Development of a thorax finite element model for thoracic injury assessment

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Abstract

Kinetic energy non-lethal weapons (KE-NLW) are now widely used by law enforcement, by military forces, by the police in situations where the use of lethal arms is not required or suitable. Unfortunately, their effects are still not well known. Therefore, there is a need to better understand the injury mechanism induced by such projectiles for a better prediction of the risk of injury. This may be beneficial for the manufacturer, the deciders or the end-users. Numerical simulations are being increasingly used for that purpose. This paper describes first steps in the development of finite element model for thoracic impacts. All the simulations were performed with Ls-Dyna code. For validation purpose, the results were compared to the results of tests made on Post-Mortem Human Subjects (PMHS) published in literature. The sensitivity of contact option and the use of two sets of parameters for the lung material model were examined.

Keywords: non-lethal weapons, risk of injury, CT-scan, PMHS

Introduction

These last decades have seen the development of a new type of weapons, the nonlethal weapons. 'Non-lethal weapons are weapons which are explicitly designed and developed to incapacitate or repel personnel, with a low probability of fatality or permanent injury, or to disable equipment, with minimal undesired damage or impact on the environment' [1,2]. They are now widely used by law enforcement or by the military forces in situations where the use of conventional weapons is not required or suitable for example in peace-keeping missions or for crowd control. Unlike conventional weapons that may result in severe or fatal injuries, non-lethal weapons are designed for temporary incapacitation with reversible consequences or minor damage. There are generally short range weapons and are generally used to gain compliance of a human subject or a group of people. Dependant of the level of threats, the spectrum range of non-lethal weapons covers from verbalization techniques to the use of a 'reasonable force', force which is necessary to achieve a legal goal. To the 'reasonable force' is opposed the 'excessive force' which is a force disproportionate to what is necessary to achieve a legal goal [3].
Although there is a variety of technologies (electric, chemical, acoustic, … [4]) used for the development of non-lethal weapons, this study is limited to kinetic energy non-lethal weapons (KENLW). Such weapons use the kinetic energy of a projectile to inflict physical injury, a result of the interaction of the projectile and the human body. The resulted injury is dependent of the nature of the projectile, the location and nature of the impacted zone and the impact conditions. The projectiles may be rigid, deformable or can break at the impact. The most known KENLW projectiles are: baton rounds, beanbags, fin-stabilised rubber projectiles, multi-ball rounds, rubber ball rounds, and sponge grenades. In Figure 1, different types of most known KENLW weapons and KENLW projectiles are presented. For example, the Flash

ball launcher and the COUGAR launcher use a pyrotechnic system to impart energy to the projectile. The flash ball projectile similar to the squash ball is a deformable projectile as well as the bliniz projectile (COUGAR). The FN 303 weapon uses a compressed air system and a thin stabilized projectile which breaks generally at impact.
KENLW projectiles are low-mass (8g - 140 g) and the high-velocity (15 m/s – 250 m/s) projectiles as opposed to the automotive crash tests field where mass are higher and velocities lower (Fig. 2).

Figure 1: Example of KENLW weapons and different projectile types

To avoid the risk of penetration wounding at impact, KENLW projectiles are designed in such a way that the primary and desired effect is blunt trauma.

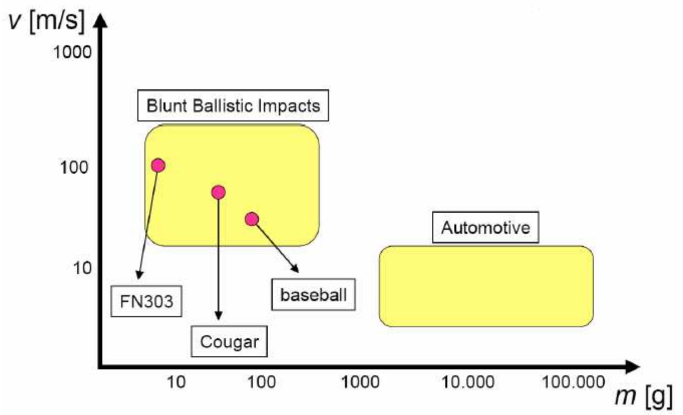

Figure 2: Differences in mass and velocity for automotive collisions and 'non-lethal' ballistic impacts on a logarithmic scale [2]

These differences between the KENLW ballistic impacts and the crash tests impacts are reflected in the biomechanical responses of the human body [5] although some injury mechanisms are similar. In this paper thoracic impacts will be considered. The reasons are threefold:

Besides the human head which is not considered as a target in KENLW field because of the low tolerance level of the eyes, the thorax encompasses vital organs of the body and represents a wide surface of the body where the hit probability is great;

It has been reported [5] that thoracic injuries represented 50% of casualties among the fatal casualties related to some type of chest trauma;

There are experimental data on Post Mortem Human Subjects (PMHS) available in the open literature for thoracic impacts [5]. Those data were used for validation purpose of the thorax finite element model (FEM) that has been developed. Force-time and deflection-time histories were compared to the experimental data. We will emphasize on problems encountered with the lung material model and the contact definition.

Thorax FEM Model

Thorax geometric model

There is an increasing interest in using numerical simulations as an important tool for the assessment and a better understanding of impact events. But reliable simulations depend on the accurate description of the geometry of the problem and on the use of appropriate material models. The description of human thorax geometry can be found in most of books related to human anatomy. The human thorax is a complex structure because of the highly non-linear material properties and the shapes of different thorax organs (Fig. 3). It consists mainly of an external protective structure and an internal structure. The external protective structure consists of bony sub-structure (sternum, vertebral column, 12 pairs of ribs) and soft-tissue sub-structure (intercostals muscles and flesh, skin). The internal structure consists of soft tissues organs (heart, lungs, the trachea …). The combination or the interaction of soft tissues and bones in the structure of the body as well as the various geometries of the thorax organs shows the difficulty in modeling the biomechanical response of the thorax to impact events. Therefore some assumptions about the geometry and the material models are made for the development of the model (Fig. 4).

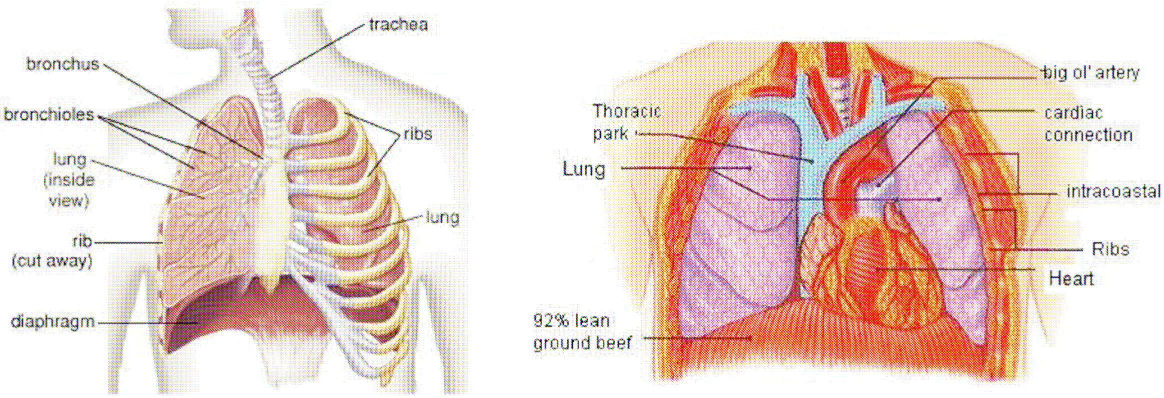

Figure 3. The cross-section of the thorax [6,7]

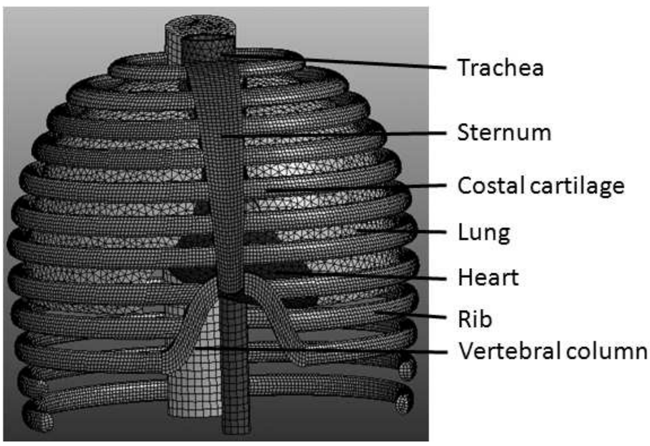

Figure 4. The human thorax model

Thorax material model

The thorax main organs are modeled. All organs materials are considered as homogenous which there are not in reality. Material model parameters are given in Table 1-2.

Material	LS-DYNA cards (Units = m, kg, s)			
	* MAT_ELASTIC			
COSTAL CARTILAGE	RO	E	PR	
	1281	4.9E+6	0.400	
RIBS	RO	E	PR	
	1561	7.9E+9	0.379	
STERNUM	RO	E	PR	
	1354	3.5E+9	0.387	
HEART	*MAT_SIMPLIFIED_RUBBER/FOAM			
INTERCOSTALS	RO	K	C	LC/TBID
FLESH/MUSCLE	1050	2.2 E+9	0.5035	1

Table 1 –Material parameters [8,9]

Two sets lung material parameters found in literature were used (Table 2).

Material	LS-DYNA cards (Units = m, kg, s)					
LUNG_01	* MAT_LUNG_TISSUE					
	RO	K	C	DELTA	ALPHA	BETA
	200	1E+5	0.5035	2.5 E-4	0.183	-0.291
	C1	C2	NT			
	0.004825	2.71	6			
LUNG_02	* MAT_LUNG_TISSUE					
	RO	K	C	DELTA	ALPHA	BETA
	118	1.18E+5	0.5035	7.02E-5	0.08227	-2.46
	C1	C2	NT			
	0.006535	2.876	6			

Table 2 – Lung material parameters [10,11]

All the organs are modeled with solid hexa-elements except for the heart, the lungs and the trachea.

Projectile FEM Model

PMHS experiments [5,6] were performed with a PVC projectile corresponding to a plastic baton round used in real crowd control situations. Its characteristics are given in Fig. 5 and Table 3. Two velocities were used: 20 m/s and 40 m/s.

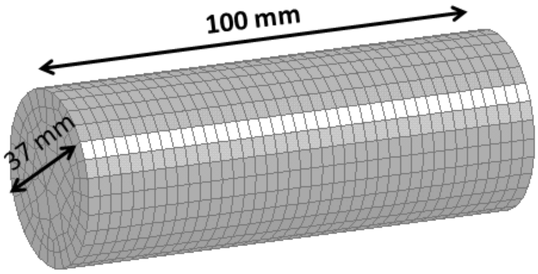

Figure 5. Projectile geometry

PVC	* MAT_ELASTIC		
	RO	E	PR
	1380	2.3E+6	0.33

Table 3 – Projectile material parameters [5,8]

Interface conditions

Because of the number of thorax organs interacting together during the impact, contact definitions between organs are pertinent for the simulations. Interface contacts have been defined between different organs. TIED_NODES_TO_SURFACE or TIED_SURFACE_TO_SURFACE were defined between the different organs of the same structure (external or internal). AUTOMATIC_SURFACE_TO_SURFACE was defined between the internal and the external structures. All the vertebral column nodes were constrained.

AUTOMATIC_SURFACE_TO_SURFACE contact was defined between the projectile and the external structure. Two cases were studied when we vary the contact parameter SOFT.

The full model contains 350408 solid elements and 165667 nodes. Most of elements are hexa-elements.

Results et Discussion

Validation of the thorax FEM model has been made against PMHS data for thoracic impacts [5]. Typical physical characteristics which are measured during impact testings for injury assessment are force-time histories and displacement (deflection)-time histories from which other characteristics or parameters are derived. Numerical results are then compared to experimental results for validation purpose. In our case, numerical results have to be within the biomechanical corridors which correspond to the upper and lower limits of the biomechanical responses [5]. Details of validation process can be found in [9,13].

Lungs are one of the vital organs of the human body, therefore there is a necessity to predict lung injury in thoracic impacts as consequently to the impact against the thorax, the lung may be affected. Therefore, one has to use a model which correctly simulates the lung behaviour under any solicitation. Because of the difficulty encountered during our simulation on the lung material, we tested two lung models found in literature as tests on human lungs are not possible in our case. Two lung models were then compared especially a comparison between two sets of parameters of a lung model (Table 2) is done in order to better understand the biomechanical response of the lung. This may give some indication of which lung model to use. Results show that for the velocity of 20 m/s, there is a good agreement regarding force-time history and deflection-time history (Fig. 7-8).

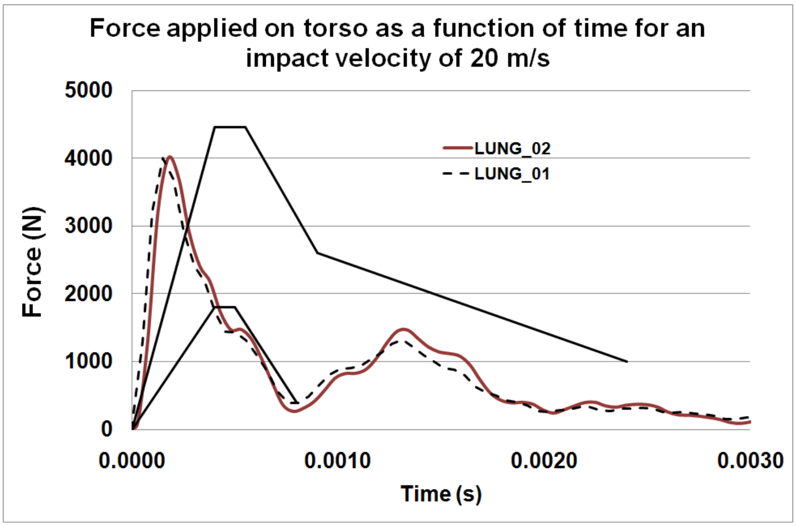

Figure 6. Dynamic force: comparison of the two models

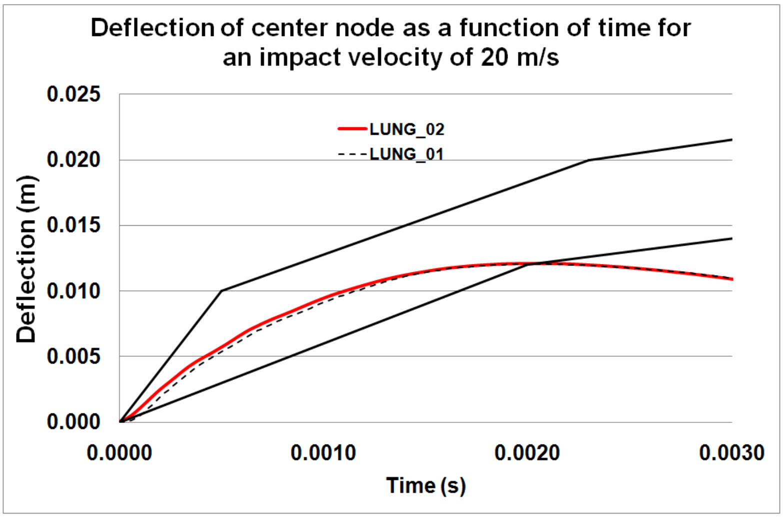

Figure 7. Dynamic thorax deflection: comparison of the two models

But at 40 m/s, results are quite similar between the two models but the calculation stops at 1.26 ms for the 'LUNG_01' (Fig. 8) with an error message 'complex sound speed in solid element in the lung'. Some elements were highly distorted (Fig. 9). We are still investigating why this model fails.

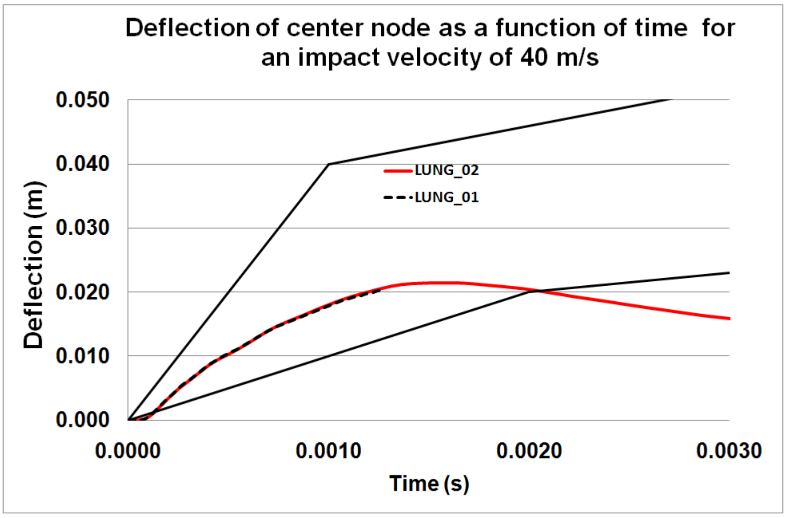

Figure 8. Dynamic thorax deflection: comparison of the two models

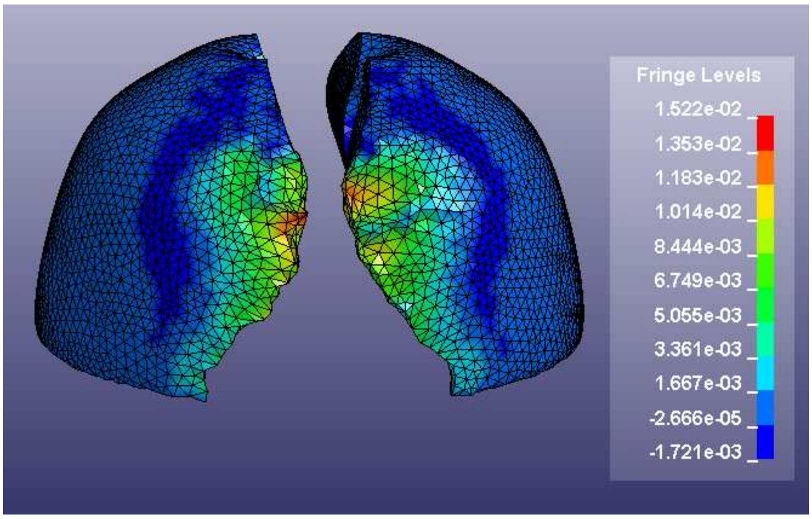

Figure 9. Highly distorted mesh of the lungs when the calculation stops

Another problem that we encountered is a contact problem. Many contact options are available for the different types of contact algorithms. Choose the best one is a challenge and require more experience in contact treatment. To better understand the contact option SOFT, AUTOMATIC_SURFACE_TO_SURFACE contact was defined between the projectile and the external structure and the SOFT option was used. Two cases were considered: SOFT=1 and SOFT=2. The option SOFT=0 was not considered as it is almost similar to SOFT=1 [14].

The results show for the two velocities that the option SOFT=1 is not appropriate for our problem as the calculation was aborted because of the complex sound speed in some solid elements in the lung. This problem of complex sound speed does not occur with the option SOFT=2.

Conclusions

Numerical simulations are an important tool in the understanding and the prediction of the biomechanical response of the human thorax against the impact of KENLW. But there are many challenges as reliable results depend not on accurate material modeling, the geometric modeling and the contact between different thorax organs. We have shown that through the problem of the lung material the difficulty in the material modeling of the human body. Each person is unique, therefore there exist a great variability in the properties of a human depending of many factors (gender, age,…).

The way all organs interact is important for the definition of the contact type. We have shown that depending of the type of the problem, the choice of which parameter or which option to use is not simple.

References

[1] NATO mission statement, October 13, 1999

[2] B. Koene, F. Id-Boufker, A. Papy, *Kinetic Non-Lethal Weapons*, Netherlands Annual Review of Military Studies, 2008

[3] C. Mesloh, M. Henych, R. Wolf, *Less Lethal Weapon Effectiveness, Use of Force, and Suspect & Office Injuries: A Five-Year Analysis*, 2005-IJ-CX-K050, September 2008

[4] N. Lewer, N. Davison, *Non-lethal technologies—an overview*, Science, Technology and the CBW Regimes, 2005

[5] C.A. Bir, *The evaluation of blunt ballistic impacts of thorax*, Ph. D. Thesis, Wayne State University, Detroit,2000.

[6] http://www.etcvsg.com/surgicalprocedures.html/

[7] http://www.valeedge.com/edgicine/cutting_edge_apr04.html

[8] A.Bouamal, H.Lévesque, *Development and validation of a finite element human thorax model under blunt ballistic trauma* –Valcartier, Canada, 2007.

[9] N. N. Nsiampa, C. Robbe, A. Papy, *Numerical simulation of non-lethal projectiles on human thorax*, ISB 2011 (to be published)

[10] Stitzel J. D., Gayzik F.S., Hoth J.J., Mercier J., Gage D.H., Morton K.A, Duma S.M, Payne R.M.,2005, *Development of a Finite Element-Based Injury Metric for Pulmonary Contusion Part I: Model Development and Validation*, Stapp Car Crash Journal, Vol. 49, The Stapp Association, pp.271-289.

[11] [5] D.L. Vawter, *A finite element model for macroscopic deformation of the lung*, Journal of Biomedical Engineering, February 1980, Vol. 102/1.

[12] K.U. Schmitt, P. Niederer, M. Muser, F. Walz, *Trauma Biomechanics – Accidental injury in traffic and sports*, 3rd Ed. – Springer – p. 161.

[13] N. N. Nsiampa, C. Robbe, A. Papy, *Numerical investigation of impact of non lethal kinetic projectiles onto human thorax*, 6th European Symposium on Non-Lethal Weapons, 2011 (to be published)

[14] http://www.dynasupport.com/howtos/contact/soft-option