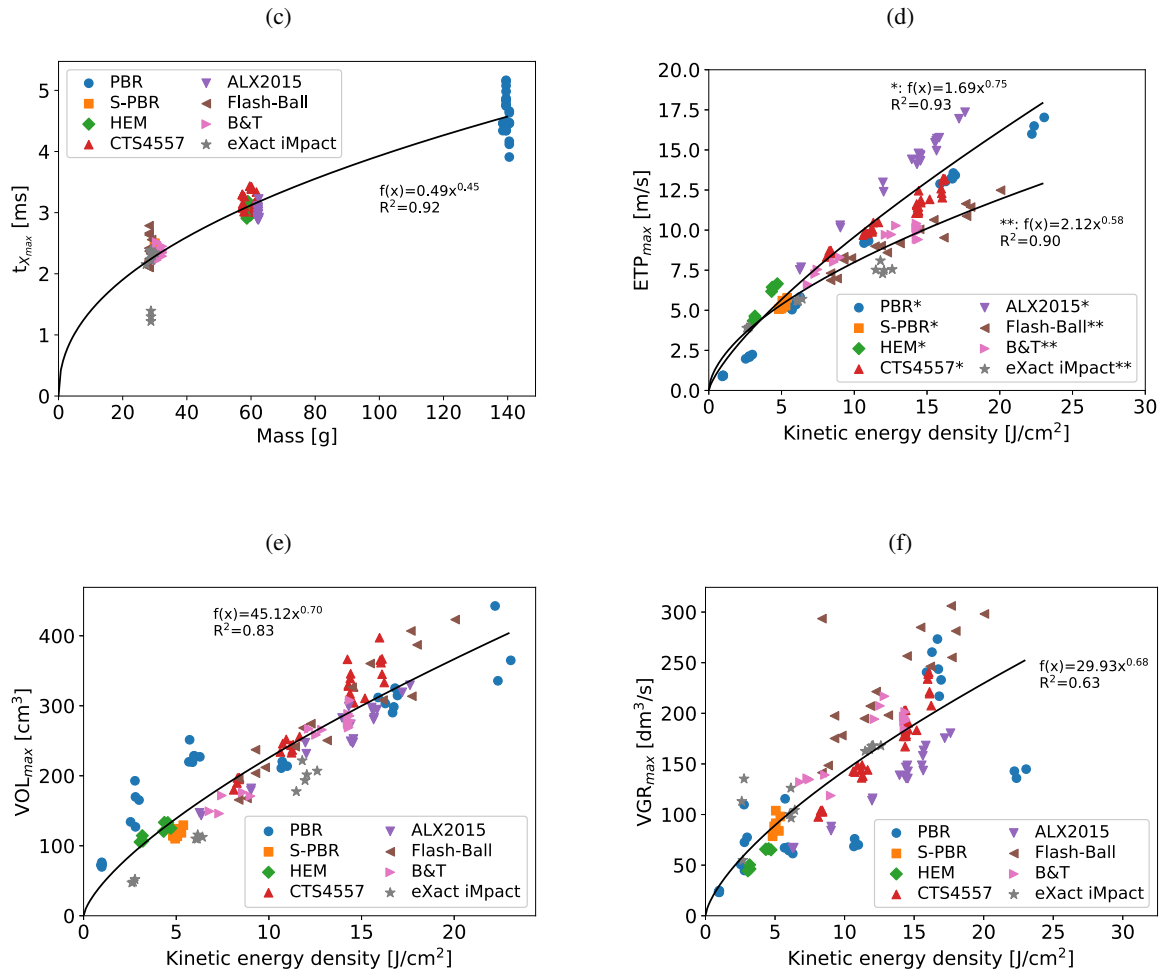


Figure 8: Plots of experimental metrics related to the ballistic target as a function of various impact parameters for eight different LLKE projectiles and respective power fitting functions.

232 These correlations highlight the interest of using a convenient ballistic target like the SEBS gel material in order
 233 to thoroughly assess ballistic impacts and LLKE projectiles. Among the experimental metrics that can be determined
 234 during ballistic tests, the most relevant are summarised hereafter:

- 235 • the maximum gel wall displacement X_{max} ;
- 236 • the maximum energy transfer parameter value ETP_{max} ;
- 237 • the maximum displaced volume when reaching the maximum gel wall displacement VOL_{max} .

238 They are chosen for their statistical robustness and their abilities to draw a distinction between stiff and soft projectiles.
239 Moreover, the ETP_{max} metric is analogous to the viscous criterion, used to predict human torso injuries. For a given
240 projectile, considering its cross section and X_{max} , the VOL_{max} metric can depict how it interacts with the gel block. In
241 spite of these outcomes, how may researchers exploit these relations to design projectiles, whilst taking into account
242 biomechanical aspects and related risk of injuries? In the next part, the authors attempt to address this major issue by
243 investigating case reports available in the literature.

244 3.3. Recreation of case reports and method for developing design guidelines for LLKE projectiles

245 Among the 138 impact conditions applied to gel blocks, three sets of impact conditions come from case reports
246 described in open literature. The first one, called “ Case 1 ” defines the impact condition of the PBR projectile at
247 an initial velocity of 40 m/s (see Table 1). The same impact condition was applied to various post-mortem human
248 subjects (PMHS) resulting in each case in an AIS score of 2 or 3 (1998 AIS injury scale) based on rib fractures [8]. The
249 second (“ Case 2 ”) is described by Kobayashi and Mellen [4] involving the projectile eXact iMpacTTM at an impact
250 velocity of 95 m/s. This impact condition induced a lung contusion to a living male (1998 AIS score=3). The third
251 (“ Case 3 ”) is described by Wahl et al. [5], where the Flash-Ball[®] projectile caused a heart and lung contusion (1998
252 AIS score=3) when impacting a living male at a velocity of 120 m/s. These three impact conditions are highlighted
253 in Fig. 9 through the relevant correlations previously identified. Only the power fitting functions and respective
254 95% confidence intervals are plotted clarifying the three diagrams. The fact that these three cases are the only ones
255 available in the literature may imply that they corresponded to low-probability events or to subjects with atypical
256 vulnerabilities. Table 4 summarises mean experimental metrics values and their standard deviation obtained for each
257 case report in brackets. Although three case reports have been recreated on gel blocks, it is not sufficient to compute
258 the risk of injury due to an impact. Numerous case reports are required where impact conditions and observed injuries

259 are known. As illustrated by Fig. 10, this could first lead to a logistic regression analysis between gel experimental
 260 metrics and the occurrence of serious injuries. Secondly, it could provide, for instance, threshold injury risks at 10,
 261 50 or 90% for experimental metrics. Finally, dependable mass-velocity guidelines could be drawn up to screen LLKE
 262 projectiles before their field deployment. However, testing projectiles on SEBS gel blocks still remains mandatory to
 263 obtain precise measurements leading to the adjustment of shooting parameters and safety distances.

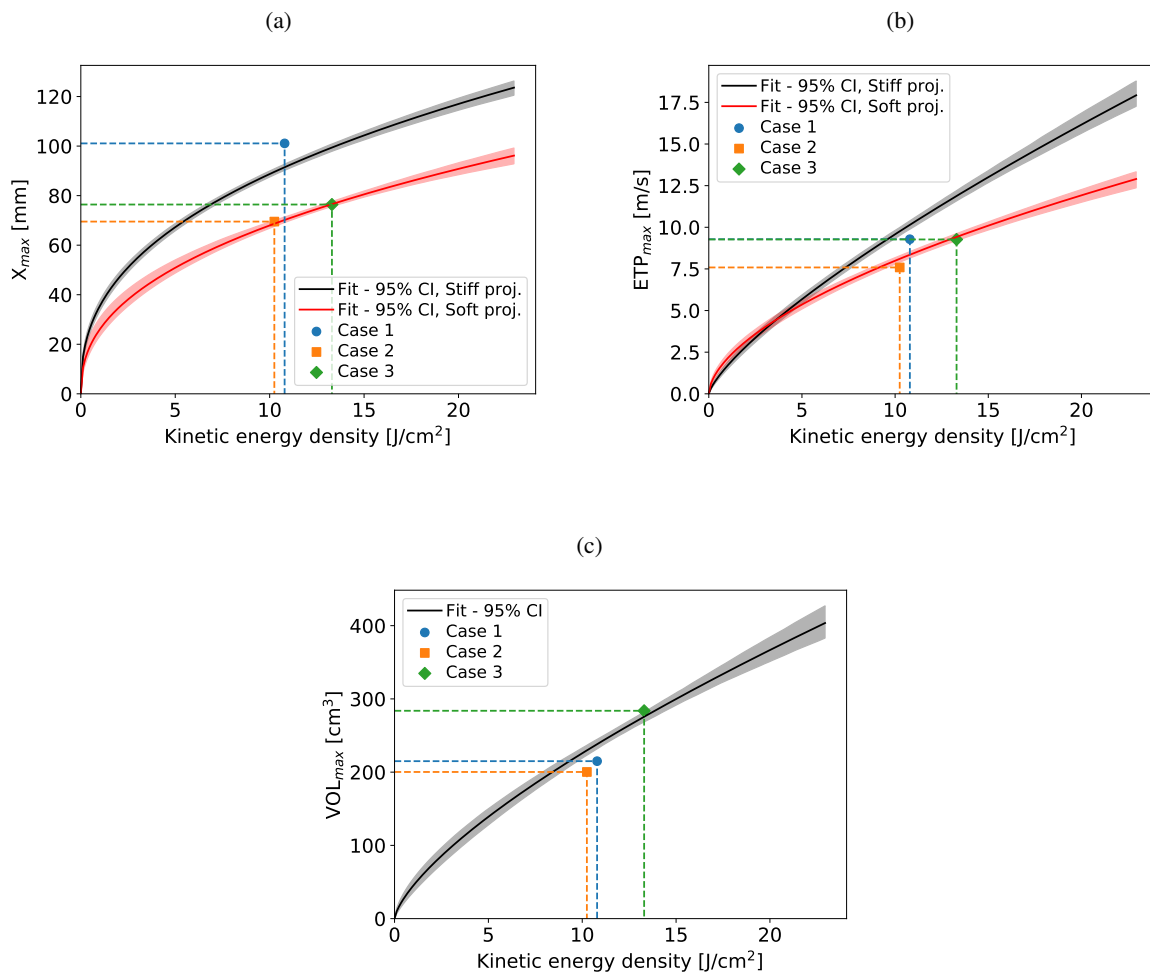


Figure 9: Plots of power fitting functions and respective 95% confidence intervals between experimental metrics and various impact parameters, with respect to stiff and soft projectiles, and case reports values.

Table 4: Experimental metric values (standard deviations are mentioned in brackets) and 1998 AIS scores (thoracic region) according to case reports mentioned in the literature.

	Experimental metrics			AIS score (thorax)	Reference
	X_{max} [mm]	ETP_{max} [m/s]	VOL_{max} [cm ³]		
Case 1	101.1 (0.7)	9.3 (0.1)	215.0 (4.8)	2-3	Bir and Viano [8]
Case 2	69.5 (1.4)	7.6 (0.3)	200.2 (16.3)	3	Kobayashi and Mellen [4]
Case 3	76.4 (3.4)	9.3 (0.7)	283.8 (38.9)	3	Wahl et al. [5]

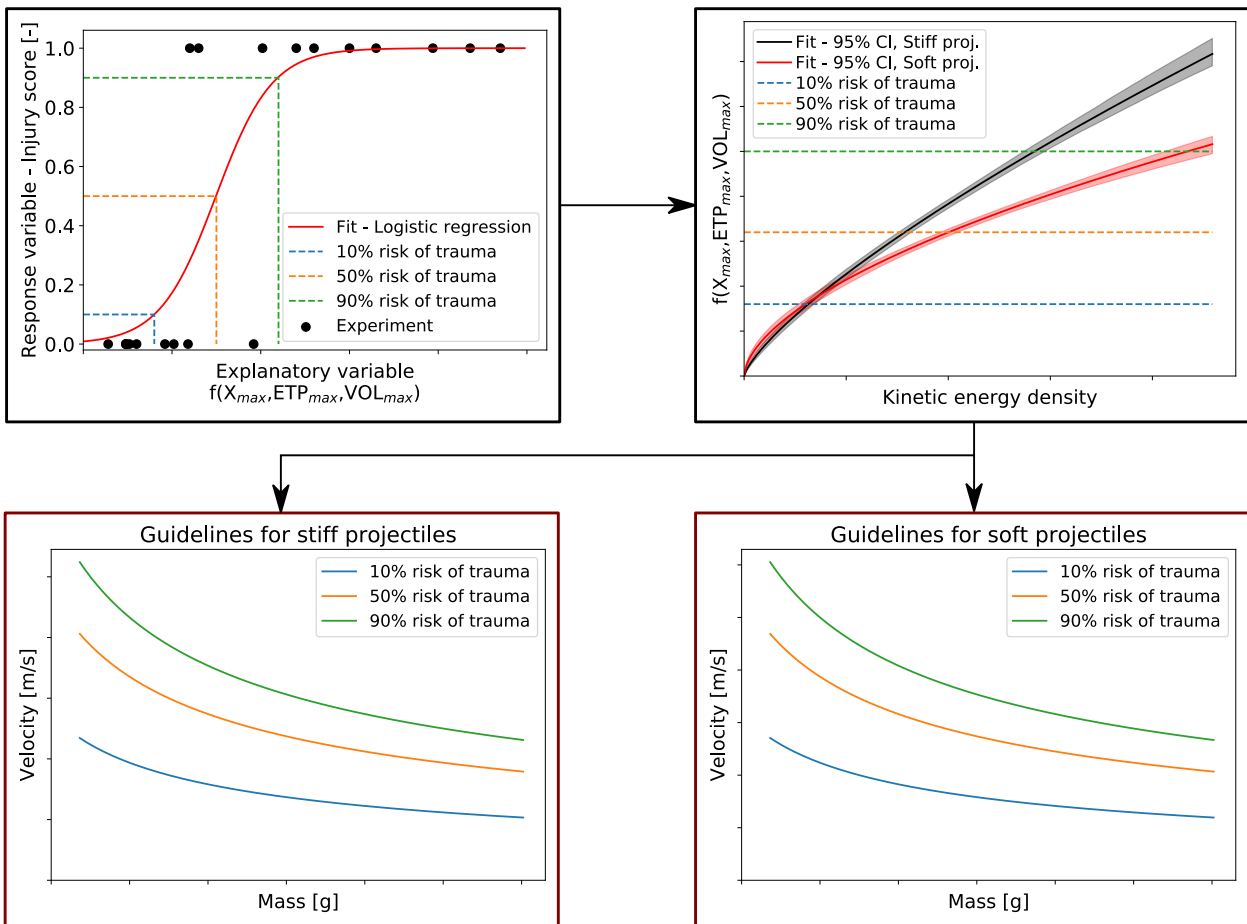


Figure 10: Flow chart describing the potential of reporting case fields with sustained injuries to determine mass-velocity guidelines for projectiles at different risks of trauma.

264 4. Conclusion

265 The SEBS gel material is proposed as a novel transparent ballistic target to assess non-penetrating ballistic impacts
 266 and LLKE projectiles before their use by law enforcement agencies across the world. High-speed imaging and a

267 specific image processing routine coded in MATLAB capture the dynamic gel wall displacement profile over time.
268 Several metrics are worked out to describe impacts such as the maximum gel wall displacement or the energy transfer
269 parameter value. The mechanical consistency and batch-to-batch reproducibility of the target are verified by an
270 ANOVA and statistical comparisons of repeated shots performed on gel blocks produced in different years.

271 A statistical analysis is then conducted based on the dataset generated by 138 impact conditions of soft and
272 stiff LLKE projectiles applied to gel blocks. Spearman's correlation matrix is computed in order to identify the
273 most relevant relations from a pool of metrics like the maximal energy transfer parameter or the projectile kinetic
274 energy density. It highlights the requirement to use a ballistic target to quantify the effects of a projectile rather than
275 kinetic energy or momentum. Dependable power law functions have been identified between projectile kinetic energy
276 density and the maximum gel wall displacement, the maximum *ETP* value as well as the maximum displaced volume
277 according to the projectile's stiffness.

278 Three case reports involving commercially available LLKE projectiles have been recreated on the ballistic target.
279 The specific impact conditions related to those cases have resulted in serious thoracic injuries as rib and sternal
280 fractures as well as lung and heart contusions. The need to gather case studies is essential to obtain reliable statistical
281 outcomes. It could lead to the identification of mass-velocity guidelines for projectiles as a function of their stiffness.
282 Quantifying the wounding potential of any LLKE projectiles would be the focus of future investigations which could
283 benefit numerous actors involved in the field of defence and safety.

284 **Conflict of Interest**

285 The authors have no conflicting interests regarding this paper.

286 Acknowledgements

287 This research is funded by the French Ministry of the Interior and is carried out within the framework of the CNRS
288 Research Federation on Ground Transports and Mobility, in articulation with the ELSAT2020 project supported by the
289 European Community, the French Ministry of Higher Education and Research, the Hauts de France Regional Council,
290 The AIP-Priméca Nord-Pas de Calais group. The authors gratefully acknowledge the support of these institutions.

291 References

- 292 [1] S. N. Kunz, U. P. Arborelius, D. Gryth, A. Sonden, J. Gustavsson, T. Wangyal, L. Svensson, D. Rocks, Cardiac Changes After Simulated
293 Behind Armor Blunt Trauma or Impact of Nonlethal Kinetic Projectile Ammunition:, *The Journal of Trauma: Injury, Infection, and Critical*
294 *Care* 71 (2011) 1134–1143.
- 295 [2] D. de Brito, K. R. Challoner, A. Sehgal, W. Mallon, The injury pattern of a new law enforcement weapon: The police bean bag, *Annals of*
296 *Emergency Medicine* 38 (2001) 383–390.
- 297 [3] P.-M. Brun, J. Bessereau, H. Chenaitia, C. Barberis, M. Peyrol, Commotio cordis as a result of neutralization shot with the Flash Ball
298 less-lethal weapon, *International Journal of Cardiology* 158 (2012) e47–e48.
- 299 [4] M. Kobayashi, P. F. Mellen, Rubber Bullet Injury: Case Report With Autopsy Observation and Literature Review, *The American Journal of*
300 *Forensic Medicine and Pathology* 30 (2009) 262–267.
- 301 [5] P. Wahl, N. Schreyer, B. Yersin, Injury pattern of the Flash-Ball, a less-lethal weapon used for law enforcement: Report of two cases and
302 review of the literature, *The Journal of Emergency Medicine* 31 (2006) 325–330.
- 303 [6] A. J. Ritchie, Plastic bullets: significant risk of serious injury above the diaphragm, *Injury* 23 (1992) 265–266.
- 304 [7] C. Bir, D. Viano, A. King, Development of biomechanical response corridors of the thorax to blunt ballistic impacts, *Journal of Biomechanics*
305 37 (2004) 73–79.
- 306 [8] C. Bir, D. C. Viano, Design and Injury Assessment Criteria for Blunt Ballistic Impacts, *The Journal of Trauma: Injury, Infection, and Critical*
307 *Care* 57 (2004) 1218–1224.
- 308 [9] J. Pavier, A. Langlet, N. Eches, N. Prat, P. Bailly, J.-F. Jacquet, Experimental study of the coupling parameters influencing the terminal effects
309 of thoracic blunt ballistic impacts, *Forensic Science International* 252 (2015) 39–51.

- 310 [10] D. C. Viano, I. V. Lau, A viscous tolerance criterion for soft tissue injury assessment, *Journal of Biomechanics* 21 (1988) 387–399.
- 311 [11] L. Gilson, L. Rabet, A. Imad, F. Coghe, Experimental and numerical assessment of non-penetrating impacts on a composite protection and
312 ballistic gelatine, *International Journal of Impact Engineering* 136 (2020) 103417.
- 313 [12] Y. Wen, C. Xu, H. Wang, A. Chen, R. Batra, Impact of steel spheres on ballistic gelatin at moderate velocities, *International Journal of Impact*
314 *Engineering* 62 (2013) 142–151.
- 315 [13] F. Bresson, J. Ducouret, J. Peyr, C. Marchal, R. Delille, T. Colard, X. Demondion, Experimental study of the expansion dynamic of 9mm
316 Parabellum hollow point projectiles in ballistic gelatin, *Forensic Science International* 219 (2012) 113–118.
- 317 [14] L. Liu, Y. Fan, W. Li, Viscoelastic shock wave in ballistic gelatin behind soft body armor, *Journal of the Mechanical Behavior of Biomedical*
318 *Materials* 34 (2014) 199–207.
- 319 [15] E. Hanlon, P. Gillich, Origin of the 44-mm Behind-Armor Blunt Trauma Standard, *Military Medicine* 177 (2012) 333–339.
- 320 [16] M. L. Fackler, J. A. Malinowski, Ordnance Gelatin for Ballistic Studies: Detrimental Effect of Excess Heat Used in Gelatin Preparation., *The*
321 *American Journal of Forensic Medicine and Pathology* 9 (1988).
- 322 [17] D. S. Cronin, Ballistic Gelatin Characterization and Constitutive Modeling, in: T. Proulx (Ed.), *Dynamic Behavior of Materials, Volume 1:*
323 *Proceedings of the 2011 Annual Conference on Experimental and Applied Mechanics*, Springer New York, New York, NY, 2011, pp. 51–55.
- 324 [18] D. S. Cronin, C. Falzon, Characterization of 10% Ballistic Gelatin to Evaluate Temperature, Aging and Strain Rate Effects, *Experimental*
325 *Mechanics* 51 (2011) 1197–1206.
- 326 [19] G. Appleby-Thomas, D. Wood, A. Hameed, J. Painter, V. Le-Seelleur, B. Fitzmaurice, Investigation of the high-strain rate (shock and
327 ballistic) response of the elastomeric tissue simulant Perma-Gel, *International Journal of Impact Engineering* 94 (2016) 74–82.
- 328 [20] T. Goode, G. Shoemaker, S. Schultz, K. Peters, M. Pankow, Soft body armor time-dependent back face deformation (BFD) with ballistics gel
329 backing, *Composite Structures* 220 (2019) 687–698.
- 330 [21] R. Pasumarthy, H. Tippur, Mechanical and optical characterization of a tissue surrogate polymer gel, *Polymer Testing* 55 (2016) 219–229.
- 331 [22] O. Mauzac, C. Paquier, E. Debord, F. Barbillon, P. Mabire, J. Jacket, A substitute of gelatin for the measurement of dynamic back face
332 deformation, in: *Personal Armour Systems Symposium*, Qubec, Canada.
- 333 [23] A. Bracq, G. Haugou, R. Delille, F. Lauro, S. Roth, O. Mauzac, Experimental study of the strain rate dependence of a synthetic gel for
334 ballistic blunt trauma assessment, *Journal of the Mechanical Behavior of Biomedical Materials* 72 (2017) 138–147.
- 335 [24] A. Bracq, G. Haugou, B. Bourel, C. Marchal, F. Lauro, S. Roth, O. Mauzac, On the modeling of a visco-hyperelastic polymer gel under blunt

- 336 ballistic impacts, *International Journal of Impact Engineering* 118 (2018) 78–90.
- 337 [25] R. A. Mrozek, B. Leighliter, C. S. Gold, I. R. Beringer, J. H. Yu, M. R. VanLandingham, P. Moy, M. H. Foster, J. L. Lenhart, The relationship
338 between mechanical properties and ballistic penetration depth in a viscoelastic gel, *Journal of the Mechanical Behavior of Biomedical*
339 *Materials* 44 (2015) 109–120.
- 340 [26] A. Bracq, C. Marchal, R. Delille, B. Bourel, S. Roth, O. Mauzac, Methodology for ballistic blunt trauma assessment, *Computer Methods in*
341 *Biomechanics and Biomedical Engineering* 20 (2017) 31–32.
- 342 [27] A. Bracq, R. Delille, B. Bourel, C. Marchal, G. Haugou, F. Lauro, S. Roth, O. Mauzac, Numerical Recreation of Field Cases on a Biofidelic
343 Human FE Model Involving Deformable Less-Lethal Projectiles, *Human Factors and Mechanical Engineering for Defense and Safety* 3
344 (2019).
- 345 [28] N. Nsiampa, C. Robbe, A. Papy, Non-lethal Projectile Characterisation Method: Application to 40-mm SIR-X and Condor NT901 Projectiles,
346 *Human Factors and Mechanical Engineering for Defense and Safety* 2 (2018) 7.
- 347 [29] M. Bodo, A. Bracq, R. Delille, C. Marechal, S. Roth, Thorax injury criteria assessment through non-lethal impact using an enhanced
348 biomechanical model, *Journal of Mechanics in Medicine and Biology* (2017) 1–17.
- 349 [30] M. Tawell, G., Kinetic Energy Less Lethal Weapons and Their Associated Blunt Trauma Injuries, Ph.D. thesis, Cranfield University, Cranfield,
350 Royaume-Uni, 2007.
- 351 [31] J. A. Kapeles, C. A. Bir, Human Effects Assessment of 40-mm Nonlethal Impact Munitions, *Human Factors and Mechanical Engineering*
352 *for Defense and Safety* 3 (2019).
- 353 [32] A. Bracq, R. Delille, C. Marchal, B. Bourel, S. Roth, O. Mauzac, Rib fractures prediction method for kinetic energy projectile impact: from
354 blunt ballistic experiments on SEBS gel to impact modeling on a human torso FE model, *Forensic Science International* 297 (2019) 177–183.
- 355 [33] O. Mauzac, C. Paquier, F. Barbillon, P. Mabire, J. F. Jacquet, E. Debord, A. Riesemann, Comparative assessment of Behind Armour Blunt
356 Trauma (BABT) by means of a novel transparent synthetic gel, in: *Personal Armour Systems Symposium*, Nuremberg, Allemagne.
- 357 [34] M. Bolduc, B. Anctil, Improve test methods for better protection, a BABT protocol proposal for STANAG 2920, in: *Personal Armour*
358 *Systems Symposium*, Qubec, Canada.

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368 **Declaration of Interest**

369 The authors declare that they have no known competing financial interests or personal relationships that could

370 have appeared to influence the work reported in this paper.

Highlights

- A polymer gel block is used as ballistic testing medium to interpret non penetrating impacts.
- The transparent target material appears to be insensitive to ageing and is reproducible from batch-to-batch.
- 138 ballistic impacts of eight commercially available less-lethal kinetic projectiles on gel blocks are assessed using high-speed imaging and specific image processing routines.
- Spearman's correlation matrix is computed to identify reliable relations between experimental metrics and projectile kinetic energy/momentum density.
- A procedure for the identification of mass-velocity guidelines is provided for less-lethal kinetic energy projectiles.