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ORIGINAL PAPER

Assessment of Non-Lethal Projectile Head Impacts

Amar Oukara [1] · Nestor Nsiampa [2] · Cyril Robbe [2] · Alexandre Papy [2]

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Abstract Anti-personnel NLW (Non-Lethal Weapons) are used to impart sufficient effect onto a person in order to deter uncivil, suspect or hazardous behaviour with a low probability of permanent or fatal injury. In many situations of conflict, where the army and law-enforcement units are involved, the use of such weapons can ensure a minimal risk of collateral damage. The most used NLW are Kinetic Energy Non-Lethal Weapons (KENLW) that involve the shooting of a deformable or breakable projectile. Since their first use, real cases indicate that the injuries inflicted by such projectiles may be irreversible and sometimes lead to death, especially for the head impacts. Therefore, there is a necessity to assess the head impacts in order to allow a safer use of such projectiles. This article concludes a 4-year study where three methods, independently developed, are considered to be applicable for the head risk assessment. The first method links force measurements on rigid wall structure with cadaveric and animal impact test results. Lesional thresholds, in terms of the maximum impact force and intracranial pressure, are proposed for unconsciousness, meningeal damages and bone damages, respectively. The second one is based on direct impact force measurements on a specific mechanical surrogate. The third method makes use of numerical simulations using a validated finite element head model. The numerical model allows the prediction of different kind of injuries. Firstly, the necessity of the assessment of the non-lethal head impacts is highlighted through some examples taken from literature. Secondly, the three different methods are detailed and illustrated for different projectiles. Outstanding results are given and a comparison between the different methods is proposed including some correlations between different criteria. Finally, some discussions and remarks conclude the present article.

Keywords Nol-lethal projectile · Injury risk assessment · Force wall · Mechanical surrogate · Finite element head models · Injury criteria

✉ Amar Oukara
amar_oukara@yahoo.fr

1 Polytechnic Military School, 17 Bordj El-Bahri, Algiers, Algeria

2 Department of Weapon Systems and Ballistics, Royal Military Academy, 30 Avenue de la Renaissance, 1000 Brussels, Belgium

Introduction

Anti-personnel NLW (Non-Lethal Weapons) are used to impart sufficient effect onto a person in order to deter uncivil, suspect or hazardous behaviour with a low probability of permanent or fatal injuries. They appear to be suitable for many law-enforcement missions and to a certain extent to the military forces. In fact, in many situations of conflict, where the army and law-enforcement units are involved, the use of such weapons can ensure a minimal risk of collateral damage. The most used NLW are Kinetic Energy Non-Lethal Weapons (KENLW) that involve the shooting of a deformable or breakable projectile with a typical mass of 5 to 140 g, at muzzle velocity of 70 to 160 m/s. Some examples of typical non-lethal projectiles are shown in Fig. 1. Such projectiles can be fired using conventional or dedicated weapons. Since their first use, real cases indicate that the injuries inflicted by such projectiles may be irreversible and sometimes lead to death, especially for the head impacts [1–6]. In fact, in the literature review that is proposed in the present article regarding the real impact situations, it appears that severe injuries can be inflicted, especially for the head impacts. Therefore, there is a necessity to assess the head impacts in order to allow a safer use of the non-lethal projectiles. The idea is to link a

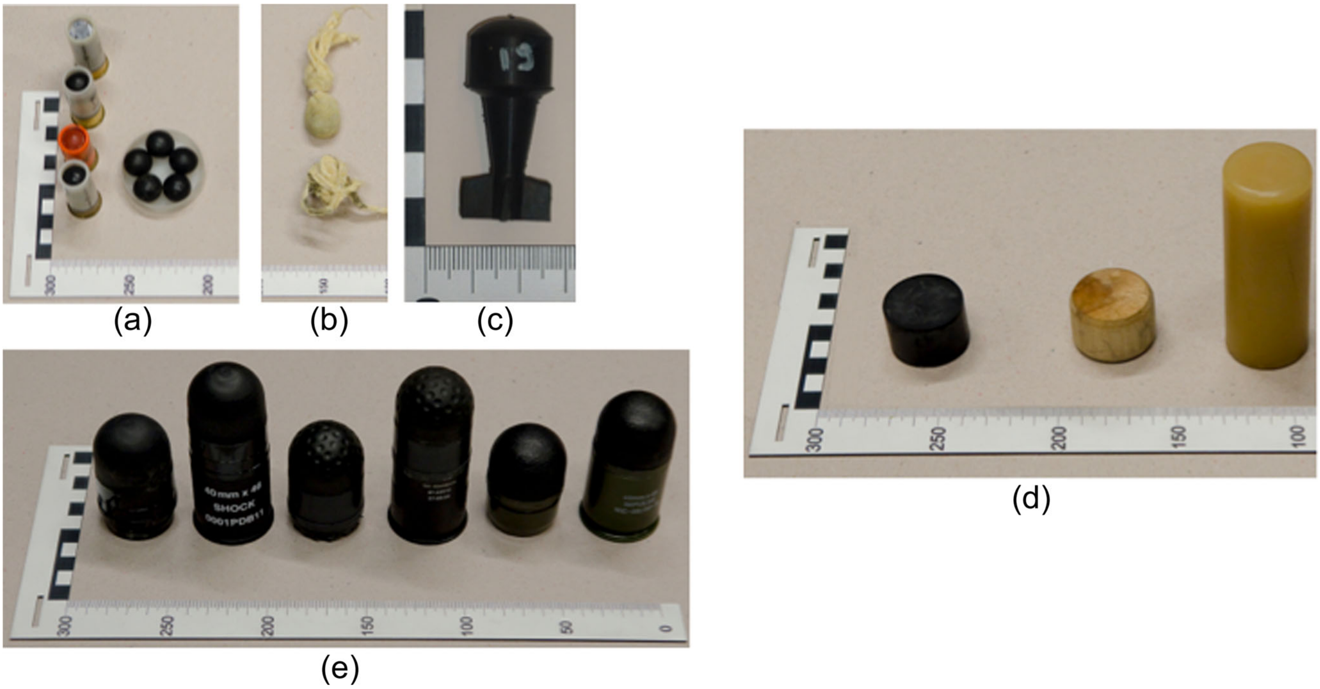


Fig. 1 Some examples of operational non-lethal projectiles. **a** 12-gauge rubber projectiles. **b** Beanbag projectile. **c** RB1FS rubber projectile. **d** 37-mm baton rounds (wood and PVC). **e** 40-mm sponge projectiles

physiological or mechanical parameter to certain levels of head injuries. In the present work, the maximum head force is taken as a benchmark mechanical parameter.

The purpose of the present article is to propose different methods in order to assess non-lethal projectile impacts through experimental and numerical investigations based on the maximum head force. The first method is based on the study carried out by DGA (Direction Générale de l'Armement, France) [7, 8]. Some data from this study have been presented and developed in different works [9–11]. This method, called Force Wall (FW) method, uses the relations between the maximum impact forces measured on PMHS (Post- Mortem Human Subjects) and animals and those measured on a mechanical rigid structure. In the article, the dedicated experimental setup used for the impact force measurements is described. The study of DGA and the application of the FW method are detailed.

The second method is based on the use of a mechanical surrogate, BLSH (Ballistic Load Sensing Headform), developed at Biokinetiks. BLSH enables a direct measurement of the dynamic head force. The BLSH experimental setup is described and some details regarding the force measurements are presented.

The third method uses numerical simulations performed with SUFEHM (Strasbourg University Finite Element Head Model). SUFEHM is described and some numerical simulations are proposed.

Firstly, the three methods are verified for a benchmark projectile regarding the maximum head force prediction. Secondly, the three methods are applied to different existing projectiles. A comparison between the different results is performed. Correlations between the maximum head force and other criteria are proposed for the non-lethal projectile head impacts. Finally, different conclusions and recommendations conclude the present article.

Real Situations of Non-Lethal Projectile Impacts

In this section, a literature review of real situations of non-lethal projectile impacts is proposed. In fact, there is an important issue that should be investigated: What are the undesired effects of KENLW on the targets when used on the operational field? Some studies have been conducted in order to record and analyse the effects of non-lethal projectile impacts. The obtained data give information about the critical and sensitive human body parts in order to assess the severity of such impacts.

One of the first studies on the reported cases was conducted in 1975 [1]. Ninety cases of impacted persons in Northern Ireland by baton rounds (Fig. 1d) are inventoried. In the reference [1], the projectiles have been referenced as rubber bullets. The term "baton rounds" is used in the present article in order to remain consistent with NLW terminology. The neck and the head are impacted in 54% of the cases. The chest impacts have represented 22%. One case of death was reported with severe brain injury and skull fracture what made of the head the most vulnerable part.

After that, ten cases of rubber bullet impacts have been reported between 1987 and 1993 [2] in Israeli-Palestinian conflict. Seven cases of death were due to brain injuries.

Another study has been performed after the riots due to the Israeli-Palestinian conflict in early October 2000 [3]. Medical records of 201 cases of injuries inflicted by rubber bullets have been analysed. Figure 2 shows the distribution of the rubber bullet impacts. The head, face and neck have represented the most impacted parts of the body. The study has shown that the neck injuries are less severe than the other ones (six of seven reported injuries are mild). The face had a very high lesional potential while head injuries can be moderate or severe.

In 2004, a study has been conducted by the US Department of Justice. This study has reported and examined 768 cases of non-lethal projectile injuries, occurred between 1985 and 2000 [4]. Different projectiles were referenced. The head has been impacted in only 2% of cases. However, it has been noted that the injuries inflicted by impacts to the head were more severe compared to other regions of the body. Seventy-four percent of the head impacts caused lacerations, fractures or penetrating injuries.

A case of death was reported for a XM1006 projectile (more details about the projectile can be found in [9]), shown in Fig. 2, after a head impact during a prison riot in 2005 in the USA. The victim suffered of intracranial trauma and lacerations on the head [5]. Other cases of XM1006 impacts were reported including severe contusions and lacerations on the head [6].

In the light of these reported impacts, it appears that head impacts should be assessed in order to define the threshold between a moderate and severe injury. The head is typically not supposed to be aimed when KENLW are used. However, it can be impacted as reported in the literature. It should be pointed out that even if thoracic impacts can also lead to severe injuries, they will not be considered in the framework of the present study.

Assessment Methods of Non-Lethal Head Impacts

As mentioned earlier, the injury risk assessment consists in linking a physiological or mechanical parameter to a given injury level. For this, tests should be performed on living materials. Tests of projectile impacts on living human persons are not feasible for obvious reasons. Consequently, tests are usually performed on PMHS (Post Mortem Human Subjects) and/or on living or dead animals being biologically the closest to the living human persons. However, for technical, ethical and legal reasons, these tests are very complicated or sometimes impossible to perform. Therefore, the development of alternative methods and tools (mechanical surrogates and numerical models) is very important in order to avoid tests on PMHS and animals. These ones remain nevertheless indispensable to validate any alternative method. In this article, three alternative methods, independently developed, are proposed.

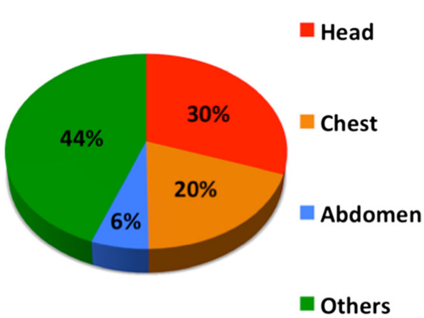


Fig. 2 Distribution of rubber bullet impacts in Israeli-Palestinian conflict during October 2000 [3]

The Force Wall Method

Since several years, DGA, in partnership with engineers and medical experts in France, have undertaken a major research project in order to understand and explain blunt-impact injuries, especially the effects of non-lethal projectiles on the human body [7, 8]. The purpose is to implement a new method that allows an easy assessment of the head injury and to propose lethality thresholds using measurable physical parameters. A substantial number of tests has been conducted on the head for a specific 40 mm diameter benchmark projectile, the eXact iMpact XM1006 shown in Fig. 3. This projectile mass is 27 g and it consists of a foam nose and a hard plastic body.

The maximum ICP (ICP_{max}) has been measured on Human Biological Models (HBM) and Animal Biological Models (ABM) for frontal, parietal and temporal impacts at different impact velocities. The Intracranial Pressure (ICP) is the pressure of the cerebrospinal fluid. The results have shown that the temporal impacts were the source of the highest ICP_{max} values [7, 8]. Therefore, only these kinds of impacts have been considered for the injury risk assessment.

Through numerical simulations, the relation between ICP_{max} and maximum head force $(F_{head})_{max}$ has been derived [8]. Equation 1 gives the relation between $(F_{head})_{max}$ and impact velocity for the XM1006 temporal impact.

Fig. 3 Benchmark projectile XM1006

This kind of raw data is very rare and constitutes the keystone of the non-lethal projectile head impact assessment. This relation can also be used to verify the reliability of other tools (mechanical or numerical) regarding the prediction of $(F_{head})_{max}$ for non-lethal projectile impacts. The clinical findings on HBM and ABM allowed defining the damage threshold values presented in Table 1, for unconsciousness, meningeal and bone damage [8].

$$(F_{\text{head}})_{max\ \ \text{XM}} = 0.083(v_{\text{XM}}/10)^{2.585} \tag{1}$$

Where:

$(F_{head})_{max\ XM}$: maximum head force of the XM1006 projectile on the head (kN) v_{XM}: impact velocity of the XM1006 projectile (m/s).

The idea of DGA experts has been using these XM1006 data as a reference in order to develop the $(F_{head})_{max}$ curve for any given non- lethal projectile without performing additional tests on PMHS and animals. DGA experts have proposed to use the impact force measurement on a rigid wall (RW). This structure should be sufficiently rigid compared to the non-lethal projectile impacts and be equipped with a force sensor. This impact force is then linked to the force on the head. In order to achieved this, an assumption has been proposed: "*two different projectiles producing the same maximum forces on the rigid structure will cause equivalent lesional effects on the head*" [7, 8].

Practically, the application of the FW method to a projectile "Y" needs an experimental setup allowing maximum force measurements on a RW for both XM1006 and the "Y" projectile. Figure 4 summarizes the application of the FW method: (1) the projectiles XM1006 and Y are fired on the RW structure and the F_{max} (the RW maximum force) vs. impact velocity relations are established, (2) the projectile Y impact velocities corresponding to those of XM1006 at the same F_{max} are defined, (3) and (4) based on the aforementioned hypothesis, the XM1006 $(F_{head})_{max}$ are related to the corresponding velocities of the projectile Y on RW and (5) the head force curve of the projectile Y is then defined. The corresponding mathematical development is developed in [9–11].

The experimental setup used for the RW force measurement is shown on Fig. 5. The impact force signal acquisition is carried out with a sample rate of 1 MHz and 2 × 10^5 measuring samples. More details about the setup can be found in the following references: [9, 12, 13].

Figure 6 shows an example of a force signal measured, for the present study, on the RW experimental setup for an impact of XM1006 at an impact velocity of 50 m/s. The force signals are filtered using an original method based on the definition the RW Frequency Response Function in order to attenuate the resonances [9].

Two parts in the signal force during the loading can be observed. There is, at the beginning of the impact, a first part with a slow rise and a relatively low amplitude followed by a second part with a faster and a higher rise leading to the maximum force value. The first part of the signal corresponds to the relatively soft nose compression of the projectile and the second one to the impact of the rear part of the projectile. This behaviour is observed for the majority of the 40-mm sponge projectiles [9]. Obviously, different behaviours are obtained for the other projectiles [9, 12].

Table 1 DGA head damage thresholds [8]

Type of damage	Maximum ICP (kPa)	Maximum head force (kN)
Insignificant	$P < 25$	$F < 2.1$
Unconsciousness	$25 \leq P < 45$	$2.1 \leq F < 3.6$
Meningeal	$45 \leq P < 150$	$3.6 \leq F < 7.5$
Bone and coma	$P \geq 150$	$F \geq 7.5$

The Ballistic Load Sensing Headform System

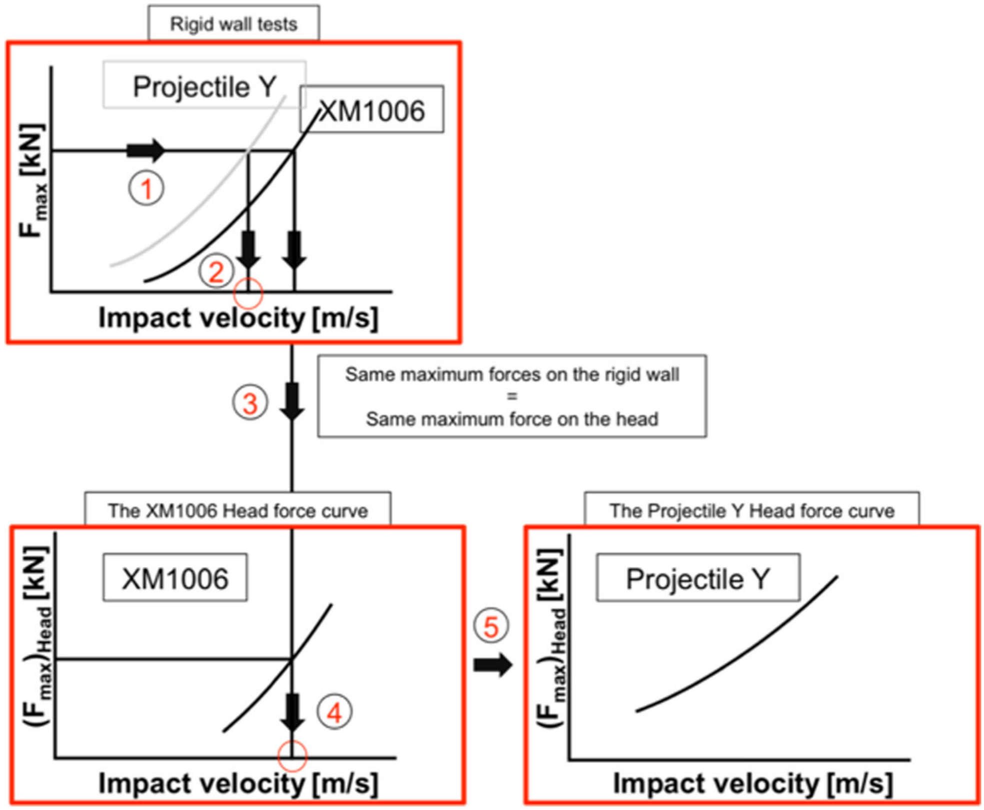
The BLSH system is shown in Fig. 7 and enables a direct measurement of both the dynamic force and acceleration imparted to the head due to a non-penetrating projectile impact [14]. Initially, the BLSH has been developed for BHBT (Behind Helmet Blunt Trauma) assessment [15]. The idea is to measure the impact force and the acceleration induced by the deformation of a ballistic helmet subjected to a non-penetrating impact.

The headform design is based on the standard shapes and sizes. It is mounted the Hybrid III anthropomorphic test device flexible neck. The substructure is made of magnesium. The impact force measurement is performed via a set of seven Kistler sensors. Four impact locations are allowed: lateral (left, right), frontal and rear. A skin pad made of silicon covers each headform impact location. A tape can be used to fix the pad on the impact location as shown in Fig. 7. The experimental setup used for BLSH is similar to the RW one as shown in Fig. 8.

An example of XM1006 impact, carried out in the framework of the present study, on BLSH lateral location at 50 m/s is shown in Fig. 9. The total force signal is the sum of the individual signals. The centre load cell has the highest amplitude being the targeted load cell during the tests.

The impact force signal structure is similar to the RW one. For XM1006, there is a first slow and low amplitude signal at the beginning of the impact, followed by a steep rise leading to the maximum value. The first part of the signal corresponds again to the relatively soft nose impact and the second to the rigid part of the impact. However, the impact duration is longer while the amplitude is smaller for the same impact

Fig. 4 The force wall method applied for a given projectile Y



velocity. This is probably due to the presence of the skin pad that plays a role of a damper.

The Strasbourg University Finite Element Head Model Approach

The first version of SUFEHM was developed in 1997 at the Strasbourg University [16]. The different parts of the head that have been modelled are as follows: skull, falx, tentorium, CSF (Cerebrospinal fluid), scalp and brain (cerebrum, cerebellum, brainstem). The SUFEHM geometry is shown in Fig. 10. The finite element mesh is continuous and represents an 50th percentile male head with hexahedral elements. SUFEHM consists in 13,208 elements and its total mass is 4.7 kg [17]. SUFEHM works under the LS-DYNA. Its units are as follows: g, mm, ms, MPa and mJ. SUFEHM enables the prediction of different meningeal injuries and skull fractures [18].

The numerical approach applied in the present work is based on three different steps as shown in Fig. 11. These three steps are summarized as follows:

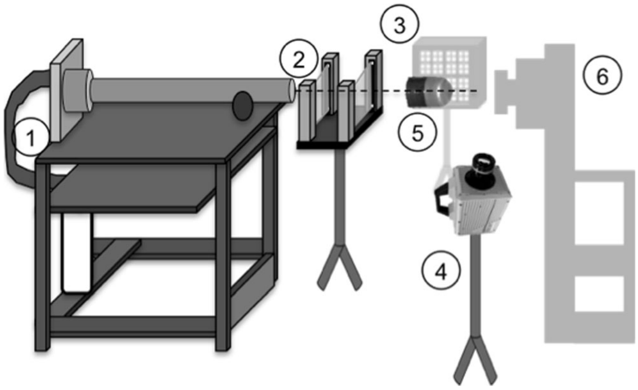


Fig. 5 Rigid wall experimental setup. *1* Pneumatic launcher. *2* Lights for the high-speed camera. *3* High-speed camera for velocity and attitude (yaw) measurement. Parameters are as follows: a frame rate of 50,000 fps and a shutter speed of 100,000 Hz. *4* The projectile *5* Rigid Wall equipped with a piezoelectric dynamic sensor Kistler 9061A

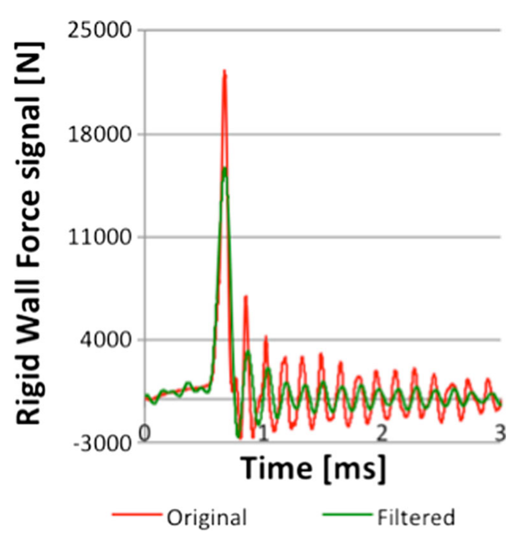


Fig. 6 The original and filtered Rigid Wall impact force signals at 50 m/s

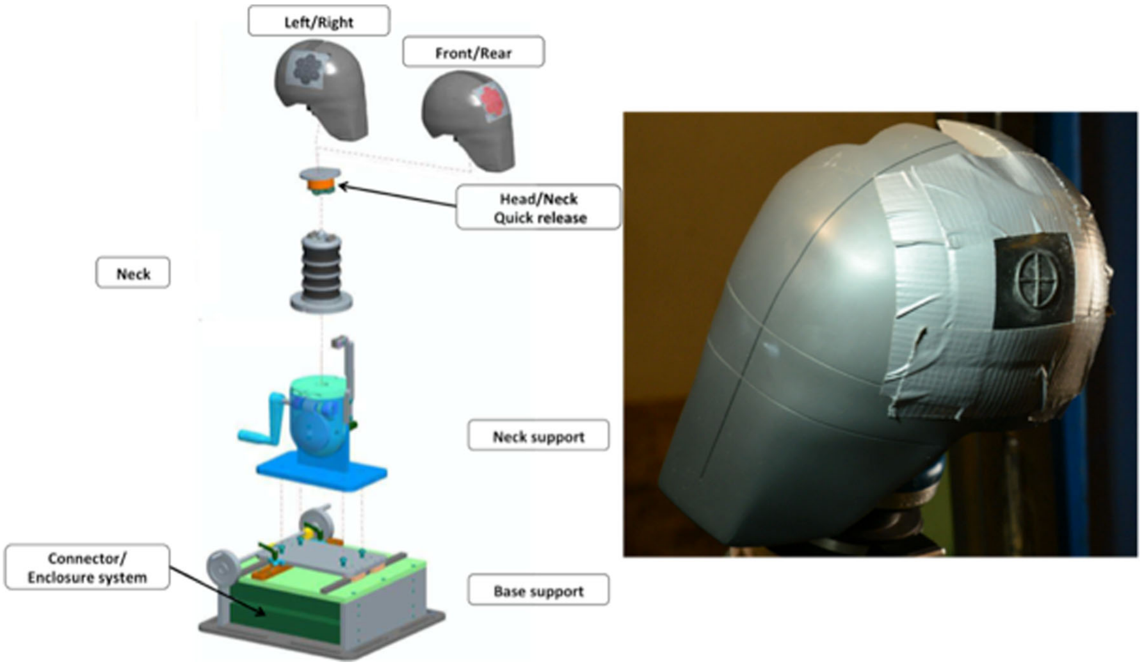


Fig. 7 The Ballistic Load Sensing Headform system

Firstly, the numerical model of the studied projectile is designed. This step includes: the geometry and mesh generations, the definition of contacts between the projectile parts and the material model validation. The validation of the numerical model of the projectile is performed using the RW results.

Secondly, the impact numerical simulation on SUFEHM is carried out. Different points should be considered: definition of contact between SUFEHM and the projectile and definition of different simulation parameters. It has to be noted that different impact zones can be considered (temporal, frontal,...).

Finally, the processing of the output results is carried out.

Details about the validation tests and lesional thresholds of SUFEHM can be found in [9, 18, 19]. Different methods are used for the characterization of the finite element models of the projectiles [20, 21]. The characteristics of the numerical models of the projectiles used in this study can be found in [9, 10, 20, 21].

Comparison between the Different Methods

In this section, it is proposed to compare the three aforementioned methods. Firstly, the consistency of the BLSH and

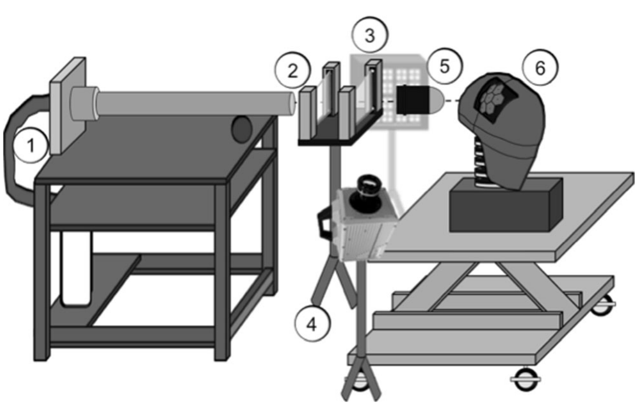


Fig. 8 BLSH experimental setup. *1* Pneumatic launcher. *2* Drello 10-cm-IR Light screen barrier LS66 for the velocity measurement *3* Lights for the high-speed camera. *4* High-speed camera for velocity and attitude (yaw) measurement. Parameters are as follows: a frame rate of 50,000 fps and a shutter speed of 100,000 Hz. *5* The projectile. *6* The BLSH system mechanically fixed on a table

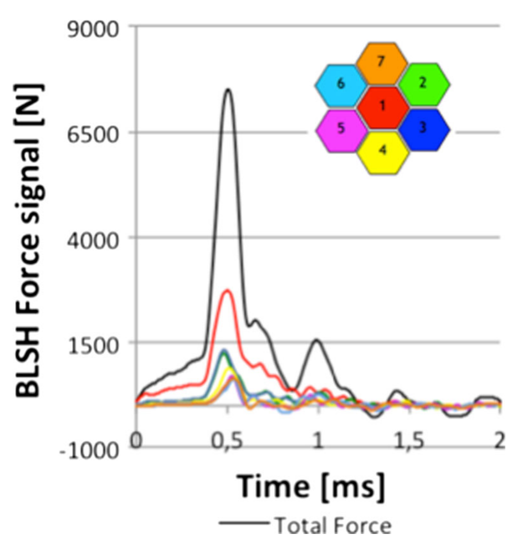


Fig. 9 The original BLSH impact force signals for XM1006 impact at 50 m/s

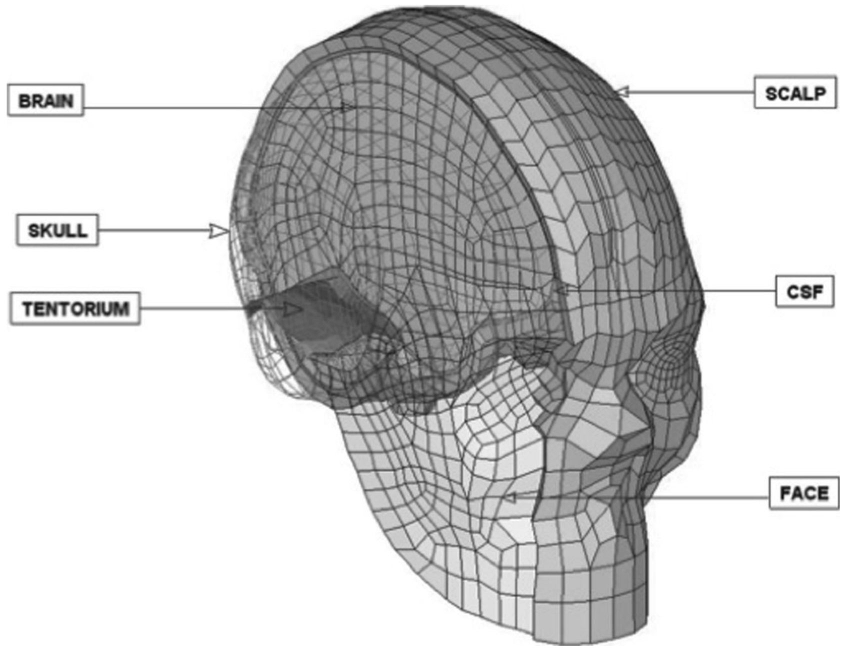


Fig. 10 Strasbourg University Finite Element Head Model (SUFEHM) [18]

SUFEHM methods in terms of $(F_{head})_{max}$ for a XM1006 impact is verified. Secondly, the three methods are compared for a representative selection of non-lethal projectiles available on the market.

XM1006 Projectile Results

Figure 12 shows the XM1006 impact results regarding the levels. Two numerical impact configurations are considered for the SUFEHM calculations: temporal (lateral) and frontal. Corridors are defined based on the dispersion of the $(F_{head})_{max}$ on the BLSH system using a specific statistic method with a coverage interval of 95% [9]. For the temporal impacts, there is a good agreement between the three methods. The values obtained for the frontal impacts are generally lower than those obtained for the lateral impacts calculated with SUFEHM. These results confirm that the FW method and the BLSH system predict the good $(F_{head})_{max}$ for temporal impacts that represent the worst-case for the blunt impacts. It should be pointed out that the BLSH system predicts the same values of $(F_{head})_{max}$ for the four locations [9]. The SUFEHM and BLSH system are able to predict the same $(F_{head})_{max}$ than those obtained from PMHS and animal tests. The two tools can then be considered for the assessment of non-lethal projectile head impacts using $(F_{head})_{max}$ as criterion. The BLSH system and SUFEHM have been independently developed for other applications than non-lethal impacts. Therefore, the result of the present study broadens the application field of the two tools.

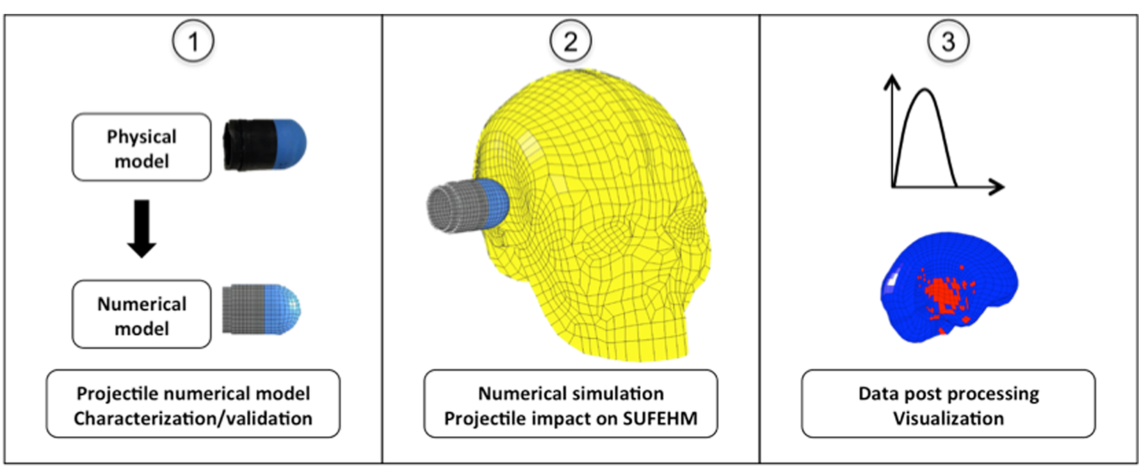


Fig. 11 Numerical approach for non-lethal projectile head impacts on SUFEHM

Application of the three Methods for Different Projectiles

Two different tools independently developed are able to predict the same levels of $(F_{head})_{max}$ for XM1006 impacts as PMHS and animal tests. This result is very precious for the development of assessment approaches for the non-lethal head impacts. However, it is primordial to verify the hypothesis (see Section 3.1) of the FW method for different projectiles for lateral (temporal) impacts regarding the $(F_{head})_{max}$ levels. A selection of three projectiles is proposed for this study: two 40-mm deformable projectile-SIR-X from Brügger & Thomet (32 g) and 40 mm from Nobel Sport (41.9 g) and FN303 from FN herstal which is a breakable 17.3-mm projectile with a mass of 8.2 g and a muzzle velocity of 90 m/s. It is composed of a plastic hollow structure filled with bismuth powder and glycol. The three projectiles are shown in Fig. 13. These projectiles are supposed to represent the most common ones available in the market: 40 mm deformable nose projectiles and breakable projectiles. Corridors are defined based on the dispersion of the experimental RW results regarding F_{max} [9].

Figure 14 shows the comparison between the three methods regarding the prediction of the $(F_{head})_{max}$ levels for SIR-X, Nobel Sport and FN303 projectiles. The agreement level between the three method is projectile-dependant. There is consistency between the three methods only for XM1006, which is the benchmark projectile of the FW method and SIR-X projectile. For the rest of the projectiles, the FW method underestimates the $(F_{head})_{max}$ values. The question is: why are the results consistent for SIR-X and not for the other projectiles?

The response is not in projectile calibre and structure as the 40 mm are typically composed of a sponge nose and a rigid body. In fact, for the Nobel Sport Spartan LE40, the comparison shows that there is no consistency at all between the results. One should note that the Spartan LE40 makes use of a unique inhomogeneous rubber structure. The mass of SIR-X is 32 g what is closer to the XM1006 one (27 g) than the LE40 one (42 g). The foam structures used for both SIR-X and XM1006 are also almost comparable. Therefore, one hypothesis is that the FW method is verified for the projectiles that have characteristics close to XM1006 in term of mass and structure. These findings are consolidated for another 40 mm deformable nose projectile with a mass of 27 g [9].

There is a good agreement for the three projectiles for the BLSH system and the SUFEHM impacts. These last two tools seem to represent relevant methods for the assessment of head impacts of different non-lethal projectiles.

The BLSH system has probably advantages for an operational use. Indeed, the advantage of an experimental tool is that it can be directly used when the physical projectile is available. It is not the case for a numerical tool where the numerical model of the projectile should be developed, which can be time-consuming and difficult. However, with SUFEHM, it is possible to calculate several parameters for different impact configurations where the BLSH system enables the measurement of only the force. Moreover, SUFEHM can be used for various design variations during the very first phases of a project. This tool seems thus more indicated for the research and development purposes.

Correlations between the Maximum Force and Other Criteria

In this study, $(F_{head})_{max}$ is considered as a criterion. However, other criteria have been developed for the head blunt impacts. SUFEHM is used for the comparison between the $(F_{head})_{max}$ and other possible criteria: ICP_{max}, skull strain energy (criterion used with SUFEHM) [18, 19], and HIC (Head Injury Criterion), which is based on the head linear acceleration [22]. The different results are shown in Fig. 15.

The comparison between $(F_{head})_{max}$ and ICP_{max} shows a good agreement. The relation between the two parameters is practically linear. These results confirm that the two parameters are well correlated using numerical simulation [7, 8]. ICP_{max} can be considered as a criterion for the non-lethal head impact assessment. The same findings are achieved for the skull strain energy that is used for the fracture prediction on

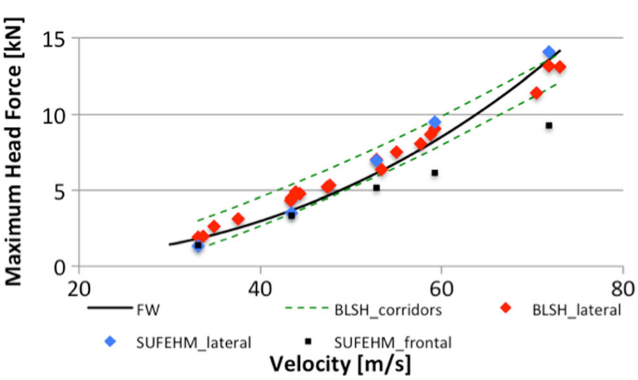


Fig. 12 Comparison between XM1006 FW, BLSH and SUFEHM maximum head force results

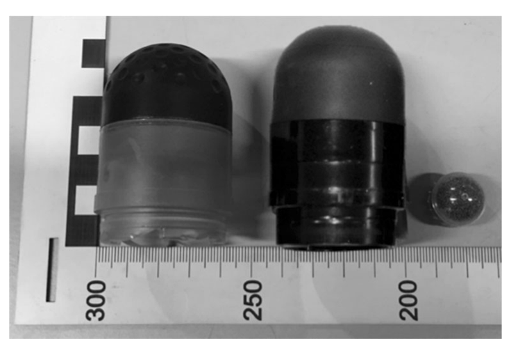


Fig. 13 From left to right: SIR-X, Nobel Sport and FN303 projectiles

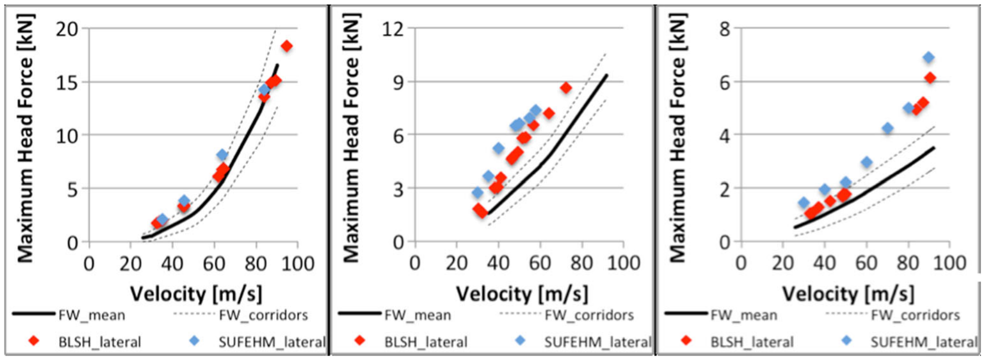


Fig. 14 Comparison between the FW method, BLSH and SUFEHM maximum head forces for different projectiles, from left to right: SIR-X, Nobel Sport and FN303

SUFEHM even if the threshold values for the fracture are not exactly the same. In fact, the FW method proposes the value of 7.5 kN, when the value corresponding to 50% injury risk of fracture using SUFEHM is 4 kN (corresponding to a value of skull strain energy of 865 mJ [17, 18]). More investigation should be performed to take into account the comparative probabilistic aspects of the SUFEHM and the FW thresholds. However, the predicted values of the HIC are very low compared to those proposed in the literature review for severe injuries (800) [23]. It seems that the HIC criterion cannot be used for the non-lethal head impact assessment with the present thresholds.

Conclusions

The present article proposes different methodologies in order to assess the non-lethal projectile head impacts regarding the injury risk prediction. Firstly, the necessity of this work is highlighted using reported cases from the literature. The reported examples show that KENLW are not used without risk especially for the head impacts. The assessment of this kind of impacts is a primordial step before use KENLW in real situations to avoid unintended effects. Therefore, three different methods are proposed in order to carry out this task. The first method, Force Wall, is based on the measurement of the maximum impact force on RW structure. The experimental setup is presented and examples of the force results are proposed. The second method is based on a mechanical surrogate: BLSH. The third one uses a validated finite element model of the head: SUFEHM, in order to perform numerical simulations. Comparisons are achieved between the aforementioned methods.

The results show a good agreement between the three methods for the XM1006 projectile in terms of the prediction of the maximum head force for the lateral (temporal) impacts. These impacts represent the worst-case for the non-lethal head impact in terms of the lesional potential. The results of XM1006 for the different methods are very important for the development of an assessment approach. In fact, two different tools (experimental and numerical), independently developed for other applications than non-lethal impacts, are able to reproduce the same maximum head force than the one obtained from cadaveric or animal tests. It seems that the maximum head force can be then proposed as an injury criterion. The comparison of the results of the other studied projectiles concludes that the application of the FW method is not without restriction. It seems that this method can be applied only for the projectiles whose characteristics are close to XM1006. The results show a good agreement between BLSH and SUFEHM for all studied projectiles. The aforementioned tools can be then proposed as assessment approaches in order to predict the maximum head force. The BLSH system provides operational capabilities being an experimental tool. SUFEHM offers research capabilities being a numerical tool.

Finally, relations between the maximum head force and other criteria are proposed. The results show that the

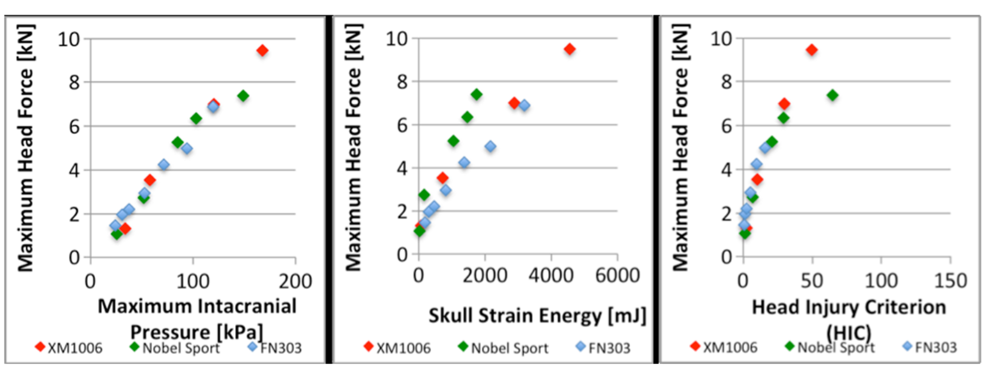


Fig. 15 Relation between maximum head force and other criteria for different projectiles

maximum intracranial pressure and the skull strain energy can be considered for the non-lethal head impact assessment, which is not the case for the Head Injury Criterion. This part of the present study should be more investigated in order to improve the correlations between the different parameters.

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