AN HYBRID EXPERIMENTAL/NUMERICAL METHOD TO ASSESS THE LETHALITY OF A KINETIC ENERGY NON-LETHAL WEAPON SYSTEM

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Assessing the lethality of Kinetic Energy Non-lethal Weapons (KENLW) is very complicated because of the wide variety of projectiles currently in use, as well as the complexity that characterises the interaction between the projectile and the human body. This article describes and applies injury criteria found in the literature to perform a lethality assessment of a 40mm Nobel Sport sponge grenade. The selected criteria are the viscous criterion $(VC)_{max}$ for the thorax, the Energy Density for the skin penetration assessment, and a dispersion criterion to avoid head impact. These criteria are evaluated thanks to a hybrid experimental-numerical approach, and are computed for different velocities of the projectile, corresponding in real life to different distances of engagement. The final results consist of the determined allowable distances of engagement corresponding to a specified risk of lethality. The method is applicable to any KENLW, requiring two experimental tests and numerical simulations.

INTRODUCTION

Minimizing civilian casualties and unnecessary collateral damage during military or law-enforcement operations has always been a tough challenge. Non-lethal weapons allow a gradual response in case of a continuous escalation in force deployment. Kinetic Energy Non-Lethal Weapons (KENLW) are the most widely spread category of these types of weapons.

Assessing the injury potential associated with the use of a KENLW is obviously a major concern for all the actors involved in their design, procurement and operational use. Due to a wide variety of available projectiles, as well as the complexity that characterises the human body, injury risk assessment for these types of projectiles is quite challenging. A lot of effort has been made during the last fifteen years to establish appropriate evaluation methods, whose ultimate objective is to improve the projectile characteristics and to give recommendations to the end-user. To achieve this goal, animal as well as Post Mortem Human Subject (PMHS) tests have been performed and injury criteria have been defined depending on the impacted zone [1-16]. These tests are however rarely performed and published because of ethical, legal or technical difficulties. Therefore only limited data is available in the literature, and only for few projectiles. This explains why other means have been explored to determine the lethality of KENLW projectiles. Depending on the impact zone and the available data in the literature, the lethality can be directly assessed from the ballistic characteristics of the projectile, using the appropriate injury criterion [1-5], or has to be determined by other means [1, 5, 6-13]. One possible solution is to develop and use a biomechanical surrogate which is a material or a mechanical structure with which one can measure or determine the associated metric of the considered injury criterion [6, 12, 14]. Another way to proceed is to compute the metric associated to the injury criterion using numerical simulations.

Based on the aforementioned considerations, the objective of this article is to propose a way to evaluate the lethality induced by a specific KENLW projectile, namely the 40mm Nobel Sport Spartan LE-40 sponge grenade (NS), which was recently acquired by the Belgian Defence (Figure 1). It is composed of a PVC body, and a deformable hollow rubber nose. The mass of the projectile is 41,8g, and the average muzzle velocity is 92m/s when fired from an F2000 universal grenade launcher.

As mentioned earlier, the lethality will be influenced by the impacted zone, but also by the impact conditions, that will strongly depend on the target distance. The final output of this study will hence be to determine the recommended engagement distances. The minimal safe distance will be determined to ensure that the projectile is not too dangerous, and the maximal distance to ensure a limited ballistic dispersion, in order to avoid an impact on a more vulnerable region of the body (e.g. head).

The proposed approach is a hybrid method, based on experimental results and numerical simulations. A review of key concepts and injury criteria is presented in the first part of this article. The selected criteria are explained and justified. In the second part, the method is developed and used to assess the lethality of the considered projectile for different conditions. Finally, the results are further discussed in detail.

INJURY CRITERIA

It has been decided to limit the study on the blunt trauma of the projectile onto the thorax, the abdomen and the head. An extra consideration is also performed to assess the skin penetration of the projectile.

Thorax

The impact on the thorax is a major concern in assessing the lethality of a KENLW projectile. Indeed, on the one hand, it's one of the most often impacted zones, and on the other hand, the projectile can cause serious injuries, even death, by impacting this zone [17]. Consequently, most of the work presented in this article is focused on the evaluation of thoracic impacts. The most often cited injury criterion for such impacts is the $(VC)_{max}$ (Eq. (1)) (Figure 2) [1, 6-11], which is based on the dynamic deformation of the target.

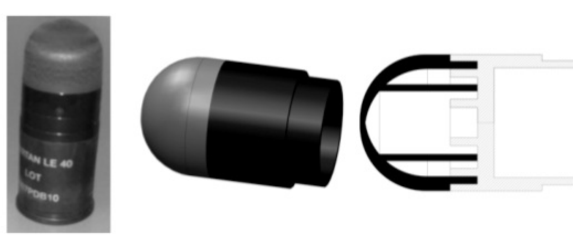


Figure 1. Left: The 40mm NS ammunition, Centre: the 40mm NS projectile,
Right: Cross section of the projectile.

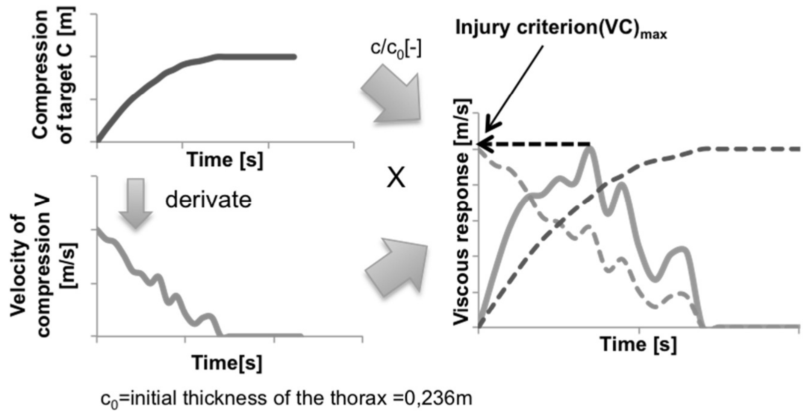


Figure 2. The $(VC)_{max}$ calculation.

The main disadvantage of this criterion is the necessity to measure it on a PMHS or on a biofidelic surrogate. A possible alternative to this is to compute it with a numerical simulation package. In this paper, this later approach has been chosen and is explained in the next section.

$$VC_{max} = max\big(V(t)C(t)\big) \tag{1}$$

Abdomen

One can find in the automotive crash test domain some studies on abdominal impacts [7-11]. These impacts are however characterised by a higher mass and a lower velocity than the impacts of KENLW projectiles. Results show that the abdominal impacts seem less critical than the thoracic impacts, as the same level of injuries (on the AIS scale) are typically obtained for higher values of the specified criteria (acceleration$_{max}$, Force$_{max}$, compression$_{max}$, $(VC)_{max}$).

Besides, the so-called Blunt Criterion (BC) has been correlated with the AIS for both thoracic and abdominal impacts of a rigid KENLW projectile (eq. 2) [5-6].

$$BC = ln\Big((M \cdot V^2)/\big(2 \cdot W^{1/3} \cdot T \cdot D\big)\Big) \tag{2}$$

Where M is the mass of the projectile in kilograms, V is the velocity of the projectile in meters per second, D is the diameter of the projectile in centimetres, W is the mass of the impacted target in kilograms, and T is the thickness of the body wall of the target in centimetres.

The BC value to get a 50% probability of observing an abdominal injury characterised by an AIS of 2 or 3 is 0,65, when the value for a corresponding thoracic injury is only 0,37. Therefore the abdominal impacts seem again less critical than the thoracic impacts when applying the BC criterion.

However, these conclusions are only applicable to rigid projectiles. One can find in the literature that the BC is not efficient to evaluate the impacts of deformable projectiles, like the Spartan LE-40 [18-19].

Taking all these considerations into account, abdominal impacts will not be considered in the present study.

Head

The head being a complex part of the human body, literature cites different criteria and tolerance levels depending on the impact location. [3-4, 12-13]. A safe approach, taking into account the worst-case scenario, is to choose a head injury criterion describing the risk on eye injury, as this is the most fragile part of the head. A criterion reported in literature to assess the risk on eye injury is the energy density criterion (ED) (Eq. (3)) [3-4].

$$ED = \frac{E_{kin}}{S} \tag{3}$$

Where E_{Kin} is the kinetic energy of the projectile at the impact location, and S is the cross section of the projectile impacting the target.

The tolerance value for this criterion is however very low: 2,35J/cm^2 and 3,55J/cm^2 depending on the source, for a 50% risk of globe rupture, and 0,15J/cm^2 for a 50% risk of corneal abrasion [3-4]. It can almost be excluded that any KENLW projectile will ever be able to guarantee that no significant eye injury is to be expected. As such, it is the authors' opinion that an impact on the head should always be avoided.

This consideration can be translated into a dispersion criterion. Supposing that the shooter always aims the centre of the target's body, the radius of dispersion should remain lower than half of the distance between the lowest part of the abdomen and the head. Such an average distance can be found in the "STANAG 4512: dismounted personnel target" [20], and is comparable to anthropometric values mentioned by other sources [21]. Finally, the considered dispersion criterion is defined as a R90, which is the radius within which 90% of the impacts are statistically located, assuming that the dispersion follows a Gaussian law and is circular (Eq. 4).

$$R90 = 2{,}146 \cdot \left(\frac{\sigma_x + \sigma_y}{2}\right) \tag{4}$$

where σ_x is the horizontal standard deviation of the impact location, and σ_y is the vertical standard deviation of the impact location.

The maximum acceptable value for R90 is then 32cm.

Skin Penetration

The energy density criterion ED (eq. 3) has been reported in the literature as an injury criterion to predict the skin penetration of a KENLW rigid projectile [2]. One can assume that a deformable projectile is less likely to penetrate the skin than an equivalent rigid projectile. Using this criterion is then a safe choice for a deformable projectile like the 40 mm NS. The tolerance threshold is defined at a value of 23,99J/cm^2. This value corresponds to a 50% probability to observe a skin penetration on an anterior rib of the thorax, which is the weakest region for skin penetration.

An overview of the selected criteria and the associated tolerance levels are summarized on the final recapitulative TABLE III.

APPROACH/METHOD

All the previously mentioned criteria will be directly or indirectly influenced by the impact velocity of the projectile. More specifically, the relative metric for the thoracic and the skin penetration criteria will decrease with decreasing velocity. As the velocity of the projectile depends inversely on the travelled distance during its flight (due to the projectile retardation), both criteria will become less critical as the distance increases. Therefore, a minimal distance of engagement can be defined taking both these criteria into consideration. The projectile retardation can be determined experimentally.

Conversely, the ballistic dispersion will increase with the engagement distance. The increasing risk on head injury will then define a maximum distance of engagement.

The proposed approach is to compute each criterion for different velocities corresponding to different distances of engagement, and to compare the values to the previously mentioned tolerances. The final result consists of a minimal and a maximal distance of engagement taking all this information into account. The considered approach will be both experimental and numerical.

Experimental tests are performed to characterize the retardation and the dispersion of the projectile. From this result, the head criterion and the skin penetration criterion will be computed. The thoracic criterion is computed based on a five-step approach described schematically in Figure 3.

(1) Data on impacts of rigid KENLW projectiles on PMHS are retrieved from literature [6];
(2) The considered projectile, in casu the 40mm Nobel Sport, is shot on a rigid structure, and the force as well as the displacement of the projectile are measured as a function of time;
(3) An FE model of the thorax is developed and validated using the data from step 1;
(4) An FE model of the projectile is developed. The impact results from step 2 are used to validate this model;
(5) The impact of the projectile on the thorax is then numerically simulated, and the $(VC)_{max}$ is computed.

Experimental Setup

Experiments have been performed in order to characterize the projectile regarding exterior and terminal ballistics. The ballistic dispersion has been determined as a function of the shooting distance and the projectile retardation has been calculated. The projectile retardation information has been used for determining the impact velocity in the numerical simulations. Besides, the force and the displacement of the projectile as a function of time were also measured during the impact on a rigid structure, for numerical simulation purpose.

Two different specific experimental setups were used: the first is used for the ballistic dispersion and the projectile retardation determination and the second for the impact force and the projectile displacement measurements (Figure 4).

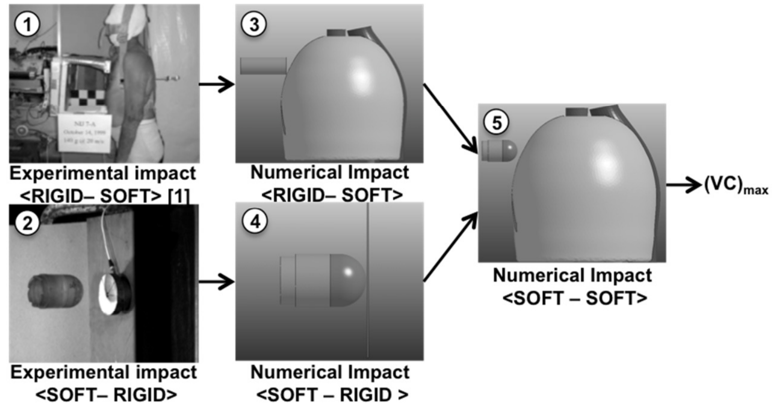
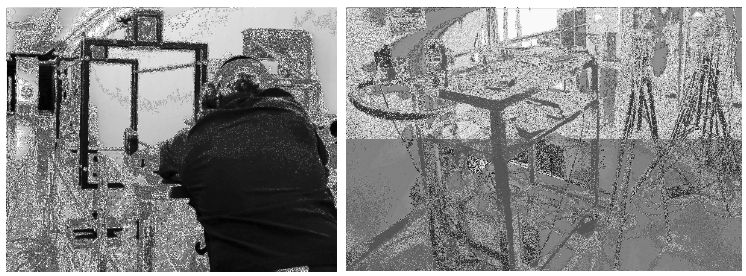


Figure 3. Thoracic injury assessment approach.



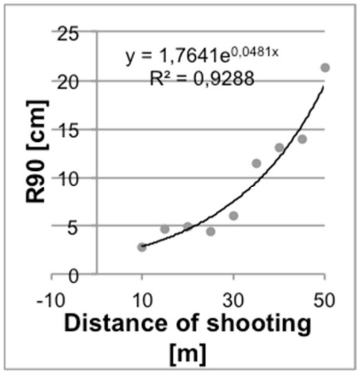
(a) **(b)**

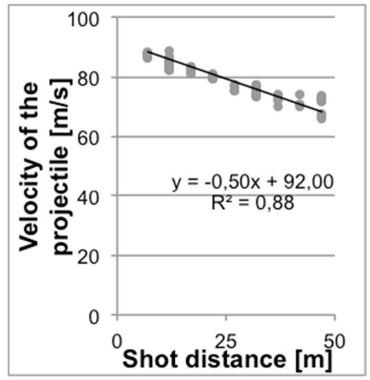
Figure 4. Experimental setups. (a) retardation determination and dispersion measurements for several firing distances, (b) measurements of impact force and displacement of the projectile as a function of time.

The first setup consists of shooting the projectiles with the F2000 UGL at distances from 10 to 50m from the target. The muzzle velocity was measured at 2,5m of the launcher with a Drello IR light screen LS19iN and at 0,5m of the target with a Photron Fastcam SA5 high-speed camera. All tests were performed indoor as to minimize the external influences. A shooter fired all shots in a supported standing position. The main aiming device of the F2000 5.56x45 mm barrel was used. For each distance, a few preliminary shots were fired to define the aiming point.

Firstly, the dispersion was measured for several firing distances, and the corresponding R90 was computed (Figure 5a). Secondly, using the velocity measurements, the relation between shooting distance and velocity was computed (Figure 5b). It can be seen that this result corresponds to a constant retardation of the projectile equal to 0,5m/s/m.

The second setup consists of shooting the projectile on a piezoelectric force sensor PCB 200C20, fixed on a rigid target. The sensor is supplied with a PCB 482B11 ICP AMP/ Supply Signal Conditioner. The projectile was shot using an in-house pneumatic launcher allowing to adjust the muzzle velocity of the projectile. The launcher was placed at a distance of 30cm from the target to assure a normal impact and to minimize effects regarding the ballistic dispersion and the stability of the projectile. Knowing the retardation of the projectile, the velocity is adjusted as to reproduce the impact conditions that would occur at different distances along its trajectory. The velocity was again measured with a Drello IR light screen LS19iN. The force, as well as the deflection of the nose of the projectile, which corresponds to the displacement of the projectile during impact, are measured as a function of time. The acquisition of the force signal was achieved with a sample rate of 1 MHz using a Nicolet pro 90 oscilloscope.





(a) **(b)**

Figure 5. (a) Dispersion and (b) Projectile velocity as a function of shoot distance.

The displacement was measured with a Photron Fastcam” SA5 high-speed camera, and processed with the associated software (Photron Motion Tools™). The results of this experimental campaign were already published [19]. Curves are used on the numerical section on (Figure 8 and Figure 9). It can be observed that the curve showing the displacement of the projectile during impact stops at about 6ms as it became difficult to track the projectile due to its tumbling.

Numerical Simulations

As described above (Figure 3), three types of simulations were performed corresponding respectively to the validation of the FE thorax model, the validation of the projectile model and the $(VC)_{max}$ computation. The simulations were performed with the LS-DYNA explicit FE code. The following section briefly describes these simulations.

The first type of simulations served to validate the FE thoracic model using data on the impact of rigid projectiles onto the human thorax. The material models were taken from the literature [22, 23]. An extended discussion of the results was previously published [24].

The second set of simulations served to validate the projectile model using the data from the impact tests of the 40 mm NS projectile on a rigid target. An elastic model was used for the projectile body and the Mooney-Rivlin model (MAT_027) was used for the projectile nose [25]. The Mooney-Rivlin model only needs two parameters (A, B) to characterize it.

The strain energy density function is defined as in (Eq. 5-7).

$$W = A(I-3) + B(II-3) + C(III^{-2}-1) + D(III-1)^2 \quad (5)$$

Where

$$C = 0.5A + B \quad (6)$$

and

$$D = \frac{A(5\upsilon-2) + B(11\upsilon-5)}{2(1-2\upsilon)} \quad (7)$$

υ is the Poisson's ratio, 2(A+B) corresponds to the shear modulus of linear elasticity and I, II,III are the invariants of the right Cauchy-Green Tensor.

A mesh sensitivity study was firstly performed (Figure 6), showing that a 2 mm tetrahedron element gave sufficient accuracy. To illustrate this, Fig. 6 also shows the simulation results for a smaller 1 mm tetrahedron element, giving very similar results to the larger 2 mm tetrahedron element, and a larger 4 mm element, giving considerably deviating results.

In order to determine the two parameters A and B, two steps were followed:

In a first step, a set of initial parameters (A,B) was determined using quasi-static compression data by matching the numerical result to the experimental result. The projectile nose was used as the specimen for this compression test. The hence obtained stress-strain curve was then introduced in the FE model and used to compare the numerical contact force with the experimentally measured force. As expected, this initial set of parameters did not allow catching the main features of the impact process, implying the need for a second step.

In this second step, the initial set of parameters was used as the start point for an optimization process through LS-OPT, which is an optimization tool associated with LS-DYNA. The experimental force curve for an initial velocity of 52 m/s was set as the target curve. The optimized material parameters for the nose material model, resulting from this optimization are given in TABLE I.

Comparing the results of the simulation to the experimental results for the force as a function of time and the displacement of the projectile as a function of time (Figure 7), a good correspondence between the experimental and the numerical results can be observed. Results at different velocities are also presented on TABLE II.

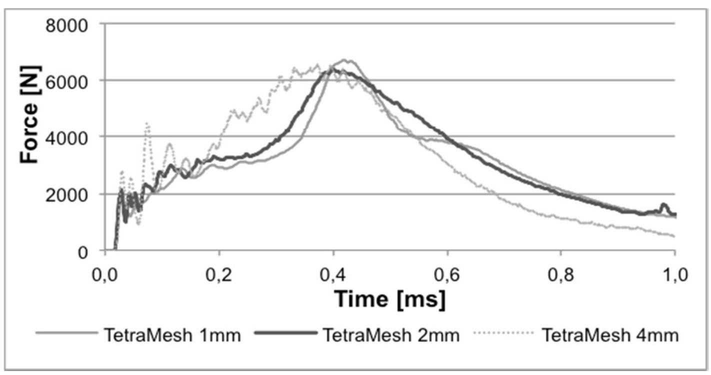


Figure 6. Mesh sensitivity study.

TABLE I. PROJECTILE NOSE MATERIAL MODEL.

Par	Material	R0	PR	A	B
Sp	*Mat_Mooney-Rivlin_rubber_Title	10	0.49	5.6	-

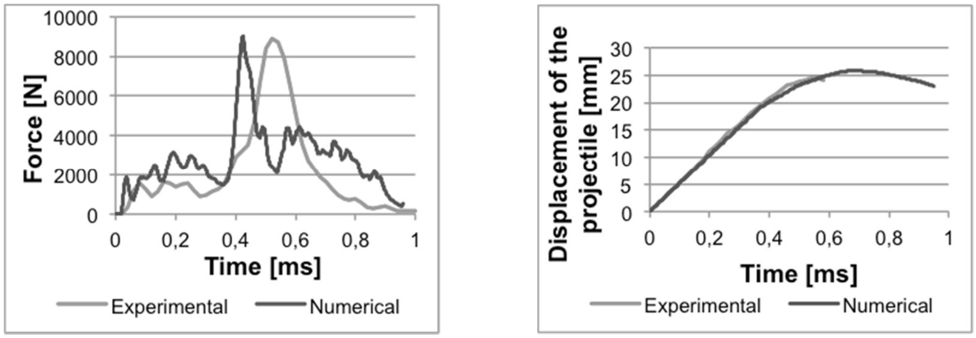


Figure 7. Comparison between experimental measurements and numerical results – 52m/s.

TABLE II. MAXIMUM FORCES MEASURED ON THE RIGID FORCE SENSOR.

Impact velocity [m/s]	Impact energy [J]	Experimental tests			Numerical results
		Number of shots [-]	Average F_{max} [N]	Standard Deviation F_{max} [N]	F_{max} [N]
35	25	15	2830	300,2	5583
52	57	15	8693	373,2	9023
70	102	10	12865	2175,3	12668

The last type of simulations consists of the computation of the $(VC)_{max}$ by numerically firing the validated projectile model onto the validated thoracic model. Figure 8 shows the impact and Figure 9 shows the horizontal displacement of the thorax at the point of impact as a function of time. The induced $(VC)_{max}$ for different velocities are given in the final recapitulative TABLE III.

RESULTS AND DISCUSSION

Results

All the results are summarized in TABLE III. It can be seen that the skin penetration criterion is always satisfied. Consequently, only the thoracic and the head criteria determine the allowable engagement distances. According to these results, the safe engagement distances for this projectile are between 30m and 61m.

Discussion

Choosing the acceptable level of risk of injury is a delicate choice that is probably not completely in the hand of the scientific community or the manufacturers of KENLW, but more in the hands of the institution that decides to use the system. However, modifying the probability levels in the proposed approach would ask a marginal effort and only change the final go/no go conclusions of Table 5. An in-house software is currently being developed that in the near future will allow a user to interactively see the effects of a probability change [26].

In the present case the probability of observing AIS>1 was set at 50%. This specific choice was made for two reasons. Firstly, the 50% value of observing a phenomenon is commonly used for ballistic protection, as for example illustrated by the STANAG2920

[27]. On the other hand, the chosen tolerances are based on a PMHS study. Because of their nature and their anthropomorphic data they tend to be weaker than an average human being. A 50% probability of wounding a naked PMHS would probably represent a lower probability to wound an average clothed human being. Case reports seem to confirm this assumption [17].

Another choice that could be discussed concerns the link between distances of engagement and velocity and dispersion. They were computed using the results of experimental tests in an indoor ballistic shooting range. One could perform these same tests in more realistic conditions, although with the added difficulty concerning reproducibility.

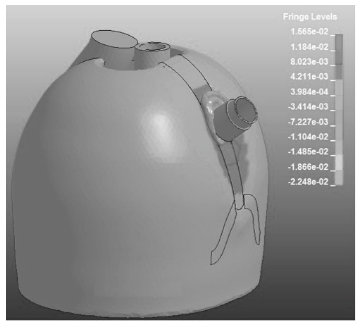


Figure 8. The FE model of the projectile impacting the FE thoracic model.

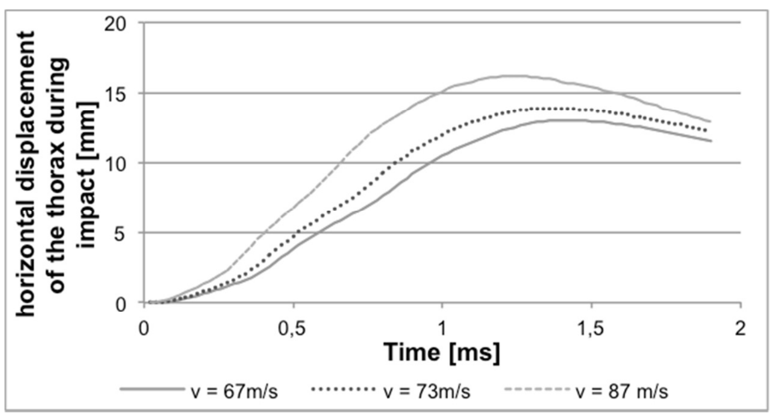


Figure 9. Horizontal displacement of the thorax as a function of time in the FE thoracic model.

TABLE III. DETERMINATION OF THE SAFE ENGAGEMENT DISTANCES IN FUNCTION OF THE CONSIDERED CRITERIA.

distance of engagement	Velocity of the projectile	Kinetic Energy	Thoracic criterion (VC)max<0,8	Skin penetration criterion DE<23,99J/cm2	Head criterion R90<32cm	Result
[m]	[m/s]	[J]	[m/s]	[J/cm2]	[cm]	[-]
0	92	177	✗ 1,08	✓ 14,08	✓ 0,00	✗
10	87	158	✗ 0,99	✓ 12,59	✓ 2,78	✗
20	82	141	✗ 0,90	✓ 11,18	✓ 4,56	✗
30	77	124	✓ 0,80	✓ 9,86	✓ 5,96	✓
40	72	108	✓ 0,71	✓ 8,62	✓ 13,15	✓
50	67	94	✓ 0,61	✓ 7,47	✓ 21,37	✓
60	62	80	✓ 0,52	✓ 6,39	✓ 30,37	✓
70	57	68	✓ 0,43	✓ 5,40	✗ 42,87	✗
80	52	57	✓ 0,33	✓ 4,50	✗ 57,76	✗
90	47	46	✓ 0,24	✓ 3,67	✗ 75,02	✗
100	42	37	✓ 0,14	✓ 2,93	✗ 94,67	✗

Finally, the chosen criteria can be discussed. A lot of effort has been made in computing the thoracic criterion, because of the previously mentioned reasons and gives good results.

The skin penetration criterion tends to overestimate the injury. Based on this criterion, it has been concluded that the projectile doesn't present any risk of penetration anyway, For other projectiles, a validated surrogate exists, and is in the process of standardisation at NATO level [14, 28-29]. In a near future, this surrogate will be included in the proposed approach.

The head criterion considered in this paper is based on the fact that the projectile should not hit the head, effectively eliminating the risk of critical damage to the eye. In the context of a risk assessment of one specific projectile, it may be important to have an idea of what kind of injuries could be expected by the impact of the projectile on any region of the head. The use of a surrogate or numerical simulations might enhance the present study, and are currently considered.

CONCLUSION AND PERSPECTIVES

A new global method to assess the lethality induced by 40mm NS projectile has been developed and performed in different conditions. The approach is based on previously published injury criteria and induced tolerances of the human body.

The thoracic criterion is the key parameter for this research, and a lot of effort has been made to perform the relevant computations.

Next to this, the skin penetration criterion was evaluated making the hypothesis that a deformable projectile is less likely to penetrate than a rigid one.

Possible head impacts have been excluded because of the risk of severe damage to the eye. This was translated into a maximum dispersion criterion.

The proposed approach is a combination of experimental testing and numerical simulations. The first experimental test consists of an external ballistic study to assess the dispersion of the projectile on the one hand, and its retardation on the other hand. The second one consists of terminal ballistic measurements, whose results are used for validating the FE projectile model afterwards.

The numerical simulations were used to validate a FE model of the human thorax, a FE model of the projectile and to simulate the impact of the projectile onto the thorax.

The criteria were computed for different distances of engagement, corresponding to different impact velocities. Finally, minimal and maximal distances of engagement were calculated to ensure a safe employment.

The same process could be applied to other projectiles for comparison. It gives direct information about lethality in different conditions, and how to safely use a specific system. The approach can be used to find which system would correspond to a specific need, or to refine the tactical procedures to use an already acquired system.

At last, some directions for improvements are proposed concerning the criteria. Numerical simulations will be developed in the near future to improve the understanding of the head impact. Next to this, the skin penetration assessment will be compared with the results of a nearly validated surrogate. Finally, due to a lack of information, the limb and abdominal impacts remain the weak point of the approach. Nevertheless, such impacts being presumed less dangerous than thoracic impacts, the proposed approach looks already very interesting and quite complete to assess the lethality of a KENLW.

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