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1. Introduction

Smoothed Particles Hydrodynamics is a numerical method initially developed for astrophysical problems (Gingold & Monaghan 1977), and which has been adapted for solid mechanics during the nineties (Randles & Libersky 1996). Indeed, researchers have seen the great potential of this method: it does not need any grid, it can easily undergo extreme loadings and large deformation of the structure without numerical errors linked to the bad evolution of the elements during the simulations. These errors can often occurred when the simulation involved large deformations and even fracture of material. In this framework, the use of these kind of methods for impact biomechanics may provide interesting results especially for penetrating ballistic impacts where tissues are damaged not only because of skeleton compression but also because of their perforation by a projectile. To do so, an axisymmetric SPH formulation has been developed to model ballistic gelatin, which is considered, in the literature, as a biofidelic soft tissue simulant. An elasto-plastic hydrodynamic law is used as a constitutive law for this structure, which is impacted by various projectiles at various velocities, as it was performed experimentally in the literature by Sturdivan (1978). Penetration time history in the gelatin is observed and good correlation can be found between the numerical response of our developed algorithm and the experimental references data, leading to the validation of the global code and the numerical model.

2. Methods

2.1. Axisymmetric SPH formulation

SPH formulation are used for solid mechanics since a few decades. 3D or 2D configurations have been largely developed for various type of perforating impacts, focusing, most of the time, on thin structures. This study focus on the development of axisymmetric simulations, introducing specific mathematical cylindrical equations for integral representation, the weighted function, and the particle approximation, as illustrated with the following example:

$$\forall (x, y) \in \Omega,$$

$$\frac{\partial f_x(x, y)}{\partial x} \approx - \iiint_{\Omega} f_{x'}(x', y') \frac{\partial W}{\partial x'} \mathrm{d}x' \mathrm{d}y'$$

$$\approx -\frac{2}{h^2} \sum_{k \in K} f_k^{\beta} \frac{1}{2\pi} \int_0^{2\pi} a_{\beta}^{x'} a_{\alpha}^{x'} \frac{\partial W}{\partial \mu_{\alpha}} \mathrm{d}\theta' w_k$$

Where f is an axis-symmetrical vector function defined over the 3D domain Ω. W is the weighted function and a_j^i means the transformation coefficient from the Cartesian basis to the cylindrical one using the Einstein notation.

2.2. Mechanical constitutive model

Characterization tests have shown the strain rate dependency of ballistic gelatine, which is considered as an efficient soft tissues simulant. At low strain rates this material behaves like linear elastic body (<1 s^{-1}), whereas it can be seen like fluids at high strain rates (>1000 s^{-1}). Hence, in this study, the ballistic gelatine, is modelled with an elasto-plastic hydrodynamic law. The Mie-Gruneisen equation of state (EOS) is used to define a non-linear pressure evolution for shock response. Strength of the gelatine is simulated with the Johnson–Cook model as defined in Taddei et al. (2015).

2.3. Impact conditions

A set of experimental tests of the literature have been carried out with various diameter rigid spheres (from 2.38 to 6.3 mm) perforating a gelatine target at various velocities (from 230 to 2229 m/s). Penetration depth time history of the projectiles were observed. A specific attention was paid to the interface between the different bodies by implementing penalty conditions between rigid projectiles and the deformable SPH-modelled target.
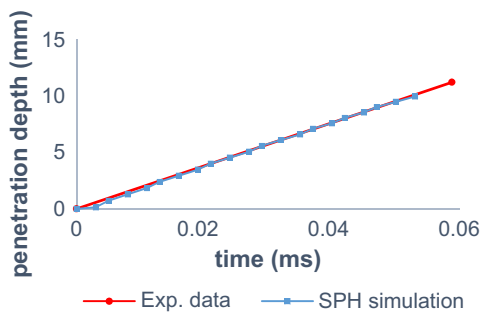

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Figure 1. Penetration depth time history.

3. Results and discussion

Ten configurations of penetrating impacts from Sturdivan (1978) have been numerically reproduced. The penetration depth time history of the projectile is compared to experimental data as illustrated in Figure 1. Figure 2 provides stress distribution.

The application of the Smoothed Particle Hydrodynamics method to bio-mechanical problems is very interesting due to the specific behaviour of the gelatine during high velocity impacts. This numerical method is well adapted to model fluids and at the same time has the ability to model solids which make of this method a powerful tool for penetrating impact investigation dedicated to human body injuries. At a numerical level, and in order to take into account the symmetries of the problems, the SPH equations have been transformed to cylindrical ones and axis-symmetric conditions have been imposed. This new formulation reduces the error of discretization since it operated quasi-exact integration over the angular axis θ. Furthermore, the SPH method is a very time consuming technics. The axis-symmetric formulation reduces considerably the number of computational points and so the global computational time of simulations. Nevertheless, some issues remain and should be kept in mind. The standard SPH method is simple to implement but suffers from instabilities which could leads to very inaccurate results. Several corrections have been proposed in the literature to overcome certain of these issues (e.g. artificial viscosity, consistency, artificial stress, stress point, etc …). These corrections have to be transformed to be introduced into the axis-symmetric SPH formulation, as well as the neighbour research algorithms.

Penetrating bio-mechanical impacts is a complex phenomenon which can be approached or simplified for normal impacts by using axis-symmetrical considerations. This work is a first step in proposing powerful numerical model for the mechanical investigation of the human body behaviour during gunshot wounds. This study allows observing quantity of information such as stress-strain field or cavity expansion. Based on the elasto-plastic hydrodynamics behaviour of bio-fidelic ballistic gelatin, soft tissues were modelled with specific EOS coupled to complex constitutive law. Results
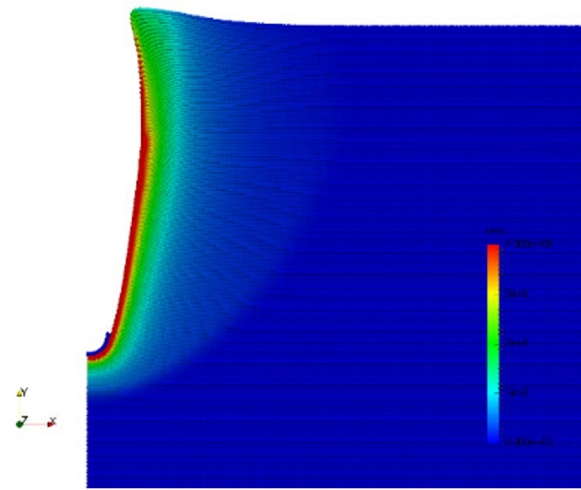

Figure 2. Von Mises stress distribution.

providing penetrating depth time history and mechanical parameters distribution give satisfying data compared to literature, as illustrated in Figures 1 and 2. These preliminary results provide interesting ways to go further in the understanding of the human body behaviour and injuries that can occurred under perforating impacts. Openings can be considered in the framework of protection device by using SPH-driven simulations coupling both human body and mechanical structures such as body armours.

4. Conclusions

The developed algorithm and models allowed simulating rigid projectiles impacting ballistic gelatine considered as a biofidelic soft tissue surrogate. The SPH formulation provide very promising results in the understanding of penetrating impact in the human body, as illustrated by the good correlation between experimental data and numerical response.

Acknowledgements

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