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FLUID-STRUCTURE INTERACTION ANALYSIS OF AMNIOTIC FLUID INTERACTING WITH COMPREHENSIVE FETUS MODEL INSIDE UTERUS EXPOSED TO EXTERNAL LOADING

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Abstract. A history of trauma during gestation is a risk factor for poor pregnancy outcomes. A multidisciplinary approach is vital to protect the mother's and the fetus' safety. Even though pregnancy-related trauma is uncommon, it is one of the leading causes of morbidity and mortality in pregnant women and fetuses. Hence, it is axiomatic to study the mechanism of the traumatic injuries to the fetus. The development of next-generation protective devices depends on our understanding of these mechanisms. Computational fluid-structure interaction simulations are used to study the effect of external loading on the fetus submerged in the amniotic fluid inside the uterus. A multitude of resulting variables is utilized to understand the cushioning function of the amniotic fluid on the fetus.

1 INTRODUCTION

Trauma during pregnancy is the leading non-obstetric cause of morbidity and mortality, and accounts for five per 1000 fetal deaths [1]. Blunt prenatal trauma is occasionally associated with intracranial hemorrhages, the most frequent are the subarachnoid hematoma and intra-parenchymal, scarcely ever the epidural hematoma. Treating these bleedings is challenging due to the ongoing pregnancy. Thus, the prognosis is often reserved, with a mortality rate of 43% and 25% of neurological sequelae [2]. A traumatic injury occurs during pregnancy in about 8% of all pregnant women [3]. Interestingly, when pregnant patients with injuries are treated in designated trauma hospitals, their birth outcomes are usually better than in non-trauma hospitals [3]. Even though pregnancy-related trauma is uncommon, it is one of the leading causes of morbidity and mortality in pregnant women and fetuses. Pathophysiology of trauma in pregnant patients presents an extra barrier due to their unusual presentation and the management of two patients at once [4].

The number of motor vehicle collisions is increasing worldwide [5]. Motor vehicle collisions are predicted to become more prevalent problem in the future. It is projected that motor vehicle collisions will be the fifth most common cause of fatalities in the world [5]. A recent review of 'traumatic injuries to the pregnant patient' shows that a motor vehicle collision is the most common life-threatening injury for a pregnant woman [6]. In the United States, state-level studies have estimated the crash risk among pregnant front-seat passengers or drivers to be between 1.0% and 2.8% [7–9]. In a retrospective longitudinal cohort analysis was concluded that motor vehicle crashes during pregnancy may be associated with an increased risk of cerebral palsy among the subgroup of cases with preterm birth [10]. Blunt abdominal traumas, such as those that happen during car accidents, can lead to traumatic uterine rupture. Of the patients who experience forceful abdominal trauma 1.6% develop uterine rupture [11]. Other adverse outcomes in pregnancy after a blunt trauma to the abdomen include placental abruption, preterm labor and preterm delivery, and pelvic fracture [12]. Given this complication's rapid onset and progression, prompt detection is essential for treating it and avoiding potentially fatal complications for both the mother and the fetus [13].

This study uses a comprehensive fluid-structure interaction models of a pregnant woman with fetus exposed to specific loading conditions. Namely, the loading conditions prescribed to the model are typical for a mine blast that occurs underneath the vehicle in which the pregnant female is present at the time of the blast. No other studies could be found investigating this kind of fetal injuries. Two distinctive fluid domains are used, namely the fetus' cerebrospinal fluid surrounding its brain, and the woman's amniotic fluid surrounding the fetus, placenta and ovaries. Numerous results is extracted from the simulations, e.g., the effect of amniotic fluid protecting the placenta, fetus' brain, etc.

2 METHODS

Three interconnected subsections are described as follows. The numerical method used is based on governing equations that solve the deformations of both the solid and fluid phases and their interaction with each other. The geometrical model is developed to preserve the small-scale features of a realistic fetus surrounded by fluid domain inside the uterus. Boundary and initial conditions are prescribed to expose the uterus to external loading.

2.1 Model

The model consists of multiple parts. Separate set of material properties is prescribed to each part according to data found in the literature. The fetus inside the uterus is surrounded by 16,731 fluid particles that, under prescribed conditions, interact with the endometrium (i.e., the inner lining of uterus) and the fetus with cord and placenta. Fluid motion and boundary interaction calculations are solved with the IMPETUS Afea γSPH Solver (IMPETUS Afea AS, Norway), while large deformations in the solid parts are calculated with the IMPETUS Afea Solver.

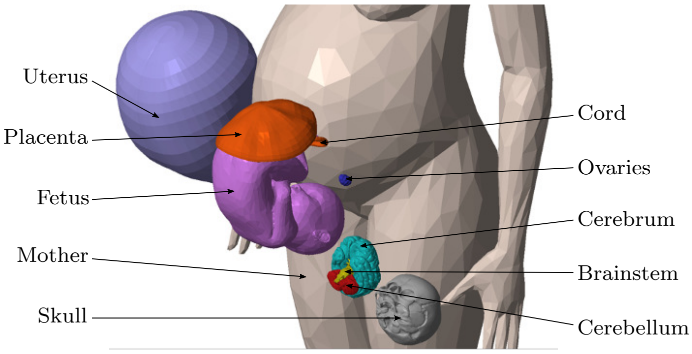


Figure 1: The model used in the computational simulations. The SPH fluid particles are prescribed to fill the space between the uterus and fetus/placenta/cord.

2.2 Boundary and Initial Conditions

The model is exposed to boundary and initial conditions typical for scenarios in which the mother experiences an exposure to the blast underneath a vehicle inside of which she is present. The measurements generated in such scenario are experimental and collected by a private equity. Hence, the data is classified as private and cannot be shared in this article. Succinctly, the blast survivability tests were performed at the General Dynamics Land Systems (GDLS) Edgefield Test Center in South Carolina. Blast experiments were conducted under very controlled and consistent procedures as the accuracy of the blast data is used to validate the numerical models used [14, 15].

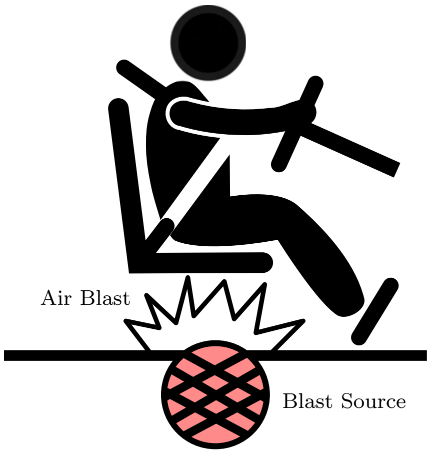


Figure 2: The model is exposed to boundary and initial conditions typical for scenarios in which the mother experiences an exposure to the blast underneath a vehicle inside of which she is present. The measurements generated in such scenario are experimental and collected by a private equity. Hence, the data is classified as private and cannot be shared in this article.

2.3 Smoothed-Particle Hydrodynamics

Smoothed-Particle Hydrodynamics is a computational meshfree Lagrangian method developed by Gingold and Monaghan [16] and Lucy [17] in 1977, initially for astrophysical problems. Since then, it has been used for simulating the mechanics of continuum media, such as solid mechanics and fluid flows. It has been used in many fields outside astrophysics, e.g. ballistics, volcanology, oceanography. Increasingly, it is being adopted by many with an interest in biomedical engineering [18]. More detailed description including the formulation used can be found in our prior publications, e.g., [19].

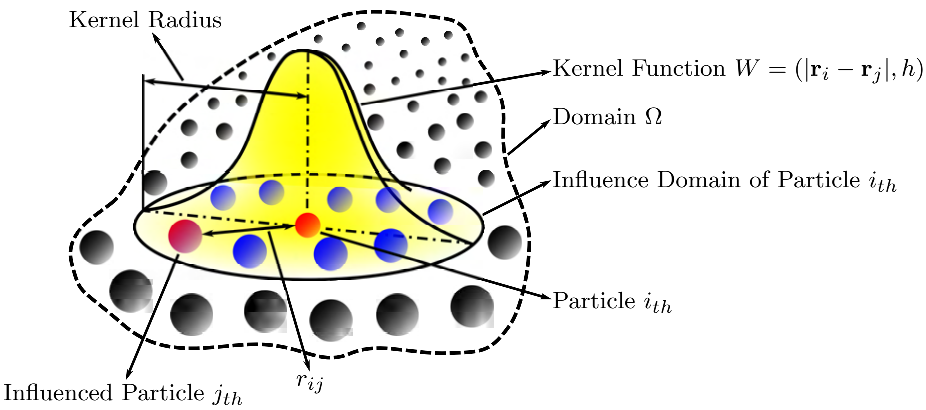


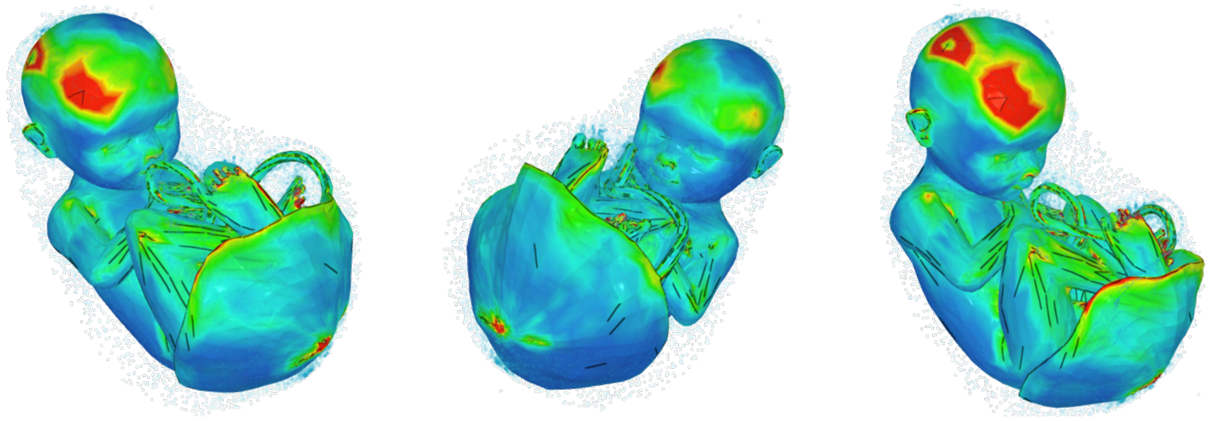
Figure 3: Smoothed-Particle Hydrodynamics Kernel approximation.

The combination of SPH methods, used to simulate the fluid domain flow, with a high-order finite element method used to simulate the solid domain deformations, is ideal for simulating FSI, especially when complex geometries are included. Using SPH methods provides numerical stability because the contact between the solid and fluid domains is easily treated numerically. Moreover, SPH is highly parallelizable. That being the case, it is possible to run FSI simulations that are numerically stable, precise, parallelized on a standard GPU workstation (as opposed to large supercomputers), which do not require the use of simplified geometries and a runtime of hours or days rather than weeks and months.

3 RESULTS

Traditionally, most studies found in the literature do not account for the fluid-structure interaction processes occurring inside the uterus. However, without a fluid-structure analysis, only structural results can be assessed. This study presents both structural (such as strain/stress, see Fig. 4) and fluid-related results (such as contact penetration and load angles, see Fig. 5).

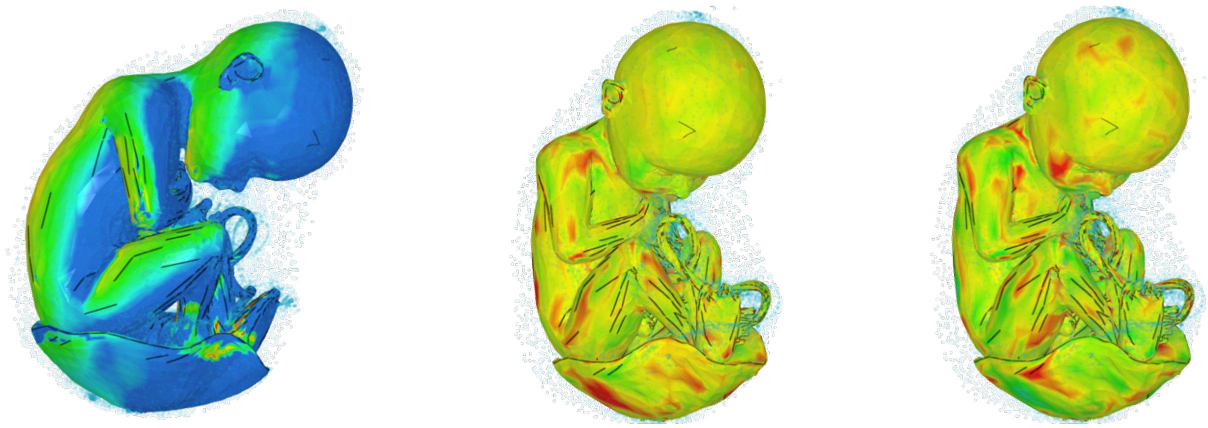
The fluid results are directly related to the fluid-structure interaction processes inside the uterus and can only be acquired by fluid-structure analyses. It is worth noting that no one parameter should be assessed without considering its meaning in the context of the other parameters available for analysis. Considering that, in the present model, the baby's position is head down (i.e., cephalic), and that the mine exploding is underneath the uterus, injuries to the head can be observed in the structural results. However, the load angles between fluid and



(a) 1^{st} Deviatoric Principal Stress (b) Effective Geometric Strain (c) Effective Stress

Figure 4: Results related to the structural parts of the model (fetus, cord, placenta). For the stress results: blue represents 0 Pa; red represents 10 GPa. Strain is a dimensionless quantity.

structure domains can be observed highest on both the placenta and the baby's face. Similarly, the contact penetration, i.e., areas where the fluid attempted to penetrate the surface of the baby before it was pushed back by the contact algorithm, can be observed mainly on the baby's backside. These fluid-related results together create a bigger picture about the flow of the amniotic fluid when exposed to external loading.



(a) Contact Penetration (b) Load Angle (c) Normalized Load Angle

Figure 5: Results related to the effect of the amniotic fluid on the structural parts of the model, i.e., these results are directly related to the fluid-structure interaction processes inside the uterus and can only be acquired by fluid-structure analyses.

4 CONCLUSIONS

A history of trauma during gestation is a risk factor for poor pregnancy outcome [20]. The most frequent etiologies for non-obstetrical pregnancy deaths include motor vehicle collisions, falls, and assaults [21]. Blunt abdominal trauma is one of the primary causes of these deaths.

To protect the mother's and the fetus' safety, a multidisciplinary approach is essential [22]. For example, the mother should be aware of the right transportation safety instructions during her prenatal appointments [11, 23]. Pregnant women are recommended to avoid driving when experiencing certain symptoms, such as tension and cramps in the lower abdomen, distractedness, and irritability. It is found that these symptoms are independent contributory factors to experiencing motor-vehicle accidents or near-miss incidents [24].

Computational simulations of biological systems, such as the interaction of the fetus with the amniotic fluid, are an intrinsic element of engineering in medicine, providing physicians the ability to visualize the pathophysiology behind diseases and disorders [25, 26]. However, human patient-specific geometries are usually of a complex nature. Consequently, it is challenging to conduct fluid-structure interaction analyses while preserving all the small-scale features of the geometries used. We argue that preserving the complexity of geometrical models used is crucial [27, 28]. The reliability of results achieved utilizing their simplified versions are questionable, especially in the context of practicality and clinical applicability. Results that are unable to reflect a close mirror of the true physiologic process cannot be used by physicians in a clinical setting to inform clinical decision-making. Moreover, achieving comprehensive predictive models of a fetus in uterus requires these models to be understandable and reproducible. Unfortunately, a few existing models are reproducible, as we lack the data sources utilized and assumptions/equations used to build the models. For example, a worldwide benchmark Food and Drug Administration (FDA) study, to standardize computational fluid dynamics techniques used to assess the safety of medical devices, shows that even results produced by experts might not be reliable [29, 30].

In the next phase of these studies, it is planned to analyze the results of the fetus brain injury. The same methodology has been previously utilized by our group to study pediatric head trauma [31] and other head injuries [32–35]. Case reports that show the evidence of fetal closed head injury by both shear and tensile forces due to a maternal motor vehicle accident will be utilized for the choice of boundary and initial conditions, e.g., [36]. The developing brain may be significantly impacted by fetal trauma during pregnancy. Skull fractures, intracranial hemorrhages, hypoxic-ischemic damage, and other intracranial diseases can all result from fetal trauma [37]. Other use of this model can include an investigation of the restraining mechanical forces of worn seat belts on the body and their effect on the fetus. Even though, it is agreed that the seat belt use has reduced mortality rates for both the mother and the fetus [38], further investigation can prove beneficial. It is important to mention that unbelted pregnant drivers suffer severe or fatal injuries to the fetus even in low-speed collisions [39].

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