Injury Risk Assessment of Non-Lethal Projectile Head Impacts

Amar Oukara[1,2,3,*] , Nestor Nsiampa[1,3], Cyril Robbe[1] and Alexandre Papy[1]

[1]*Royal Military Academy–Department of Weapon Systems and Ballistics-30 Avenue de la Renaissance, 1000 Brussels, Belgium*

[2]*Polytechnic Military School, 17 Bordj El-Bahri, Algiers, Algeria*

[3]*University of Liège (ULg)–Aerospace & Mechanical Engineering Department (LTAS) – 1, Chemin des Chevreuils, 4000 Liège, Belgium*

Abstract: Kinetic energy non-lethal projectiles are used to impart sufficient effect onto a person in order to deter uncivil or hazardous behavior with a low probability of permanent injury. 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. Given the high velocities and the low masses involved in such impacts, the assessment approaches proposed in automotive crash tests and sports may not be appropriate. Therefore, there is a need of a specific approach to assess the lethality of these projectiles. In this framework, some recent research data referred in this article as "force wall approach" suggest the use of three lesional thresholds (unconsciousness, meningeal damages and bone damages) that depend on the intracranial pressure. Three corresponding critical impact forces are determined for a reference projectile. Based on the principle that equal rigid wall maximal impact forces will produce equal damage on the head, these limits can be determined for any other projectile. In order to validate the consistence of this innovative method, it is necessary to compare the results with other existing assessment methods. This paper proposes a comparison between the "force wall approach" and two different head models. The first one is a numerical model (Strasbourg University Finite Element Head Model-SUFEHM) from Strasbourg University; the second one is a mechanical surrogate (Ballistics Load Sensing Headform-BLSH) from Biokinetics.

Keywords: Force wall approach, Finite element model, Head impacts, Injury assessment, Kinetic energy non-lethal projectiles, Surrogate.

1. INTRODUCTION

Kinetic energy non-lethal projectiles are used to impart sufficient effect onto a person in order to deter uncivil or hazardous behavior with a low probability of permanent injury. Since their first use, real cases indicate that the injuries inflicted by such projectiles may be irreversible and sometimes lead to death. The nature and severity of injuries resulting from their use depend, among others, on the impacted body part. Due to the phenomenon of ballistic dispersion, more vulnerable parts, like the head, may be unintentionally hit.

While the reported number of non-lethal projectile impacts to the head may be less compared to the other vital body parts, more serious injuries have been attributed to the head impacts [1]. Therefore, there is a necessity to assess the head impacts in order to allow a safer use of non-lethal projectiles. The goal is to define an employment doctrine for the non-lethal weapons in terms of shooting distances by predicting the lesions that can be inflicted by such weapons.

In this field, no standard exists and there is a lack of injury data, particularly on Post Mortem Human Subjects (PMHS). The only real data available in literature on this subject concern the work of Raymond from Wayne state University [2]. However, for ethical, legal, technical and financial considerations, tests on PMHS are difficultly feasible or even forbidden. Another source of information is DGA (Direction Générale de l'Armement, French Ministry of Defence) [3]. The approach developed at DGA (force wall approach) led to the definition of a simple experimental method based on shooting the projectile onto a rigid wall. Then, the force signal during this impact is measured in order to determine the maximum impact force on the head and the injury risk for such impact. So far, no study has been achieved to verify the relevance of the obtained results. This paper proposes a comparison between the results of the force wall approach and those obtained using two different head models.

The first one is a numerical model, the Strasbourg University Finite Element Head Model (SUFEHM) from Strasbourg University. The second model is a mechanical surrogate, the Ballistics Load Sensing Headform (BLSH), from Biokinetics and Associates, Ltd.

*Address correspondence to this author at the Royal Military Academy – Department of Weapons Systems and Ballistics-30 Avenue de la Renaissance, 1000 Brussels, Belgium; Tel: +32 2 742 6339;
Fax: +32 2 742 6320; E-mail: amar_oukara@yahoo.fr

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(Fig. **5**). The BLSH enables a direct measurement of the dynamic loads imparted to the skull due to non-penetrating projectiles impacts. The BLSH is equipped with seven Kistler cells in order to measure the contact force. It allows assessing the temporal (two sides) and frontal impacts. The skull substructure is made of magnesium [2, 8]. A silicon rubber pad is used as a skin surrogate to cover the load cell array. This BLSH was originally developed to evaluate the risk of skull fracture caused by back face deformation of military helmets undergoing bullet impacts (Behind Armour Blunt Trauma). Raymond compared the forces measured on PMHS and those measured with the BLSH and other surrogates and concluded that the BLSH is the most suitable one for evaluating non-lethal projectile head impacts [2].

In the current study the BLSH is used to measure the impact force of the FN303. Two different headforms that correspond to the temporal and frontal impacts, respectively, are used. The experimental setup involved in this test is similar to the setup shown in Fig. (**4**). The rigid wall is replaced by the BLSH.

3. THE NUMERICAL MODEL

3.1. The SUFEHM

The numerical head model used for this study, shown in Fig. (**6**), is the SUFEHM developed by Kang *et al.* and represents a 50 percentile adult human head [9]. The model components are: skull, face, falx, tentorium, Cerebro-Spinal Fluid (CSF), scalp and brain (cerebrum-cerebellum-brainstem). The finite element mesh is continuous. SUFEHM consists of 13208 elements and its total mass is 4.7 kg [10]. The model is to be used with the LS-DYNA software.

Material properties of the CSF, scalp, facial bones, tentorium and falx are all isotropic, homogenous and elastic [10]. The brain is assumed to be viscoelastic [11]. The shear relaxation behaviour is described with equation (4).

$$G(t) = G^{\infty} + (G^{0} - G^{\infty})\, e^{-\beta t} \quad (4)$$

With

G^0 short-time shear modulus.

G^{∞} long-time shear modulus.

β decay constant.

t time variable.

The skull material has three failure criteria expressions for four different types of in-plane damage mechanisms. Each of them predicts failure of one or more plies in a laminate. The longitudinal and transverse compressive and tensile strengths are respectively: 90 MPa for cortical bone and 34.8 MPa for diploe bone, with a shear stress parameter defined at -0.5 [10].

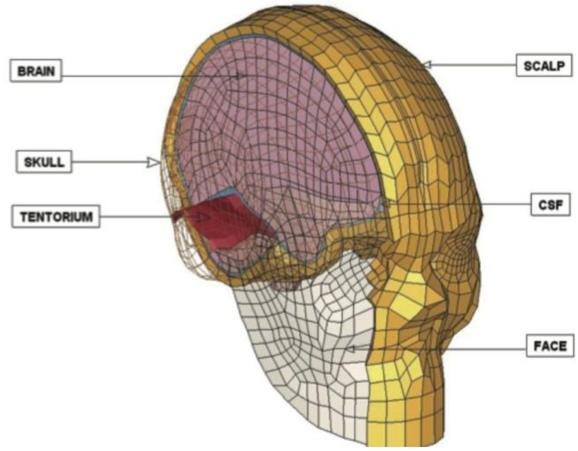

Fig. (6). Strasbourg University Finite Element Head Model (SUFEHM).

The model is validated according to three different experimental tests based on brain and skull biomechanical responses. The force contact validation on frontal bone, the skull acceleration and intracranial pressure on different skull zones are performed according to the study of Nahum *et al.* [4]. The validation of the intra-cerebral acceleration and intracranial pressure is achieved based on the work of Troseille *et al.* [12]. Moreover, the skull fracture has been validated using the Yogonandan test [13]. Tolerance limits were established for this model by reconstructing 68 real world head traumas that occurred in motor sport, motorcyclist, American football and pedestrian accidents [11]. The model allows predicting three lesional effects: Diffuse Axonal Injury (DAI), subdural hematoma and skull fracture using respectively, Von Mises stress of the brain, strain energy of the CSF and strain energy of the skull as criteria. Table **2** gives the different tolerance limits corresponding to a probability of 50% injury risk [11,14].

3.2. Numerical Simulation of FN303 Impacts

The FN303 is a 17.3 mm diameter projectile from FN Herstal (Fig. **7**). It is composed of a plastic hollow structure filled with bismuth powder and glycol. The projectile is designed to break at impact. The projectile mass is 8.5 g, and the average muzzle velocity is 90 ms^{-1} [15]. The finite element model of the FN303 projectile is shown in Fig. (**8**)

Table 2. SUFEHM tolerance limits for 50% risk of injury [11, 14].

Injury	Criteria	Tolerance limit
Severe DAI	Brain Von Mises stress [kPa]	53
Mild DAI	Brain Von Mises stress [kPa]	28
Subdural hematoma	CSF strain energy [mJ]	4950
Skull fracture	Skull strain energy [mJ]	865

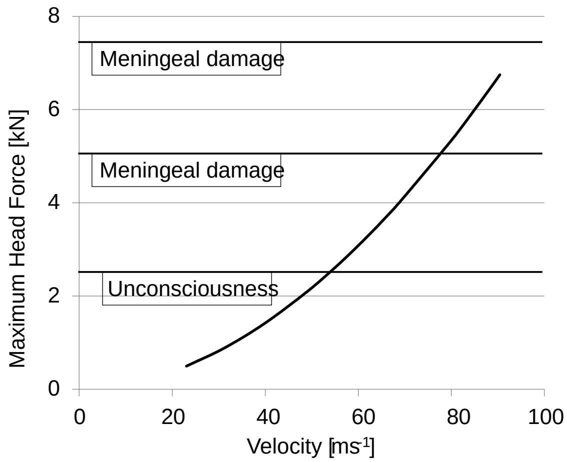

Fig. (12). FN303 maximum head force curve.

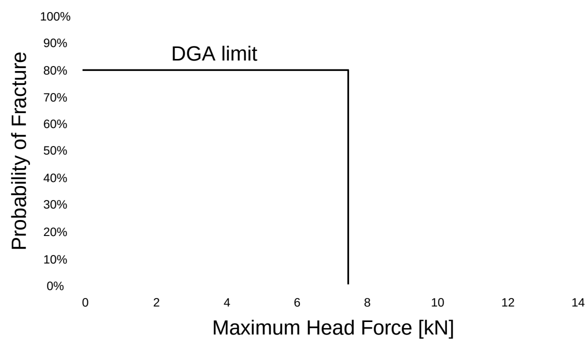

Fig. (13). Injury risk function for the prediction of skull fracture based on the maximum force [2].

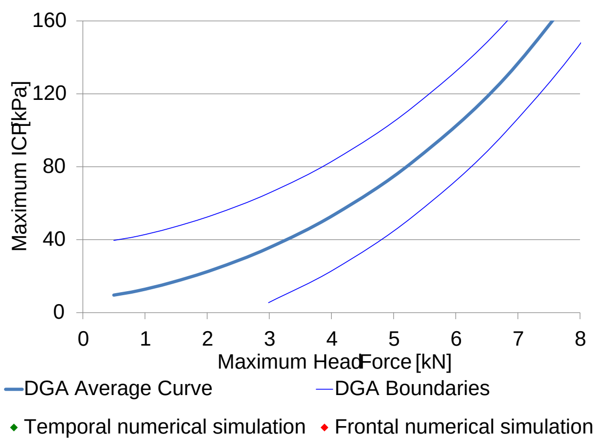

Fig. (14). Comparison between the SUFEHM and the DGA ICP curve.

within the boundaries and the general trend is good. These results confirm that the ICP curve from the DGA refers to the temporal impacts, especially for the high velocities. The choice of the maximum pressure calculated in the CSF is also coherent with the DGA results. The same findings were observed for another projectile in a previous study [17]. This first observation confirms that the relation used by the DGA to link the ICP for the head force is reliable.

Fig. (**15**) summarizes the different results obtained for the head force. In general, the trend is the same for all methods. There is a good agreement between the results of the SUFEHM and the force wall approach for the temporal impact. The computed average error is 6.98 % for the temporal impacts and 12.47 % for the frontal impacts. A good agreement of the results is also noted for the BLSH tests with average errors corresponding to the temporal and frontal impacts are 10.62 % and 8.35 %, respectively.

The last issue of the comparison concerns the injury prediction. The SUFEHM is used to predict the injury that can be caused by the FN303 impact. The threshold values presented in Table **2** are used. For our application, the SUFEHM does not predict a SDH or a DAI. The force wall approach indicates that there is a meningeal damage. The force wall injury descriptions are nevertheless not precise enough to be directly compared to SUFEHM. The fracture prediction will however constitute an interesting comparison point between the two methods.

Fig. (**16**) shows the evolution of the strain energy with the impact velocity. The threshold value for a skull fracture is 865 mJ. Therefore, there is a 50% of probability of skull fracture for temporal impacts at 60 ms^{-1} and for frontal

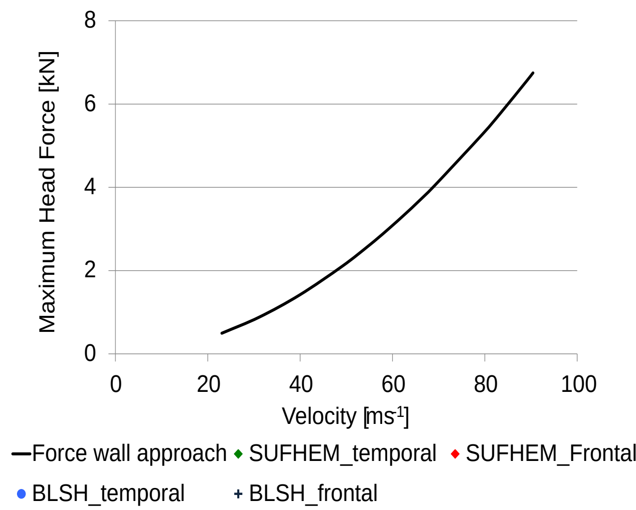

Fig. (15). Comparison of the maximum forces between the SUFEHM, the BLSH and the force wall approach.

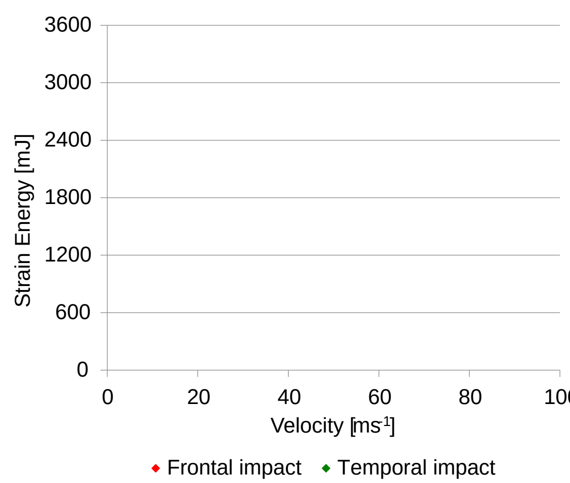

Fig. (16). Evolution of the strain energy in the SUFEHM against the impact velocity.

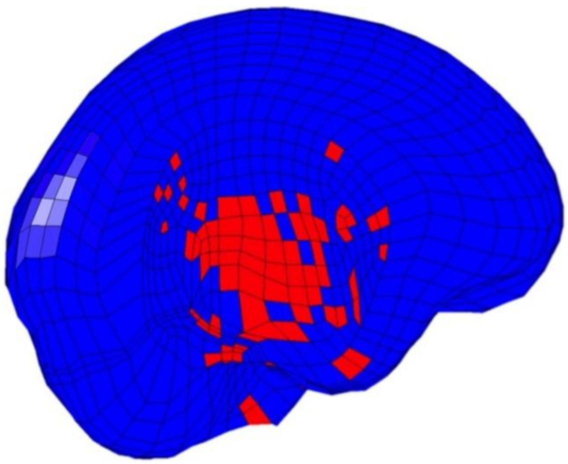

Fig. (17). Example of fracture predicted by the SUFEHM for a temporal impact.

impacts at 70 ms^{-1}. An example of the predicted fracture for temporal impacts is shown in Fig. (**17**). The impact velocity of 60 ms^{-1} for the temporal impact corresponds to an impact force of 2.95 kN. According to the probability curve of Raymond, at this value, the probability of a skull fracture is 5 % (Fig. **13**). The injury predictions of the SUFEHM are not the same compared to the force wall approach or Raymond study predictions. The shape, the caliber and the behavior during the impact of the projectiles used in the Raymond study or in the force wall approach (XM1006) are different from the FN303 projectile. That can explain the differences in the injury prediction. These parameters are essential for the occurrence of injuries and are not taken into account in the force wall approach. This issue should be investigated in order to define critical maximum impact forces according to these parameters. Nevertheless, the contact forces predicted by the SUFEHM are coherent with the forces calculated with the force wall approach or measured with the BLSH.

CONCLUSION

In this paper, a comparison was proposed between an original approach (force wall) to assess non-lethal projectile head impacts, a numerical model (SUFEHM) and a biomechanical surrogate (BLSH) for temporal and frontal impacts. The force wall approach is presented and applied for the FN303 projectile. This approach proposes a simple method to predict the maximum force and the injury that can result from a non-lethal impact on the head, using maximum force measurements on a rigid structure. The FN303 results show that the force wall approach can predict the relation between the maximum force on the head and the impact velocity. The proposed thresholds for the force wall approach are used to define critical velocities that correspond to unconsciousness, meningeal damage and bone damage, respectively.

In order to verify the consistency of the results, a surrogate and a numerical model were used. The SUFEHM predicts on the one hand the same relation between the ICP and the maximum impact force on the head, which is the base of the force wall approach. On the other hand, the maximum impact forces calculated with the SUFEHM are close to those predicted by the force wall approach. The same results are retrieved using the BLSH. Therefore, the results are consistent between these three approaches.

Despite the current limitations to carry out the injury assessment of the non-lethal projectiles head impacts, including accessibility to cadaveric data, the present work is the first study in the literature comparing assessment methods of the injury risk for such impacts. According to the different results, the force wall approach seems to constitute an alternative way to easily predict the maximum impact force that results from a non-lethal projectile impact. The SUFEHM and the BLSH predict equivalent maximum impact forces for non-lethal projectile head impacts. The maximum impact force seems to be a good predictor to assess the injury risk of the non-lethal projectile head impacts. These measurements and acceptable injury risk can then define an employment doctrine for non-lethal weapon users. Nevertheless, further investigations should be carried out in order to refine the critical thresholds of the maximum impact forces, including other parameters: the calibers, the shape and the behavior during the impact of the projectiles.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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None Declared.

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