Title: **Sensibility study of viscous criterion for kinetic energy non-lethal projectile thoracic impacts**

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There are two main injury mechanisms that have to be considered when the thorax is subjected to kinetic energy non-lethal projectile impacts: skin penetration and blunt trauma. The thoracic injury is one of the most important blunt traumas. In order to predict the lethality of a thoracic non-lethal impact, different injury criteria and tolerance limits have been defined, based on animal and cadaver testing. The viscous criterion – $(VC)_{max}$ - is considered for thorax injury as widely accepted and used in the non-lethal community. It is based on the thorax deflection and thorax deflection rate during the impact. Nevertheless there are many parameters that can influence the calculation of $(VC)_{max}$ such as the projectile impact yaw angle and the location of the thorax deflection measurement. Experimentally, normal impacts are generally considered, which differ from real shootings. Moreover, it is difficult to predict with accuracy the location where $(VC)_{max}$ will be maximal. However, thanks to numerical simulations, we can take into account the general case and deduce practical guidelines.

INTRODUCTION

To cope with low-intensity conflict situations like crowd & riot control and access denial…, military and law enforcement agencies are generally equipped with kinetic energy non-lethal weapons.

The use of these kinetic energy non-lethal weapons and the need of better understanding their effects on human body have resulted in the development of impact testing methods. As a consequence, different types of tests and injury criteria have been developed depending on the impacted zone (head, thorax, abdomen) for the injury risk assessment. In this paper, thoracic impacts will be considered.

Injury criteria link the thorax biomechanical responses resulting from a blunt impact to the risk of injury [1-2]. The viscous criterion $(VC)_{max}$, a criterion which usually correlates very well with thoracic injury, is used in this study.

Many issues are still to be investigated concerning the pertinent parameters that might have an influence on the non-lethal impact outcome. Those parameters may be external environment conditions, projectile characteristics, impact conditions or target characteristics. Experimentally studying the influence of these various parameters might be time consuming, highly expensive and in some cases impossible to carry out for technical reasons. Therefore numerical simulations offer an interesting alternative tool in order to study, by using the $(VC)_{max}$ criterion, their influence on the risk of injury.

In this paper, impacts of 40 mm Spartan LE sponge grenade from Nobel Sport (NS) impacting a human thorax have been simulated to see the influence of each parameter on the $(VC)_{max}$ criterion.

THE VISCOUS CRITERION $(VC)_{max}$

The viscous criterion is one of the criteria developed for thoracic impact risk assessment especially in automobile field. More details can be found in the literature [1-4]. It was applied and adapted to non-lethal (rigid) projectiles in [2] after experimental tests carried out on Post Mortem Human Subject (PMHS). Based on the dynamic deflection of the thorax, $(VC)_{max}$ is the maximum of product of the thorax deflection (compression) and the thorax deflection rate normalized to the thorax thickness (See Figure 1). A value of $(VC)_{max} = 0.8$ m/s is taken as a reference value. It corresponds experimentally to a 50 % chance of sustaining thoracic injury (rib facture) of AIS =0 or 1[2]. At this time, in Belgium for example, only injuries for which $VC)_{max} < 0.8$ m/s are acceptable.

PARAMETERS LIKELY TO INFLUENCE $(VC)_{max}$

In operational situations, it is difficult to measure physical parameters associated to a given injury criterion because of the difficulty of monitoring or mastering the many parameters likely to influence the phenomenon. Therefore, tests are performed in a controlled environment with specific constraints in order to limit the influence of a number of parameters. Most of them are then generally not taken into account. We have identified a few of them that may affect the value of $(VC)_{max}$ and will be examined hereafter. Those parameters can be divided into two groups, the target related parameters and the impact conditions related parameters.

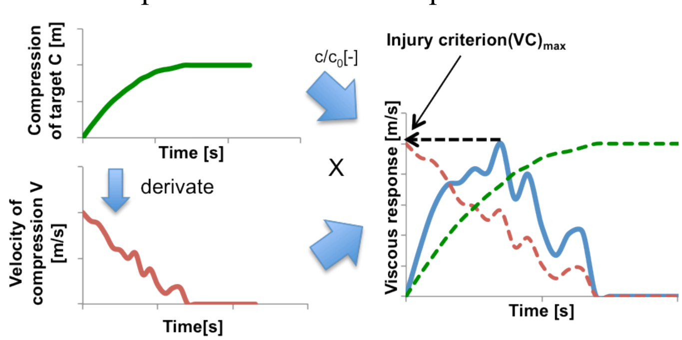

Figure 1. The $(VC)_{max}$ calculation [5]

Target related parameters

The measurement of the thorax dynamic deflection is generally obtained through high-speed videos images [2,6]. The measurement is performed globally and in the impact direction. Two parameters can be then considered, *the measurement location in the impact section* and *the measurement direction*:

On the one hand, the measured value of thorax displacement (and its rate) is an average value. It does not take into account the localized displacements of the thorax in the impact section. Therefore, the local values of the displacement in the impact section can differ from the global measured value.

On the other hand, the direction in which the displacement is measured will also influence the result, and there is no guarantee that the impact direction is the one that maximize the $(VC)_{max}$.

A third parameter that has to be considered is *the impact location*. Indeed, the value of $(VC)_{max}$ depends on the impact location as the material and geometric properties of the thorax are not homogeneous.

Impact conditions related parameters

To a large extent, the effect of the projectile on the target is determined by the projectile ballistic parameters and by the projectile attitude at the time of impact (which are also influenced by external conditions like the wind). To minimize these external influences and to ensure the reproducibility and the quality of the results, tests are generally performed in a controlled environment. To guarantee the stability of the projectile, tests are generally limited to the case of normal impacts.

But in real situations, because of external influences, the heavy mass of the 40 mm NS projectile and its relatively low velocity, the 40 mm NS ballistic trajectory is not straight. Therefore the impact is usually not normal to the targeted body zone. Two parameters are then considered here: *the impact angle,* which is the angle between the projectile velocity and the normal to the impact surface and *the yaw angle,* which is the angle between the longitudinal axis of the projectile and the velocity vector.

As mentioned previously, the influence of each parameter will be investigated through numerical simulations.

NUMERICAL SIMULATIONS

The thoracic finite element (FE) model and the projectile FE models that are used for this study have been developed previously [7]. The numerical set-up is the same as the one used in [8] for a comparison in terms of lethality between the 40 mm NS projectile (which is a deformable projectile) and a 37 mm rigid projectile. Figure 2 shows this set-up. Different numerical simulations have been performed to see the influence of each parameter on the $(VC)_{max}$. Through all simulations, the impact velocity is set to 73 m/s (which corresponds to a shooting distance of 38 m [5]) and horizontal impacts are considered unless stated otherwise.

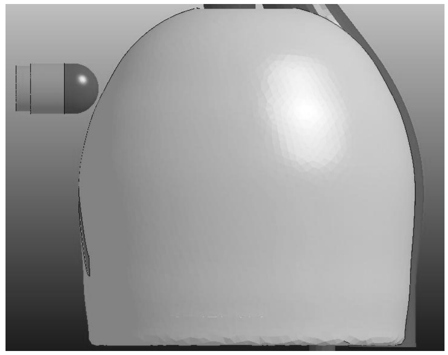

Figure 2. (a) Numerical set-up of impact of 40 mm NS on thorax

Influence of target related parameters

INFLUENCE OF IMPACT LOCATIONS

Different impact locations on the thorax have been defined (see Figure 3-left) for the sensibility study of impact locations on $(VC)_{max}$.

Results are given in Figure 4. We see that the value of $(VC)_{max}$ depends on the impact location (see Figure 4). Indeed, the local stiffness of the thorax will be influenced by a combination of material and geometric characteristics of the different organs (costal cartilages combined with sternum and ribs, heart, lungs,…).

The value of $(VC)_{max}$ increases from top to bottom (Locations h-a-f-g). This increase is probably due to the fact that, locally, the thorax stiffness decreases from top to bottom. As we are getting to the lowest region of the thorax where most of tissues/organs are soft tissues/organs, $(VC)_{max}$ increases drastically and its value reaches up to 3.75 m/s (an increase of 275% of the $(VC)_{max}$ reference value). This might be surprising at first glance, but in this region, on the one hand, the $(VC)_{max}$ or the tolerance limit may be inappropriate as the only injuries noted for the development of this criterion was rib or sternal fracture while impacting at the center of sternum at the 8th thoracic vertebrae level [2]. On the other hand, the fact that the diaphragm and the abdomen organs which act as constraints to the thorax were not modeled may partly result in this increase.

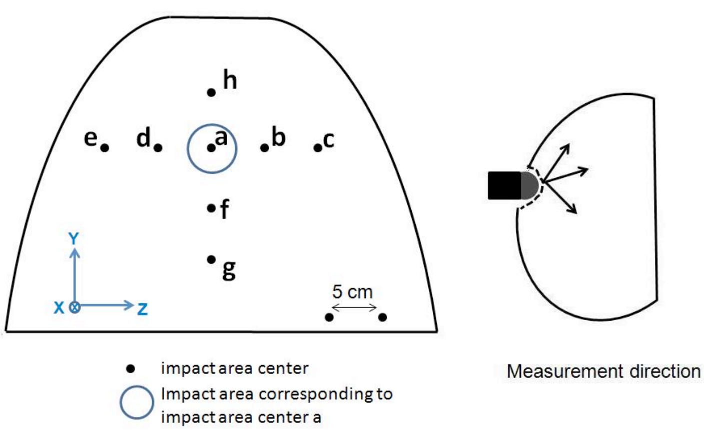

Figure 3. (Left) Scheme of impact locations (face view) – (Right) measurement direction (sideview)

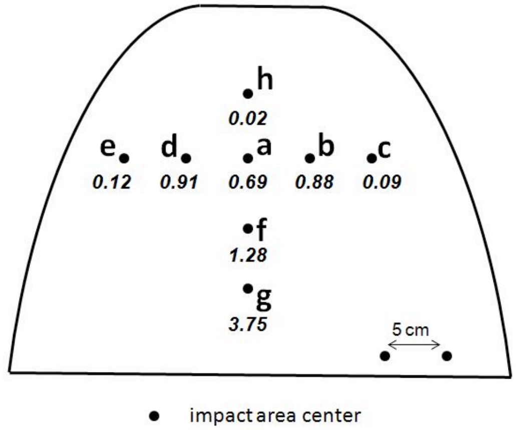

Figure 4. $(VC)_{max}$ values in [m/s] at different impact location

Considering the impact locations left-right (Locations e-d-a-b-c), from the reference location (a), we see an increase of $(VC)_{max}$, then a decrease afterwards almost in a symmetric manner. This symmetric behavior may be a consequence of the (quasi-)symmetry of the thorax in regard to the midsagittal plane.

We see that the value of $(VC)_{max}$ leads to a different injury outcome as we move 5 cm from the location reference (a) to the left or to the right (an increase of maximum 32%). This result was achieved at costal cartilages zone between the sternum and the ribs. Again, the local (material and geometrical) properties play an important role in the occurrence of injury. The pending question is what criterion to apply in such case.

Evolution of the $(VC)_{max}$ with the measurement location

Because of the localized nature of kinetic energy non-lethal impacts, only a limited zone on the target is affected by the deformation during the impact. But in the experimental testing, a global measurement is done. A $(VC)_{max}$ mapping scheme of the impact area (see Figure 3-left) is considered in order to study the influence of $(VC)_{max}$ on the criterion.

Figure 5 shows the variation of $(VC)_{max}$ for an impact at the same location (a) in the coronal (face view) plane. The value of $(VC)_{max}$ depends on the measurement location in the impact zone. The highest local value $(VC)_{max}$ in the impact area is used for the evaluation of the risk of injury while experimentally a global value is obtained.

A symmetric pattern of $(VC)_{max}$ relative to the midsagittal plane has been observed as a consequence of the (quasi-)symmetry of the model relative to the same plane.

Influence of the measurement direction

As mentioned previously, the experimental measurement of the $(VC)_{max}$ is performed in the impact direction. But in a broader sense, the deflection can be measured in any direction and the $(VC)_{max}$ can consequently be calculated in any direction.

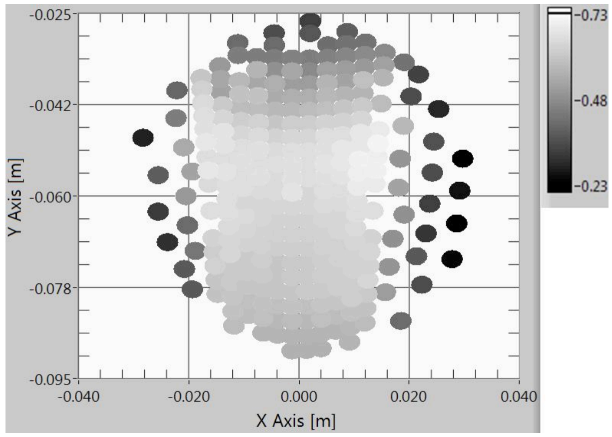

Figure 5. Evolution of $(VC)_{max}$ in the impact zone

The evolution of $(VC)_{max}$ regarding the measurement direction has been studied at impact location (a). The azimuth and the elevation angles were varied from -90° to 90°(see Figure 6). The highest $(VC)_{max}$ and its corresponding direction is then computed. The method used to calculate the $(VC)_{max}$ is described hereafter.

Consider the vector $\vec{u}$ as the direction in which the $(VC)_{max}$ has to be calculated and a given vector $\vec{v}$ in the reference coordinate system (see Figure 5(left)). The projection of this vector $\vec{p}_{\vec{u}}(\vec{v})$ in the direction $\vec{u}$ is given by Eq. 1.

$$\vec{p}_{\vec{u}}(\vec{v}) = \|\vec{v}\| \cos\beta \frac{\vec{u}}{\|\vec{u}\|} = \frac{\vec{v}.\vec{u}}{\|\vec{u}\|^2}\vec{u} \tag{1}$$

Where $\|.\|$ is the Euclidean norm, β the angle between the two vectors and $\vec{v}.\vec{u}$, the scalar product.

If we assume that $\vec{u}$ is a unit vector, it is thoroughly characterized by the parameters (θ, ϕ), respectively the azimuth angle θ and the elevation angle ϕ (See Figure 4). Its components are then given by (Eq. 2).

Based on the Eq 1-2, the $(VC)_{max}$ at a given location can be calculated for any direction.

$$\begin{pmatrix} \cos\phi\cos\theta \\ \sin\phi \\ \cos\phi\sin\theta \end{pmatrix} \tag{2}$$

Figure 7 shows the evolution of $(VC)_{max}$ when the direction (θ,ϕ) varies. The maximum of the surface corresponds to $[(VC)_{max}]_{max}$, the maximal value of $(VC)_{max}$ as a function of the measurement direction. Its value is equal to 0.88 m/s for $(\theta,\phi)=(1°,-28.2°)$. Due to certain limitations of the model (for example a curved upper part of the thorax), the elevation angle (-28.2°) is probably overestimated as a real thorax is typically flatter. For comparison, the value of $(VC)_{max}$ in the impact direction ($(\theta,\phi)=(0°,0°)$) is only 0.69 m/s.

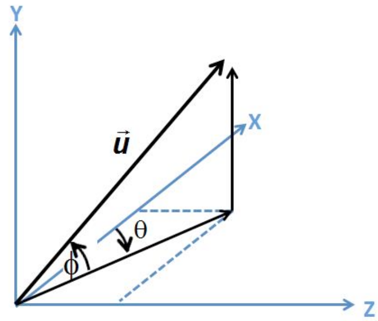

Figure 6. Characteristic angles of the unit vector $\vec{u}$

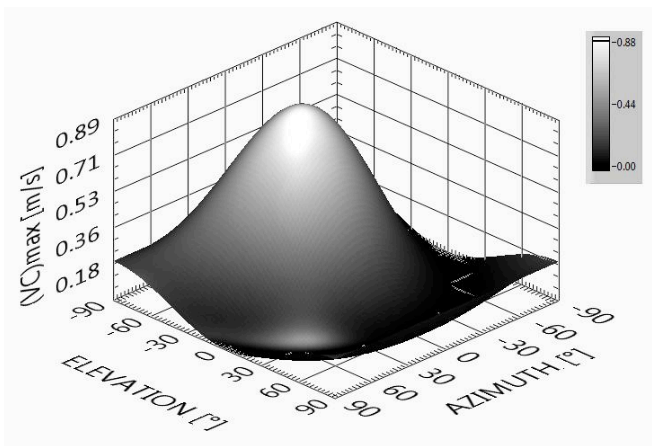

Figure 7. $(VC)_{max}$ as function the azimuth and the elevation angles for horizontal impact

These two values of $(VC)_{max}$, compared to the $(VC)_{max}$ reference value (0.8 m/s), lead to different lesional outcomes as one satisfies the criterion and the other not. The question of whether the direction is critical in terms of risk of injuries remains open.

For $\phi = 0°$, we obtain a curve (See Figure 8) which is symmetric. The reason of this symmetry may be due to the (quasi-)symmetry of the model relative to the midsagittal plane.

The curve corresponding to $\theta = 0°$ is given at Figure 9 is quite different from the one corresponding to $\phi = 0°$.

Influence of impact conditions related parameters

The impact conditions (impact angle, yaw angle) play a key role on the target response to a ballistic impact (see Figure 10). Simulations have been performed for the sensibility study of each parameter. The impact angle was varied from -20° to 20° in the midsagittal plane while the yaw angle was varied from 0 to 7.5° in the same plane.

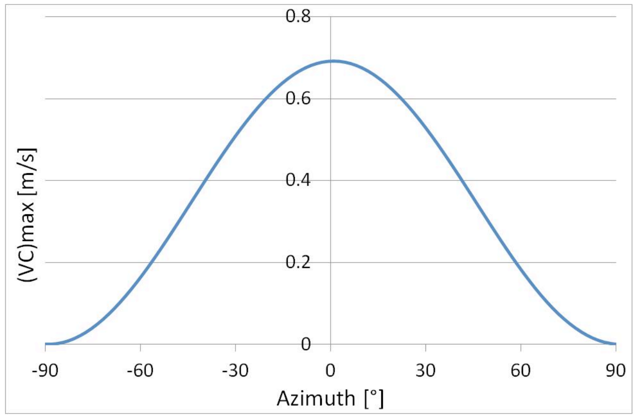

Figure 8. Curve of $(VC)_{max}$ for ϕ=0° as function of the azimuth angle

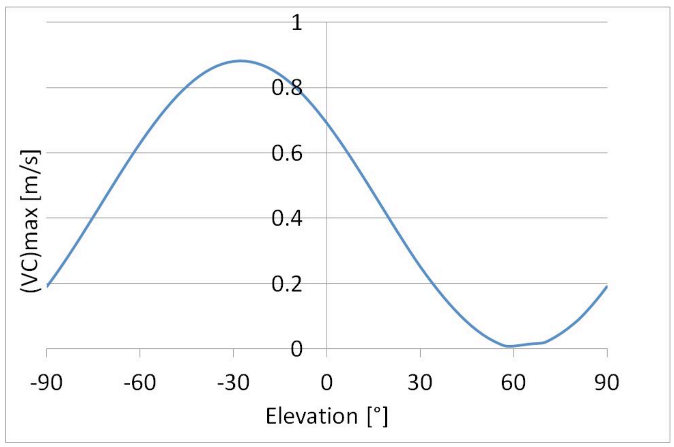

Figure 9. Curve of $(VC)_{max}$ for θ=0° as function of the elevation angle

INFLUENCE OF THE IMPACT ANGLE

Figure 11 shows the influence of the impact angle on the $(VC)_{max}$. The highest value of $(VC)_{max}$ is achieved for normal impact. A maximum decrease of $(VC)_{max}$ of 27% has been achieved when the impact angle increases from 0° to 20°. Therefore, experiments at normal impact will lead to higher potential lesional effects than the ones at oblique impacts.

The decrease of the $(VC)_{max}$ is greater for the negative values than for the positive values of the impact angle. This decrease may be explained not only by the tumbling of the projectile at this location as the angle increases, but also by the local characteristics at the impact location.

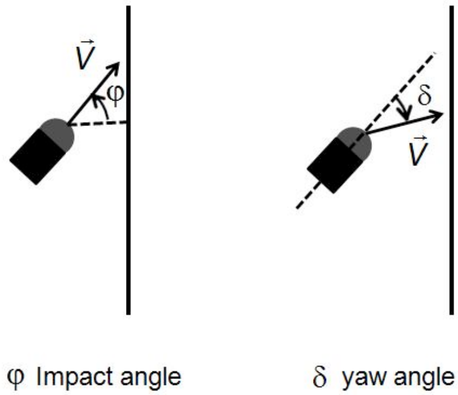

Figure 10. $(VC)_{max}$ as function the azimuth and the elevation

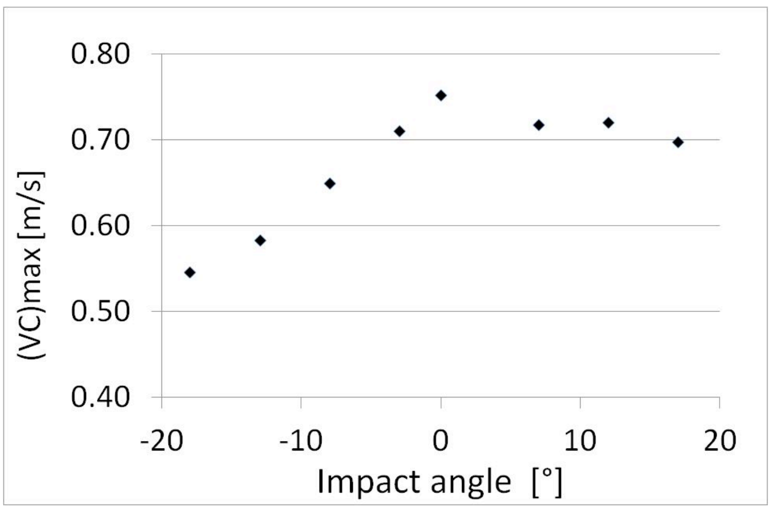

Figure 11. $(VC)_{max}$ as function of the impact angle

INFLUENCE OF THE YAW ANGLE

Figure 12 shows the influence of the yaw angle on $(VC)_{max}$. When the yaw angle increases, $(VC)_{max}$ decreases as greater angles are likely to make the projectile tumble easily. Highest value of $(VC)_{max}$ is achieved for zero yaw angle. Increasing the yaw angle from 0° to -7.5° leads to a decrease of 16% in $(VC)_{max}$.

Therefore, the normal impact (zero yaw-angle and zero impact angle) shows to be more critical in terms of potential lesional effects than other impact type.

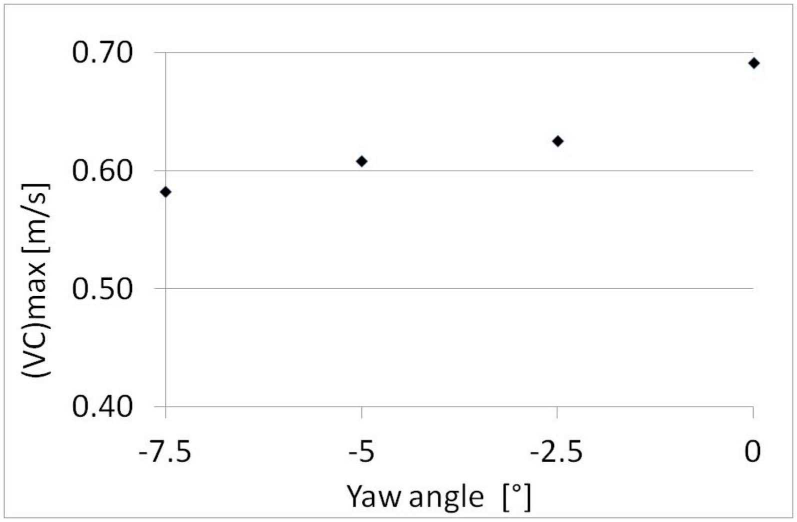

Figure 12. $(VC)_{max}$ as function of the yaw angle

CONCLUSIONS

In this article, the influence of parameters that can affect the risk of injury has been studied using the viscous criterion $(VC)_{max}$ thanks to numerical simulations of the impact of the 40mm NS projectile on the thorax. It has been shown that:

- The value of $(VC)_{max}$, consequently the risk of injury depends on the thoracic impact location. Therefore the corresponding risk of injury is not the same as the local characteristics are not the same. The thoracic lowest part has shown a higher value of $(VC)_{max}$. However, in this region of soft tissues, the $(VC)_{max}$ or the corresponding tolerance limit may not be appropriate. Certain limitations of the model can partly explain these high values. Except for locations where the criterion or the model can be questionable, the highest value of $(VC)_{max}$ will be considered to be the primary parameter for describing the severity of the possible injury outcome.

- At a given measurement location, the impact direction is not necessarily the direction where $(VC)_{max}$ is maximal. As such, the current global assessment method may not necessarily give the highest value of $(VC)_{max}$. As a consequence, the risk of injury may be higher in a direction different from the impact direction. In practice, the criterion has experimentally only been applied in the impact direction (on PMHS). Numerical simulations although allow to highlight the influence of the considered direction on the value of $(VC)_{max}$. Experimental validation of the numerical simulations is nevertheless still lacking.

- Because of the localized behavior of the non-lethal impact, a limited area is affected during impacts. It has been seen that the $(VC)_{max}$ local values in this area are different. It is the author's opinion that the highest value is the one that determines the risk of injury, even if the experimental conclusions are based on global values of $(VC)_{max}$.

- The $(VC)_{max}$ depends on impact conditions namely the impact angle and the yaw angle. It is maximal for normal impact (zero-impact angle and zero-yaw). Therefore the risk of injury is also maximal for normal impacts. It means that in experiments, one can characterize the potential lesional effects of a non-lethal projectile only by considering normal impacts.

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