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Effect of blast loading on the risk of rib fractures: a preliminary 3D numerical investigation.

Lorenzo Taddei¹, Anthony Bracq², Remi Delille², Benjamin Bourel², Christophe Marechal², Franck Lauro², Sebastien Roth¹

¹ Laboratoire Interdisciplinaire Carnot de Bourgogne, site UTBM, UMR CNRS 6303/Univ. Bourgogne Franche-Comte (UBFC), Belfort, France

² Laboratory LAMIH UMR 8201 CNRS, Univ. Polytechnique Hauts-de-France, 59313 Valenciennes, France

Corresponding author:

sebastien.roth@utbm.fr

Abstract

Blast is a complex phenomenon which needs to be understood, especially in a military framework, where this kind of loading can have severe consequences on the human body. Indeed, the literature lists a number of studies which try to investigate the dangerousness of such a phenomenon, both at experimental and numerical level, and the injuries that could occur when the fighters or police officers are stroke by blast wave. When focusing on primary blast effect, this paper analyses the effect of this loading on the occurrence of rib fracture, using previously developed injury risk curves.

Keywords

Blast, 3D Finite Element Analysis, biomechanics, ribs fracture

INTRODUCTION

Computer science allows, nowadays, indeep investigations of several phenomena of the Physics, which are complex to study at experimental level. In the context of impact biomechanics, numerical simulations allow capturing physical parameters, and observing very fast phenomena, which are difficult or impossible to observe using experimental devices. In addition, when the human body is concerned, numerical simulation is an essential step allowing avoiding ethical limitations due to experimental protocols. For these reasons, numerical biomechanics have seen important development these last 30 years, and have seen the use of numerical models, more or less efficient, to investigate the consequences of severe

loadings on the human body. Focusing on the blast framework, the literature list a number of study which try to investigate how such a loading can wound the body: Stuhmiller et al. in 1999 [1] began these investigations with the development of first model, and years after have seen the development of animal or human models [2-26], with an aim of primary blast injury (PBI) analysis. Among these studies, lots of them try to investigate PBI which affects air-containing organs such as the lungs [9], and some injury risk curves have been proposed for this specific organ. However, the question about other potentially injured organs can be raised, and if a blast loading could affect other type of organs such as skeletal and specially ribs, with more or less severe injuries: What are the consequences of a blast on the skeleton? How ribs fractures can occur? Can a numerical metrics be correlated with clinical observations?

This question has been widely studied in recent literature, in the automotive crashworthiness [27, 28] or high velocity impacts framework [29, 30, 31]. The question can still be raised concerning the consequences of a blast loading. Studies of the literature concluded that extremities bones are injured most of the time [32, 33]. Indeed, Ramasamy et al. 2011 [32] explain “Primary orthopaedic blast injury”, which consists in the interaction of blast waves which interacts with the body leading to cellular disruption, soft tissue destruction and also bone micro-factures. The example of a blast wave travelling in the tibia was provided in this study, leading to shear and axial stresses inducing fracture of the bone, as explained by Hull et al. 1995 [34]. Considering the ribs, Christensen et al. in 2013 [35], investigated ribs fractures which could be the consequence of blast trauma, based on existing study [36] concerning skeletal blast trauma on pigs. They concluded that ribs fractures occur more often in lower ribs, with a specific feature called “butterfly fracture pattern”.

Primary Blast injuries focus on injuries caused by the wave. Other injuries that can occur

like impact fragments on the human body or throwings of the body against a structure for example, are classified in other categories (secondary, tertiary or quaternary effects [25]).

Focusing only on primary blast injury, this paper aims to study, at a numerical level, the possible occurrence of ribs fractures, caused by a blast wave interacting with the human body. A previously developed and validated finite element model of the thorax named HUByx is used in a reference blast configuration of the literature. The simulations consist in the interaction of a blast wave travelling from a 2.268 kg of C4 explosive to the human body model which is positioned at 2.3 m from the explosive device. Furthermore, in order to analyse the effect of blast on the positioning of the human body, in relation to the incident blast wave, sensitivity study has been conducted, making the incident angle varying from -90° to 90° . Post-processing of the simulations were conducted, using previously developed methodology dedicated to kinetic energy projectile. Specifically, mechanical parameters in the ribs structures were observed, especially specific energy parameter, which is considered as an interesting injury metric for ribs fracture occurrence [31]. Indeed, considering several candidate for injury criteria, the specific energy parameter was previously pointed out, and highlighted as a performing metrics for ribs fracture occurrence in a context of kinetic energy projectile impacts.

The previously developed methodology on kinetic energy projectile was then extended to various blast configuration, under the assumption of validity for blast loading: results of each configuration are evaluated in relation to the injury risk curve, confirming several statements of the literature on the potential dangerousness of blast loading on rib fracture occurrence.

MATERIAL AND METHOD

Biomechanical model and blast configuration

Modelling of blast loadings involving biomechanical models are complex to conduct, since very few validation data exist in the literature to ensure the reality of such simulations. Thus, a reference experimental study was chosen as a reference, in this study, for validation purpose. The experiment conducted by Merkle et al. [37], was then considered in this study, and which was already taken as reference for previous studies involving the biomechanical model impacted by a blast wave [23, 25, 26].

The biomechanical finite element model named HUByx was used in the study (figure 1). This model was validated against experimental data of the literature and is widely detailed in [23, 25, 26]. Mechanical properties of each components included in the digital model are listed in the following table 1, especially the soft tissue which are modelled by the Mie-Grüneisen EOS with thermodynamical coefficients, as follow:

$$P = C_0 + C_1 * \mu + C_2 * \mu^2 + C_3 * \mu^3 + (C_4 + C_5 * \mu) * E_{v0}$$

where $\mu = 1 - \frac{\rho}{\rho_0}$ and E_{v0} is the internal energy per initial volume unit. Coefficients C_i are defined here after, with typical values extracted from the literature [34]:

$$C_0 = P_0;$$

$$C_1 = k_1 - \frac{\Gamma_0}{2} * P_0 = \rho_0 * C_0^2 - \frac{\Gamma_0}{2} * P_0;$$

$$C_2 = k_2 - \frac{\Gamma_0}{2} k_1 = \rho_0 * C_0^2 * (2s - 1) - \frac{\Gamma_0}{2} \rho_0 C_0^2;$$

$$C_3 = k_3 - \frac{\Gamma_0}{2} k_2 = \rho_0 * C_0^2 * (s - 1)(3s - 1) - \frac{\Gamma_0}{2} \rho_0 C_0^2 (2s - 1);$$

$$C_4 = C_5 = \Gamma_0;$$

| Tissues | Material model | Density (g/mm ³) | Young's Modulus (MPa) | Poisson ratio | Yield stress (MPa) |
|---------|----------------|------------------------------|-----------------------|---------------|--------------------|
| Aorta | Elastic | 0.001 | 25 | 0.3 | |
| Trachea | Elastic | 0.001 | 25 | 0.3 | |

| | | | | | |
|--------------------------|---------------------------------|---------|--------|------|----|
| Diaphragm | Elastic | 0.001 | 3 | 0.3 | |
| Muscles | Elastic | 0.001 | 1 - 10 | 0.3 | |
| Skin | Elastic | 0.001 | 31.5 | 0.45 | |
| Inter-organs space / fat | Elastic | 0.001 | 0.5 | 0.45 | |
| Abdomen/intestine | Elastic | 0.001 | 0.5 | 0.45 | |
| Spongy bone | Elastic | 0.001 | 50 | 0.4 | |
| Cortical bone | Elastic-plastic Johnson-Cook | 0.001 | 14000 | 0.3 | 70 |
| Cartilage | Elastic | 0.001 | 50 | 0.3 | |
| Intervertebral disc | Elastic | 0.00125 | 5 | 0.3 | |

| | | | | | | | |
|--------------|--|----------|-------|--------|--------|------------|-------|
| Soft tissues | Elasto-plastic law with Mie- Grüneisen equation of State | E_{v0} | C_1 | C_2 | C_3 | Γ_0 | P_0 |
| | | 0.5882 | 2449 | 6502.2 | 9251.9 | 0.17 | -0.1 |

Table 1: material properties implemented in HUByx FE model. Parameters of the Soft tissues correspond to the Mie-Grüneisen EOS with thermodynamical coefficients.

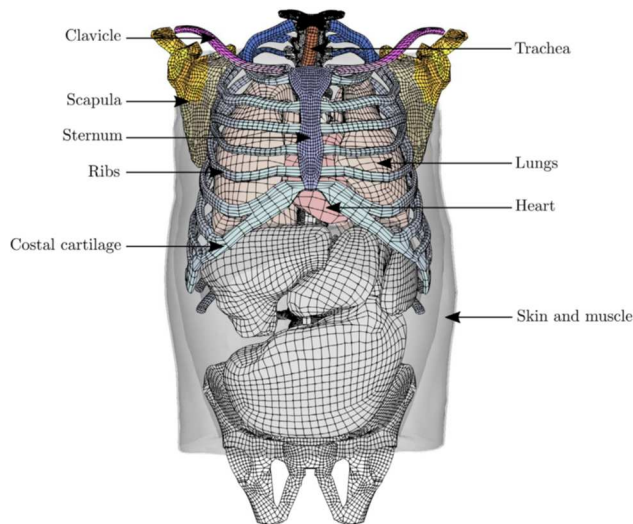


Figure 1: HUByx FE model: thoracic part.

The biomechanical model is included in air field. This air field also include an explosive device, in order to reproduce the reference blast configuration of Merkle et al. [36] consisting of a 2268 g of C4 charge, which generate a blast wave impacting the human body placed at 2,3 m from the explosive device. The work of Merkle et al. provides a detailed configuration of the blast case. Then, in order to use a non-random configuration of blast wave and to match an existing blast configuration of the literature, Merkle's configuration was chosen as a

reference. In extension to the initial blast configuration which involve a 0° incident wave (the blast strikes the face of the thorax), the human body position varied from -90° to 90° , in keeping constant the stand-off distance and the explosive weight. The extension of the initial configuration to various angle allows investigating the influence of the position of the body using a given blast configuration.

As described by Bodo et al. [25], the air field is simulated by an hydrodynamic law with polynomial equation of state, whereas the explosive device is modelled using the Jones-Wilkins-Lee (JWL) equation of state.

Methodology of ribs fracture criteria assessment

The basis of the methodology is the validation of the biomechanical model HUByx against experimental data of Bir et al. 2003 [38]. The following figures 2 to 4 illustrate the numerical response superimposed to the experimental corridors, extracted from [39].

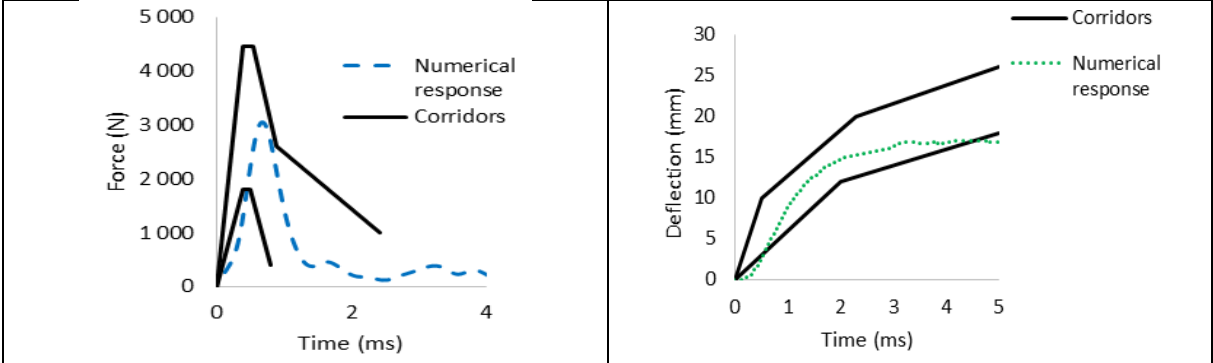


Figure 2 : validation of the numerical model against experimental corridor. case A (140g, 20 m/s)

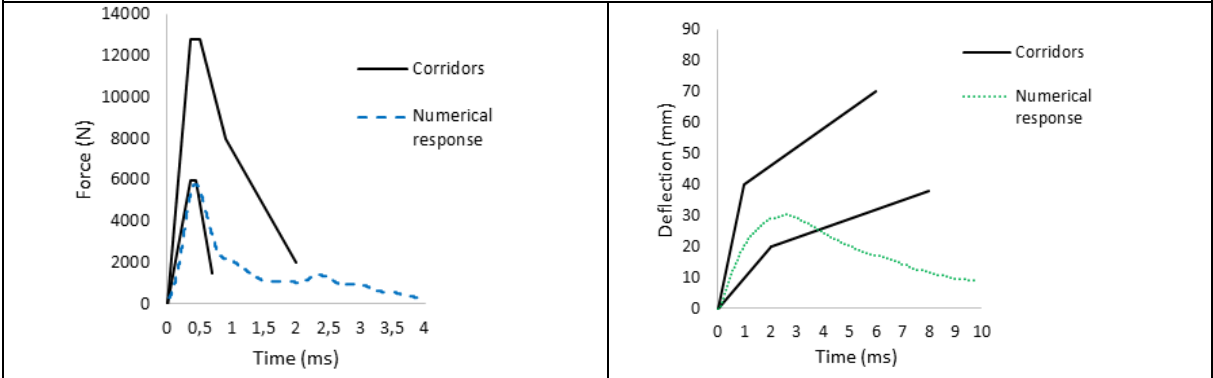
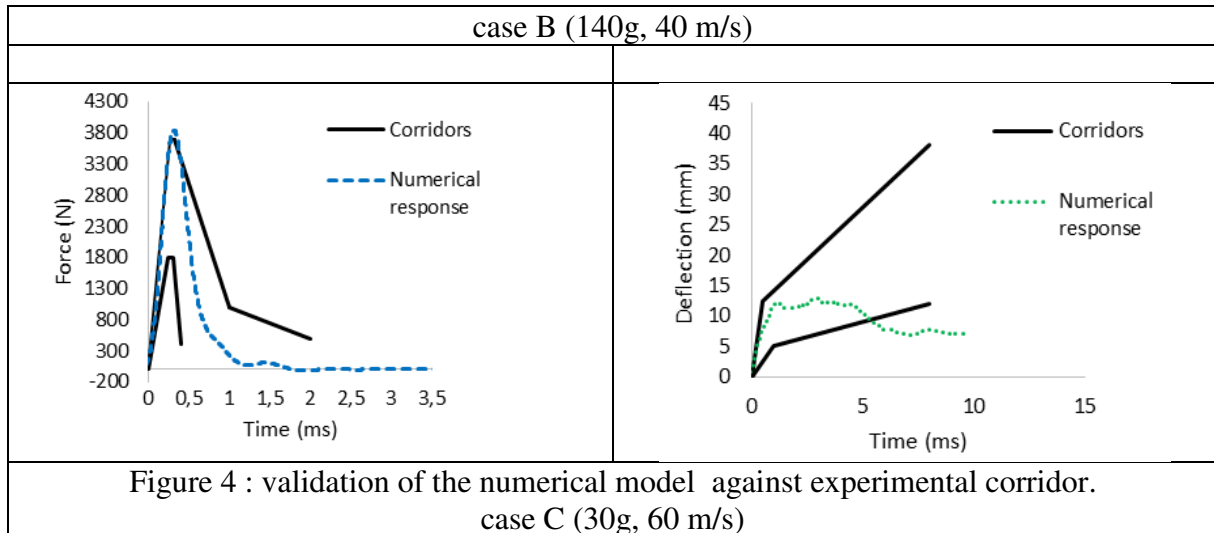


Figure 3 : validation of the numerical model against experimental corridor.



In addition to these curves, the parameter VC_{max} was evaluated on the numerical model and compared to the experimental values, as provided in table 2.

| | VC_{max} | | |
|--------------------|------------------------|------------------------|------------------|
| | Experimental Min value | Experimental Max value | Numerical values |
| Impact condition A | 0.24 | 0.51 | 0.36 |
| Impact condition B | 0.65 | 2.35 | 1.33 |
| Impact condition C | 0.14 | 0.60 | 0.27 |

Table 2: comparison between experimental and numerical VC_{max} parameter

Bir et al. 2004 also provided an injury risk curve from a logistic regression analysis, based on the VC_{max} criteria [40]. Thus, combining injury risk curve, and numerical values obtained with the numerical model, the HUByx model is then able to predict AIS score (AIS 2-3) during an impact using the VC_{max} parameter.

Indeed, the numerical replication of Bir experiments, has shown the ability of the numerical model to provide biofidelic values of the VC_{max} parameter. The following figure 5 adapted from [30, 39] illustrates this ability, case B providing ribs fracture.

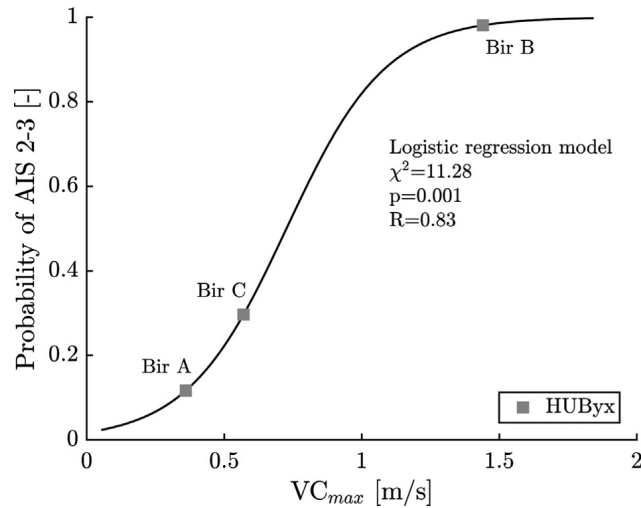


Figure 5: Injury risk curve for AIS = 2–3 as a function of the viscous criteria: regression curves from [33], and numerical results with the biomechanical model.

However, this injury risk curve can only be used for impacts in the middle of the sternum, since the curve has been developed from frontal impacts. In addition, the calculation of VC_{max} value is based on the deflexion of the thorax in the antero-posterior (longitudinal) plan. For that reason, and in order to have a tool able to predict the ribs fracture occurrence whatever is the impact location on the ribcage, it is necessary to correlate VC_{max} value with another mechanical parameter extracted from the numerical simulation. To do so, Bracq et al. conducted some statistical analysis, based on 18 impact cases involving non-lethal projectiles impacting the sternum [29,30], including 12 rigid projectiles, 3 deformable projectiles, and 3 bullet projectiles impacting body armours. A statistical analysis and an intraclass correlation was then conducted, and 4 mechanical parameters were calculated: the VC_{max} value, the Von Mises Stress of the cortical bone, the plastic deformation of the cortical bone, and the specific energy of the cortical bone of the ribs for each impacts. These parameters were chosen considering their importance on the behaviour of the rib structure. The details of the different impact conditions and modelling are explained in Bracq et al. studies [29, 30]. For each impact configurations, all these obtained values were used to build a Pearson correlation matrix, as illustrated in table 3.

| Variables | VC_{max} | σ_{VM} | ϵ_{pl} |
|-----------------|------------|---------------|-----------------|
| VC_{max} | | | |
| σ_{VM} | 0.839 | | |
| ϵ_{pl} | 0.756 | 0.603 | |
| E_{spec} | 0.950 | 0.820 | 0.874 |

Table 3: Pearson correlation matrix obtained from statistical analysis.

The analysis of the correlation matrix highlights the high correlation between the VC_{max} value and the E_{spec} value with a high correlation coefficient of 0.950. A polynomial correlation between these two parameters is illustrated in figure 6 with a very good correlation parameter. In addition, the 95% confidence interval is also provided, pointing out the significant correlation between the VC_{max} value and E_{spec} .

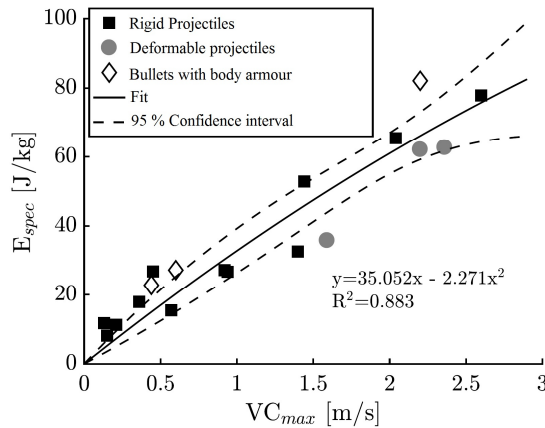


Figure 6: Correlation between the V_{cmax} value and the E_{spec} parameters [30, 31]. Extracted from [31]

Finally, this link between VC_{max} value and the E_{spec} value, provides the possibility to correlate the AIS score with the E_{spec} value, and then the E_{spec} value with the ribs fracture occurrence whatever is the impact location on the ribcage (figure 6).

Based on this correlation, injury risk curve has been developed, providing the probability of skeletal injury as a function of the specific energy, as illustrated in the following figure 7.

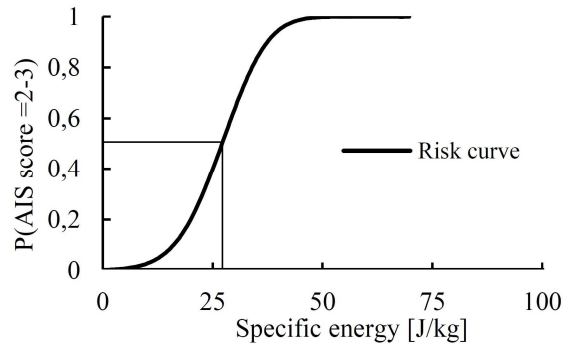


Figure 7: probability of skeletal injury as function of the specific energy

Thus, this curve provides a value of 25.84 J. Kg^{-1} for a 50% risk of AIS =(2-3) occurrence, with a 95% confidence interval ranging from 19.96 J. Kg^{-1} to 31.73 J. Kg^{-1} .

As well as the study of Roth et al. [26], who investigated the effect of the position of the thorax submitted to a blast wave and its consequence on lung injuries, several simulations were conducted in this study, changing the incident angle from -90° to $+90^\circ$, for an aim of investigation of blast consequences on rib fractures (figure 8).

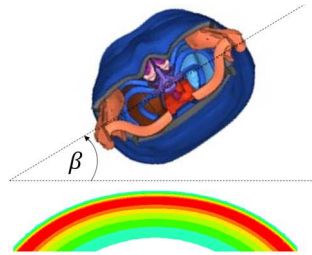


Figure 8: various orientations of the human body interacting with the blast wave, β varying from -90° to 90° (extracted from [26])

Distribution of mechanical parameters was analysed in the rib structure. In addition, a specific feature concerning the rib fracture pattern was observed in the simulation and described in the literature as “butterfly pattern”.

This correlation initially developed for impacts of a projectile on the ribcage has been extended for the study of the risk of rib fracture, when a blast wave strikes the thorax. The equivalence between projectiles impacts and blast impact is assumed and discussed in the following section.

Computations have been performed on the supercomputer facilities of the “Mésocentre de calcul de Franche Comté.” All the computations were performed with the non-linear FE code Radioss © (Altair Engineering).

RESULTS

Several blast configurations were simulated with the variation of the position of the thorax facing the blast wave. Specific energy were observed in the ribs components of the biomechanical model (figure 9). This choice was made based on previous studies on the assessment of rib fractures. This metric was observed for 13 configurations. The initial configuration was with a $\beta = 0^\circ$ incident angle, until -90° and 90° with a step angle of 15° .

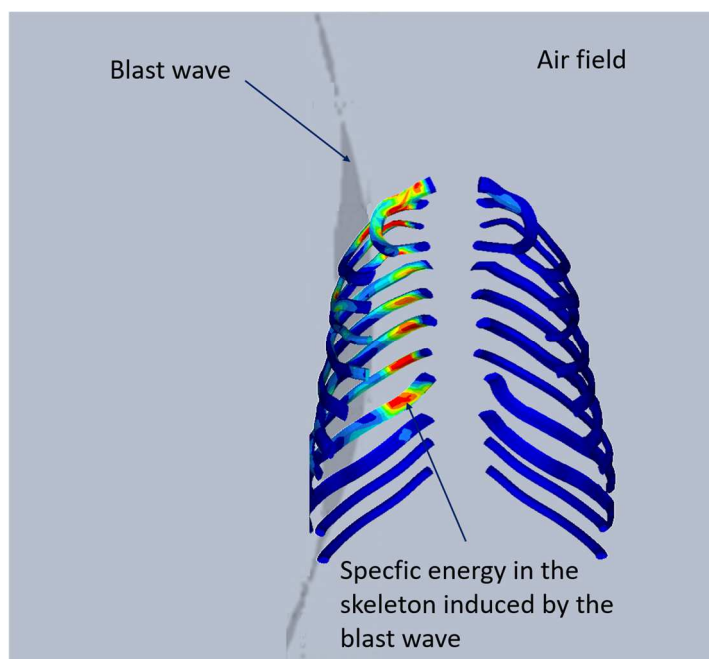


Figure 9 : Interaction between blast wave and ribs structure in the biomechanical model. Specific Energy distribution in the ribs The wave strike the body with a 90° incident angle.

The following table 4 list the results of the 13 simulations based on the test of Merkle, with blast wave impacting the thorax at different incident angle. In addition, the values were placed on the rib fracture injury risk curve, as illustrated in figure 10.

| | Specific energy in cortical bone ($J.Kg^{-1}$) |
|-------------------------------------|--|
| Merkle 0° (reference configuration) | 57 |
| Merkle -15° | 50 |
| Merkle 15° | 50 |
| Merkle -30° | 38 |
| Merkle 30° | 40 |
| Merkle -45° | 55 |
| Merkle 45° | 56 |
| Merkle -60° | 66 |
| Merkle 60° | 68 |
| Merkle -75° | 78 |
| Merkle 75° | 80 |
| Merkle -90° | 68 |
| Merkle 90° | 70 |

Table 4 : Specific energy metric of the simulations based on Merkle's test's configuration, and for several angles

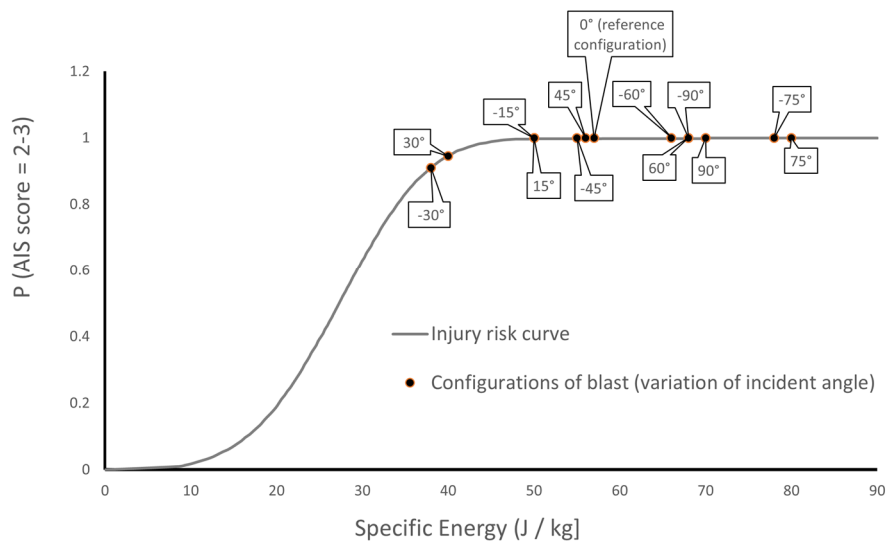


Figure 10: Risk of rib fracture for each configurations of blast loading

DISCUSSION

Blast is a complex loading, combining several physical phenomena. The interaction between a blast wave and the human body for investigation of injury occurrence, is also complex, since

experimental studies can be restricted by ethical issues. One way of analysis is the numerical simulation. Combining biomechanical models, and also numerical modelling of the blast, the concept of “numerical twin” can be a very promising way to understand how the human body reacts when submitted to a blast wave, and to attempt to predict soft tissues or skeletal trauma. Blast trauma can be classified into four categories [25]. The present study focus on PBI and do not take the secondary blast phenomena into account. This last phenomena results from disintegrated penetrating fragments into the human body, and is generally with the tertiary injury, the main cause of rib fractures [41, 42]. That point lead to a difficulty to understand what is the real cause of a blast loading on the skeletal: the only blast wave (primary blast injury), the impact of fragments on the human body (secondary blast injury), the throwing of the human body on a structure or a combination of these three factors. When a violent blast impacts the human body, it is of interest to analyse the presence of fractures, and if they have been caused by the wave itself or by fragments. This distinction should be understood to assist forensic experts in the interpretation of clinical observations and to then distinguish primary and secondary blast injuries. At a numerical level, the methodology used to develop injury criteria and tolerance limit using HUByx numerical model, is based on blunt impact of projectile on the thorax, with a specific energy in ribs of 25.84 J. Kg^{-1} for a 50% risk of AIS = (2-3). All the simulations provided higher values of specific energy, compared to the limit of 25.84 J. Kg^{-1} , even considering the 95% confidence interval which ranges from 19.96 J. Kg^{-1} to 31.73 J. Kg^{-1} . For all configurations, the risk of rib injury ranges from 90 % to 100 %, as illustrated in figure 10. What can be observed is that the obtained values are significantly higher than the tolerance limit (50% risk), and that the present configuration of blast may lead to ribs fractures. In the same way than previous study, based on the same blast configuration and for soft tissue observations [26] “for this specific explosive weight (2.268 kg of C4), with a specific observation point positioned at 2.3 m from the explosive”, all the values were quite

higher than the damage threshold. This blast configuration allowing a validation of the numerical results in terms of pressure wave and pressure in the soft tissues, it was also chosen as a reference for skeletal fracture investigation. The same kind of study should be conducted at a lower distance with lower explosive weight, in order to have smaller blast wave, to get closer to ribs fracture threshold. More generally, other blast configurations are planned to assess the risk of ribs fractures for more or less severe blast configurations.

The methodology used in the present paper was initially designed for blunt impact configuration. The present study uses scrupulously this methodology without questioning the way it has been designed and already published. Using the initial methodology allow assessing the severity of a blast wave on the body, based on blunt impact statistical analysis, even if questions can be raised about the correlation between blast and blunt impact, or about the fitting analysis in the method. The method is used under assumption that it may also be valid for blast loading. In that context, the use of a numerical model for various impact configurations is of interest: from crashworthiness to ballistic impact, free falls or blast impact, the validity of such numerical tools have to be check for all these different impact frameworks. Studies of the literature have already investigated this point, exploring civil or military loadings and their related injury metrics for lung injuries [43]. Interesting correlation was found, and for different kind of configurations: results of the numerical reconstructions of free falls and ballistic impacts with a biomechanical model enabled to evaluate the injury risk for each real world accident in relation to existing blast injury risk curve, providing coherent estimation of lethality and lung damage for each scenario. The equivalence of the results for civil and military impacts were then evaluated, providing interesting openings for the validity of such a method. The extension of the method from blunt impact to blast loading in this paper, has to be investigated more deeper and has to be confirmed with more simulations, but

may bring first and interesting steps in the understanding of blast effect on skeletal, as it was the case in previous studies, in terms of injury mechanisms and tolerance limit.

Christensen et al (2012) [36], investigated primary and secondary skeletal blast trauma at an experimental level, submitting pigs specimen, to various blast configuration, with different stand-off distances, different explosive charges, and different explosive types, until 4kg of C4 with a 0 stand-off distance. He also analysed ribs fractures resulting from these experiments [35]. The study noticed specific fracture patterns on ribs, named “butterfly fractures”, whose characteristics are illustrated in the following figure 11.

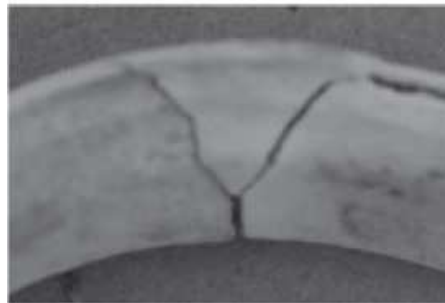


Figure 11 : Characteristic butterfly fracture pattern on ribs (extracted from [30])

Although the numerical modelling does not provide the pattern of this specific fracture, it can be noticed on the numerical model, illustrated in figure 12, that a high level of stress is located near the most angular portion of the ribs, where butterfly fracture tend to occur, as explained by Christensen et al (2013) [35].

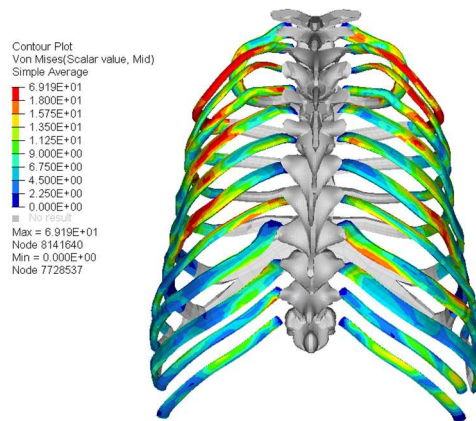


Figure 12 : stress level near the most angular portion of the ribs. Back view of the skeleton

It is also of interest to keep in mind that these results depend on the modelling of ribs structure. Indeed, a more biofidelic constitutive law for bone, may enhance the results and particularly, the butterfly patterns, in order to simulate more closely the effect of the blast on ribs. Recent studies on the dynamic behaviour of skeletal under dynamic loading can help to improve the results of the simulations [44]. In that context, it may be possible to distinguish clearly the values of the numerical injury metric on each rib, showing which rib is the most exposed to the loading and then providing the injury risk for each rib. Butterfly fractures generally occur in lower ribs, due to the higher resistance of upper ribs, as suggested by Christensen et al (2012) [30], and distinguishing clearly the values of the numerical injury predictors on each ribs may allow improving the location and the accuracy of rib fracture. Finally, this study attempts to analyse effect of a blast loading on skeletal trauma, based on numerical process, and using a human thorax model. Interesting results have been found, and are preliminary results for deeper investigations on ribs fractures under blast.

CONCLUSION

The present study investigates blast wave impacting the thorax and specifically the ribs, at various orientations. The objective is to observe the effect of this phenomena on skeletal

structures and to compare mechanical parameters to existing injury criteria derived from blunt impacts. Specific energy, an interesting candidate for rib fracture injury predictor, is then compared to the existing limit of 25.84 J.Kg^{-1} for a 50% risk of AIS = (2-3), which were found to correlate well with ribs fractures observations in previous study using the biomechanical model. The numerical simulations conducted to higher values of specific energy, allowing concluding to ribs fractures for every simulated blast configurations. Finally, this is a first investigation of blast impact on the thorax and its consequences on skeletal trauma; numerical simulations of primary blast providing sufficient energy to induce ribs fractures.

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