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Adverse fetal outcome in road accidents: Injury mechanism study and injury criteria development in a pregnant woman finite element model

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ABSTRACT

This study documents the development of adverse fetal outcome predictors dedicated to the analysis of road accidents involving pregnant women. To do so, a pre-existing whole body finite element model representative of a 50th percentile 26 weeks pregnant woman was used. A total of 8 accident scenarios were simulated with the model positioned on a sled. Each of these scenarios was associated to a risk of adverse fetal outcome based on results from real car crash investigations involving pregnant women from the literature. The use of airbags and accidents involving unbelted occupants were not considered in this study. Several adverse fetal outcome potential predictors were then evaluated with regard to their correlation to this risk of fetal injuries. Three predictors appeared strongly correlated to the risk of adverse fetal outcome: (1) the intra uterine pressure at the placenta fetal side area ($r = 0.92$), (2) the fetal head acceleration (HIC) ($r = 0.99$) and (3) area of utero-placental interface over a strain threshold ($r = 0.90$). Finally, sensitivity analysis against slight variations of the simulation parameters was performed and assess robustness of these criteria.

1. Introduction

Road accidents are the leading cause of fetal injuries resulting from trauma (Weiss et al., 2008; Mirza et al., 2010; Cheng et al., 2012). Several physical or computational pregnant woman models dedicated to car occupant safety were previously reported in literature (Pearlman and Viano, 1996; Rupp et al., 2001; Moorcroft et al., 2003; Jansova and Hyncik, 2008).

Adverse fetal outcome (AFO) predictors resulting from motor vehicle accidents (MVAs) were proposed in Rupp et al. (2001) and Moorcroft et al. (2003). The method used to develop these predictors was similar in both studies and consisted in simulating various car accident conditions associated to a corresponding estimated risk of AFO previously reported in Klinich et al. (1999a).

In Rupp et al. (2001), a pregnant woman dummy (so-called MAMA-2B) representative of a 30-week pregnant woman, was used to evaluate the correlation between the anterior intra-uterine pressure and the risk of AFO. To do so, 15 frontal car impacts at initial speed ranging from 13 to 55 km/h were performed with two different occupant positions (driver and front seat passenger) and three different restraint conditions (three-point belt, three-point belt + airbag, none). In Moorcroft et al. (2003), a similar approach was followed, based this time on a computational model and limited to 12 frontal car impact conditions, and focusing on the peak strain in the uterus.

Such criteria appear mandatory to estimate the risk of AFO in multiple car accidents scenarios and to evaluate the efficiency of safety devices developments. However, the two here above mentioned criteria are specific to their own model environment and could not be exported straight forward to another model without preliminar evaluation. Moreover, these two criteria are based on injury curves published in 1999 that were significantly updated since by the same authors (Klinich et al., 2008).

In an attempt to improve AFO prediction, new injury criteria possibly linked to real injury mechanisms are presented in this paper. Our approach was based on an already available finite element (FE) model representative of a 50th percentile 26 weeks pregnant woman, developed in the LS-DYNA environment. This Pregnant car Occupant Model for Impact Simulation (PROMIS) was detailed in Auriault et al. (2014).

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2. Material and methods

2.1. The PROMIS model and the sled environment

The PROMIS model is a FE model representative of a 26 weeks pregnant woman in a true driving position (Auriault et al., 2014). It resulted from a coupling between a 50th percentile woman model validated in a wide range of loading conditions and a detailed gravid uterus model including placenta, uterine wall, amniotic fluid, ligaments and fetus. Mechanical properties of the gravid uterus components were extracted from experimental results proposed in the literature: a hyperelastic law was applied to the uterine wall and the placenta based on experimental tensile and indentation tests (Manoogian et al., 2012; Pérès et al., 2014). An arbitrary lagrangian eulerian (ALE) formulation was used to model the amniotic fluid (with water properties) and its interactions with its environments. The fetus was defined rigid and the ligaments elastic.

For the simulations, the PROMIS model was positioned on a sled on which an imposed deceleration pulse was applied.

The sled included a 3 points belt with a 4 kN load limiter.The steering wheel was defined rigid. The belt was built as a mix between 1D elements in contact with the anchor points and 2D elements in contact with the PROMIS model. The belt in contact with the FE model was modeled with an elastic material with a Young modulus of 5 Gpa and a poisson's ratio of 0.3. The belt was 46 mm wide and 1 mm thick. 1D belt elements were modeled with spring elements from the LS-DYNA library.

Penalty-based interfaces were used to model the interactions between the sled environment (2D belt elements, the seat and the floor) and the PROMIS model. The static friction coefficient between the seat and the pregnant woman FE model was set to 0.3. The static friction coefficient between the belt and the FE model was set to 0.2. The belt load limit function was modelled with a spring element with tension-only characteristics.

The PROMIS model position relative to the sled components was set according to the results proposed by Klinich et al. (1999b):

- The abdominal belt was set at the iliac crest level with 24% of the gravid uterus above the midline belt
- The shoulder belt was set with a sternum ratio of 0.53, a clavicle ratio of 0.45 and a shoulder ratio of 0.33, see (Klinich et al., 1999b) for details on this ratio
- The shortest distance from the abdomen to the steering wheel was set to 85 mm
- The steering wheel was oriented at an angle of 24° relative to vertical
- The seatback was oriented at an angle of 17° relative to vertical

2.2. Simulated accident scenarios

A total of 8 frontal car accident simulations at different speeds ranging from 10 to 65 km/h were performed with the PROMIS model (Table 1). Each of these cases was linked to the corresponding risk of AFO (fetal death or major complications including placenta abruption, uterine rupture or laceration, direct fetal injury and premature delivery before 32 week's gestational age) based on real car crash investigations proposed by Klinich et al. (2008).

2.3. Adverse fetal outcome criteria evaluation

During simulations, a total of 5 mechanical parameters were recorded because a priori condidered as possibly good adverse fetal outcome predictors:

Table 1
Simulation conditions.

Simulation	Crash speed (km/h)	Risk of adverse fetal outcome (Klinich et al., 2008)
1	10	1%
2	20	4%
3	25	8%
4	30	12%
5	35	20%
6	40	30%
7	50	55%
8	65	88%

Table 2
Sensitivity analysis.

Simulation id	Varying parameter	parameter value
R1	Belt thickness	2 mm
R2	Impact speed	Reference speed + 5%
R3	Impact speed	Reference speed – 5%
R4	Belt Young modulus	Reference modulus + 5%
R5	Belt Young modulus	Reference modulus – 5%
R6	Placenta mass density	Reference mass density + 10%
R7	Friction coefficient between the occupant and the belt	0.3
R8	Lap belt retensioner (4 kN load limit)	20 mm
R9	Lab belt pretensioner (4 kN load limit)	40 mm
R10	Load limiter (no pretension)	2 kN
R11	Load limiter (no pretension)	6 kN

- UPI (Utero-Placental Interface) strain
- Maternal HIC (Head Injury Criterion)
- Fetal HIC
- Intra-uterine pressure
- Force belt/abdomen

All correlations analysis were performed with STATISTICA v9.

2.4. Sensitivity analysis

The effect of several parameters and initial conditions on the criteria robustness was evaluated in one single reference accident scenario,chosen amongst all those listed in Table 1. Configuration 6, i.e.40 km/h impact speed with belted occupant, was arbitrary selected.

In these references conditions, one parameter at a time was slightly modified and the resulting AFO criteria were compared to the reference criteria.

Always in the reference conditions, sensitivity to pretensioner length and belt load limiter was also evaluated. The list of varying parameters for the sensitivity analysis is given in Table 2.

3. Results

3.1. Kinematics description

The frontal accident at 40 km/h was analysed to detail the pregnant occupant kinematics in MVAs (see Fig. 1). During the first 45 ms, there is whole-body forward translation due to the pulse deceleration and the occupant inertia. During this phase, the chorial pressure and the resultant force between the lap belt and the abdominal wall increase almost linearly. The fetus contacts the placenta at t = 32 ms. Starting from 45 ms, the 4 kN limit force in the shoulder belt is reached. Then, thorax starts bending forward. At t = 50 ms, the abdomen forward translation is suddenly stopped by the lap belt. The abdomen is then compressed by the abdominal