Modelling the Fetus for Pregnant Occupant Safety

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ABSTRACT

Annual fetus mortality rates due to road traffic accidents are much higher than the infant mortality rates in motor vehicle crashes. The goal of this study is to generate a computational model of the unborn occupant (fetus) for crash protection research. The multibody fetus model is accommodated in the Finite element uterus model of 'Expecting', the computational pregnant occupant model which tackles the complexity of a pregnant women's anatomy and incorporates pregnant female anthropometry.

In particular, 38 weeks gestation level is focused upon since at this stage of pregnancy the fetus is at greatest risk during a crash due to the size increase of the abdomen resulting in a close proximity to the vehicle steering wheel and awkward routing of the seatbelt. This article explains in detail all stages of modelling the unborn occupant and the links to its environment, the uterus with a placenta and the computational female model.

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1. INTRODUCTION

It has been shown in the literature that motor vehicle collisions are the leading cause of accidental fetal death [1]. In the UK alone there are approximately 750,000 pregnant women each year all of which are likely to be vehicle drivers or passengers during some or all stages of their pregnancy [2-4]. It has been estimated that around 3400 women in the second half of pregnancy are involved in car crashes annually [5]. Fetus mortality rates due to accidents are much higher than the infant mortality rates in motor vehicle crashes and the number of children die because of the bicycle accidents [2].

The risks to the fetus in the case of an automobile impact have been described in medical studies as being; placental abruption [6], [7], maternal death [8], direct fetal injury [9], feto-maternal transfusion [10], onset of labour and preterm delivery [11].

The safety of pregnant women as car occupants may be compromised due to the size and shape changes that occur during pregnancy as well as due to the added complexity of having an occupant within an occupant. Early investigations using pregnant baboons and monkeys concluded that the standard 3-pt seatbelt system provided better protection to both mother and fetus compared to just the lap portion of the belt [12]. In the mid 90's a pregnancy insert for the Hybrid III small female was developed in [13] to further explore the affect of loading of vehicle safety systems on the approximately 28-week pregnant occupant. This physical model included a urethane fetus which fitted inside a urethane casing that fitted inside a urethane uterus. The model had many limitations such as a non-anthropometric shape, unrealistically high stiffness and attached weights which would affect overall ATD kinematics. A

second-generation physical model of pregnancy insert was developed [14]. The model has more realistic anthropometry however it has neither a placenta nor fetus instead the uterus is filled with water. A computational model to represent a pregnant driver was also developed [15], using MADYMO, combining a FE model of a liquid-filled uterus, without fetus, within an existing 5th percentile female occupant model available in the MADYMO package.

The significant mass of the considerably solid fetus during the later stages of pregnancy almost fills the entire volume of uterus but is reasonably free to move during an impact, only constrained by the boundaries of the uterus. The fetus has therefore the potential to affect the entire dynamic response to impact. Hence the magnitude and location of the forces exerted by the solid fetus and the consequent stresses and strains would be significantly different than those exerted by the fluid alone. Hence the lack of any representation of a fetus in recent models, both physical and computational, warrants further investigation in this area.

The focus of this paper is on the generation of a detailed computational representation, multibody model of the unborn occupant, the fetus, as part of the computational model of pregnant women 'Expecting'.

2. FETUS AND UTERUS ANATOMY

Figure 1 shows the general anatomy of fetus and uterus near term, as with 95% of all pregnancies the fetus assumes an upside-down position with its head downwards nestled within the confines of the pelvis bones. The fetus is surrounded by amniotic fluid; this fluid physically cushions the embryo as it

develops and permits free movement of the fetus. At term the volume of amniotic fluid relative to that of the fetus is at its lowest.

The placenta, a large vascular organ covering approximately a quarter of the inner surface of the uterus, is generally, in around 80% of pregnancies, located at the fundus (top) of the uterus. The placenta has a flattened discoidal mass with a roughly circular shape. It has an average weight of around 470g (range 200-800g), an average diameter of 185mm (range 150-200mm) and an average thickness of 23 mm at its centre (range 10-40 mm). The placenta attaches to the internal surface of the uterus via small finger-like protrusions from the surface of the placenta known as microvilli, as well as connecting the two structures; this utero-placental interface (UPI) facilitates nutrient transportation to the fetus [16], [17].
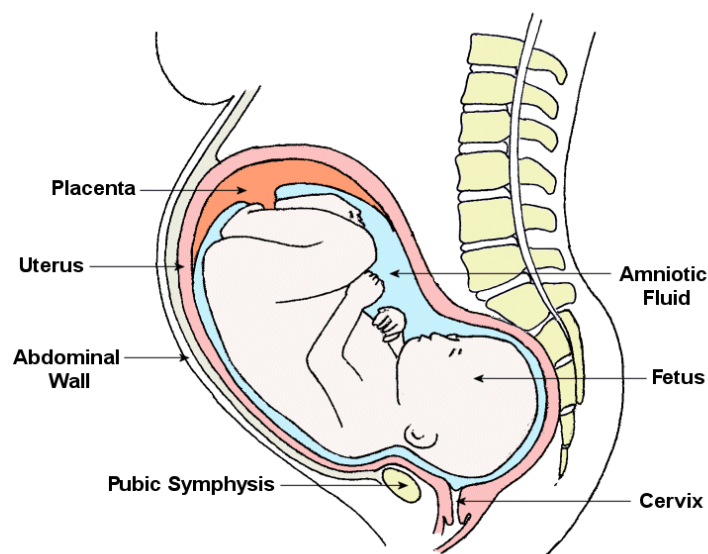
Fig 1 Anatomy of the pregnant abdomen.

The uterus grows dramatically during pregnancy increases in weight significantly and it expands out of the pelvic basin displacing other abdominal organs upward with the uterine fundus reaching the level of the xiphisternum by

the 36th week of gestation. At this stage the uterine wall thickness is approximately 10mm. The uterus is attached at the cervix to the pelvis and sacrum via ligaments but is otherwise unattached in the abdominal cavity; from around the 16th week onwards the uterus makes contact with the anterior abdominal wall and the lumbar and sacral spines.

3. MODELLING THE UNBORN OCCUPANT: FETUS

At later stages of pregnancy, beyond 30 weeks, as the abdominal size increases, its proximity to the steering wheel during driving gets closer. Also in the later stages of pregnancy the amount of amniotic fluid surrounding the fetus, which is thought to offer some degree of protection, is at a minimum and the fetus occupies the majority of the uterine volume. It is therefore decided in this study to model a 38-week fetus and uterus, a very close to term, in order to create a model for the investigations where the pregnant women are most concerned [18].

The multibody model of the fetus is composed of 15 rigid bodies representing the different body regions of the fetus interconnected by kinematic joints. Each rigid body is defined by its mass, moments of inertia and its centre of gravity position. The geometric surface of the various body segments are represented by ellipsoids with dimensions estimated from fetal biometric measurements or scaled from anthropometric data of newborns found in the literature. Ellipsoids are positioned with respect to their parent rigid body. Kinematic joints connect the rigid bodies. Mass and moment of inertia properties of the segments along with the characteristics of the joints connecting them have been scaled from existing multibody models of infants. The details of geometry, mass and inertial

properties, joint properties and the contacts are given in this section.

3.1 Geometry

The anatomy of the 38th week fetus is represented by hyper ellipsoids, which require the specification of the lengths of the three semi-axes as well as the position of the centre and ellipsoid orientation relative to their parent rigid body. The dimensions of the various segments were mostly derived from a combination of fetal biometric measurements and scaling of anthropometric measurements from newborns. When direct fetal biometric measurements or newborn data is not available at all, existing infant and child models available in the MADYMO dummy database are scaled and used.

Head: Ultrasound measurements of the biparietal diameter (BPD) and occipito-frontal diameter (OFD) (measured from the outer borders of the skull) were used to define the semi-axes or the head [19-20]. The mean BPD (96mm) and OFD (115mm) measurements for a 38th week old fetus correlate well with the recorded mean head breadth (95mm) and head length (120mm) respectively of newborns [21].

Limbs: Ultrasound measurements of the fetal long-bones as presented in [22] were used to derive the semi axes of the leg and arm segments. For the femur or upper leg segment the measured bone length for a 38th week fetus was 76mm, this length defines the distance between the hip and knee joint in the model, the primary axes of the ellipsoid used to represent the segment is slightly longer to allow overlapping of the segments. Similarly for the tibia, or lower leg, the measured length of 66mm defines the distance between the knee joint and ankle joint. Foot length was obtained from [23]. For the arms measured bone lengths of 66mm and 61mm for the humerus and ulna

respectively have been taken from [22]. For the upper arm the humerus length defines the distance between the shoulder and elbow joints. No body is defined to represent the hands in the model so the ellipsoid used to represent the lower arms incorporates the added length of the hands.

Pelvis Abdomen and Torso: The measured abdominal circumference of 339mm for a 38th week old fetus measured and recorded by [19] was used to obtain a scaling factor for other trunk measurements where direct fetal measurements are not available. The mean waist circumference of 163 0-3 month old new-borns were recorded in [24] as 356.1mm. This gives a scaling factor of 0.95. This scaling factor was used to determine the ellipsoid dimensions of the pelvis and abdomen.

Table 1: Inertial and geometric data used for the rigid bodies of the fetal model.

| Name	Parent Body	Mass	Moments of Inertia			Origin of local coordinate system w.r.t parent coordinate system			Position of CoG		
			I_{xx}	I_{yy}	I_{zz}	s_x	s_y	s_z	g_x	g_y	g_z
		kg	kg.cm^2			mm			mm		
P1 Pelvis	Ref	0.42	19.0	14.0	17.0	0.0	0.0	0.0	2.6	0.0	5.6
A1 Abdomen	P1	0.12	10.0	10.0	10.0	-15.4	0.0	30.0	14.0	0.0	23.0
T1 Thorax	A1	0.62	54.0	31.0	32.0	0.0	0.0	55.0	0.1	0.0	43.0
N1 Neck	T1	0.08	10.0	10.0	1.0	0.0	0.0	57.0	0.0	0.0	27.0
H1 Head	N1	1.02	20.1	21.6	25	0.0	0.0	54.0	6.0	0.0	30.0
HL1 HumerusL	T1	0.11	5.0	5.0	1.0	5.0	43.0	63.0	-2.7	-1.9	-26.4
HR1 HumerusR	T1	0.11	5.0	5.0	1.0	5.0	-43.0	63.0	-2.7	1.9	-26.4
UL1 UlnaL	HL1	0.062	3.0	3.0	1.0	0.0	0.0	-65.0	-3.8	1.5	-41.7
UR1 UlnaR	HR1	0.062	3.0	3.0	1.0	0.0	0.0	-65.0	-3.8	1.5	-41.7
FL1 FemurL	P1	0.18	3.0	8.9	8.9	0.0	35.0	0.0	45.0	-2.8	-1.7
FR1 FemurR	P1	0.18	3.0	8.9	8.9	0.0	-35.0	0.0	45.0	2.8	-1.7
TL1 TibiaL	FL1	0.13	10.0	10.0	1.0	0.0	0.0	-76.0	-2.0	-4.0	-4.5
TR1 TibiaR	FR1	0.13	10.0	10.0	1.0	0.0	0.0	-76.0	-2.0	4.0	-4.5
FL1 FootL	TL1	0.04	1.0	1.0	1.0	0.0	0.0	-66.0	17.0	0.0	-7.0
FR1 FootR	TR1	0.04	1.0	1.0	1.0	0.0	0.0	-66.0	17.0	0.0	-7.0

3.2 Mass and Inertial Properties

An estimated fetal weight of 3.3kg, from [25] based on the biparietal diameter and abdominal circumference used in the model, was selected. This corresponds to the mean fetal weight (male and female averaged) of 3.28kg for

a 38th week old fetus. Segment weights were scaled from the TNO 9-month-old child dummy using the major dimensions of each segment to determine respective scaling factors. The mass of each segment is shown in Table 1.

The inertial properties of the fetus are lumped into the rigid bodies. The position of the centre of gravity of a particular body is given with respect to the local coordinate system of that body, g_x, g_y, g_z (Table 1). The positions of the centre of gravity for each rigid body were obtained from the TNO 9 month old child dummy, for each body segment a scaling factor was obtained from the respective ellipsoid surface in x, y and z directions and used to scale the CoG position for each axis. Table 1 also lists the CoG position for each of the rigid bodies in the fetus model.

The principle moments of inertia of each body are defined with respect to the centre of gravity and parallel to the local coordinate system. Non-linear regression equations for the estimation of segmental inertia properties of the human body is published in [26]. The equations were derived from anthropometric measurements and segmental moments of inertia taken from the study reported in [27]. The calculated moments of inertia of the various body segments of the fetus are given in Table 1.
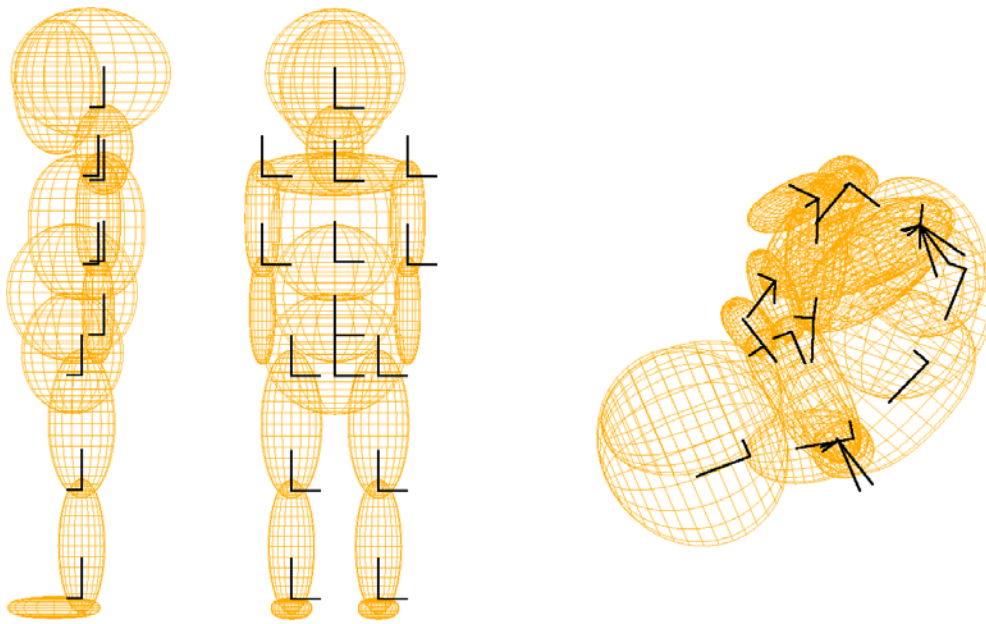
Figure 2 Left: lateral and frontal view of the fetus model showing the ellipsoid surfaces with their body local coordinate systems. Right: Lateral view of fetus model in fetal position.

3.3 Joint Properties

The pelvis forms the base of the model with its local coordinate system being the reference coordinate system of the model. The origin of the pelvis is located at the hip joint centre in the sagittal plane. The spine of the fetus model is divided into four joints: lumbar, thoracic, and lower and upper cervical. Spherical joints are used together with Cardan restraints consisting of three torsional parallel springs and dampers. The torques are dependent on the Bryant angles that describe the relative orientation between the two relative restraint coordinate systems. There are no translational degrees of freedom between the joints. The joint properties for the spinal joints are scaled from adult values found in the literature [28]. The hip, ankle and shoulder joints are described using spherical joints permitting three rotational degrees of freedom while the

knee and elbow joints are represented by revolute joints allowing one degree of freedom in the physical plane of rotation. Joint restraints are used to limit the range of motion of each anatomical joint within the physiological range of motion allowed for each joint for each degree of freedom. This resistance is modelled as a sharp linear increase in stiffness past the maximum allowed free range of motion in each direction.

3.4 Contacts

Due to the position the fetus takes within the uterus during pregnancy, it is expected that during an impact situation there will be a large degree of interaction between body regions. It was therefore important to model body to body contact between the various anatomical surfaces. A force-penetration characteristic is defined for each ellipsoid surface that is capable of coming into contact with another region of the body. The force-penetration characteristics for the various body regions of the fetus model are determined, based on the values used in the TNO dummy models, as actual values for these material characteristics are not available in the literature, and are shown in Figure 3. It follows that the head and pelvis are the stiffest sections of the fetus due to the large skeletal bones in these areas while the abdomen is the softest. The damping and friction coefficients of 30 and 0.3 respectively as used in the TNO child dummies are used in the fetus model for all body to body contacts. The effect of the amniotic fluid is simulated by Cardan restraint element [29], which consists of three torsional parallel springs and dampers. It is used to connect the pelvis of the pregnant female and pelvis of the fetus.
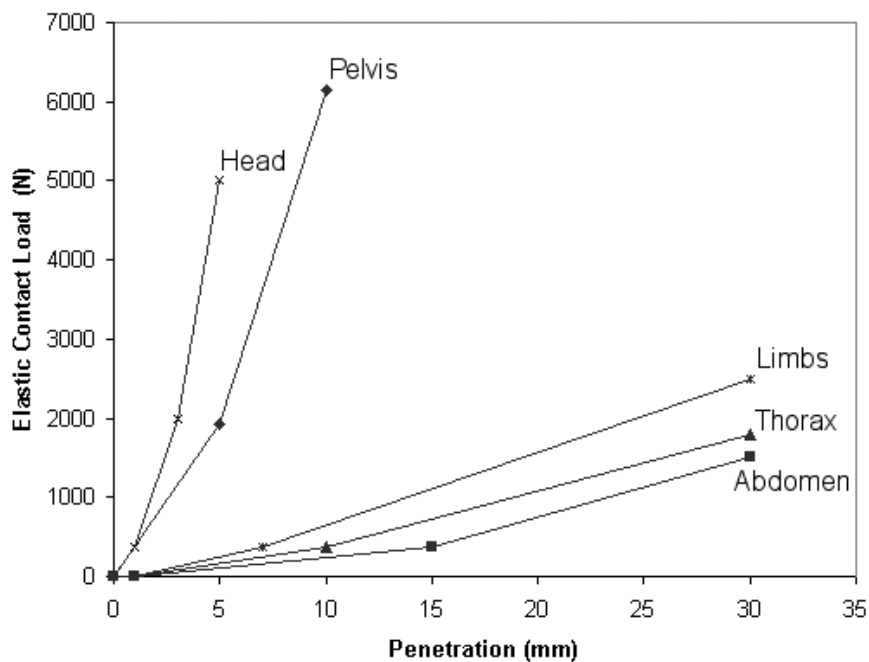
Figure 3 Force-penetration contact characteristics for the various body regions of the multibody fetus model.

## 4. THE ENVIRONMENT OF THE FETUS: 'EXPECTING'

Physical or computational models of the human body are usually validated against experimental tests on cadavers or live human volunteers. Typically, abdominal response of dummies are based on, or validated against force-deflection data collected from dynamic testing of cadavers. In the case of human fetus, due to ethical issues, there is no force deflection data based on cadaver or volunteer tests. This means that the fetus model cannot be validated in isolation in the sense that other models are validated, but the pregnant occupant model containing the fetus model could be subjected to rigid bar impact and belt loading tests for validation.

The detailed multibody fetus model is integrated into a finite element uterus model, which is later integrated into a female human model of MADYMO. The resultant pregnant woman model carrying a multibody fetus model is named 'Expecting'.

Generating the uterus and placenta; incorporating the 'bump' into the female model and validation of 'Expecting' are described in detail in [30]. Brief descriptions of the uterus, placenta and 'Expecting' are included in this section for completion.

4.1 Finite Element Uterus and Placenta Model

The finite element uterus model was developed in conjunction with the multibody fetus model with the fetal dimensions and configuration controlling the dimensions of the uterus based on data reported in [31]. This also provides a snug fit around the fetus. The material properties for the three components of the uterus model, namely the fat layer, uterus and placenta are similar to earlier FE uterus models without the fetus. For example, the uterine wall thickness is taken as 10mm [17]. Further 10mm of fat layer was meshed around the outer surface of the uterus. The placenta is generated as a discoid with a diameter of 185 mm and thickness of 20 mm at its centre which is gradually reduced to 4mm at the edges [16]. Two elements are used through the thickness of the uterine wall, fat layer and placenta.
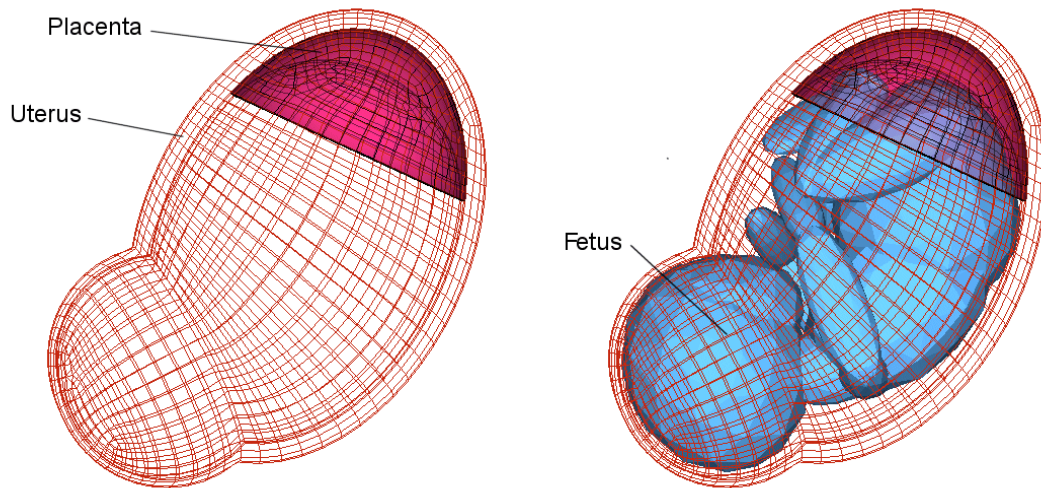
Figure 4 Side view of the FE uterus and placenta with and without the multibody fetus in position.

The uterus and placenta were meshed using Hypermesh (Altair) by first meshing the inner surface of the uterus using quad elements then mapping the elements to the outer surface to create the uterus, and mapping the corresponding elements of the placental outer surface to the inner surface of the placenta to create the placental elements. The nodal coordinates and element configuration was then exported into MADYMO where the first order 8 noded (3-D hexahedral) solid elements were used for FE components.

4.2 'Expecting' model

The multibody fetus, model of an unborn occupant and its environment were integrated into an existing multibody female model to complete the pregnant occupant model. The facet occupant model available within the MADYMO package represents a 5th percentile female, 1.52m in height and 49.8 kg in weight. The 5th percentile model was altered to represent the anatomy of a pregnant 5th percentile female using the anthropometric data collected from

female volunteers in their final trimester of pregnancy [31]. The outer nodes of the portion of the FE uterus that nestles within the pelvis bones are fixed relative to the pelvis body of the human model. The remainder of the uterus is reasonably free to move, its motion being restricted only by the contact relationships with the lumbar vertebrae and the skin surface of the MADYMO human model. The resultant pregnant woman model carrying a multibody fetus model is named 'Expecting'.
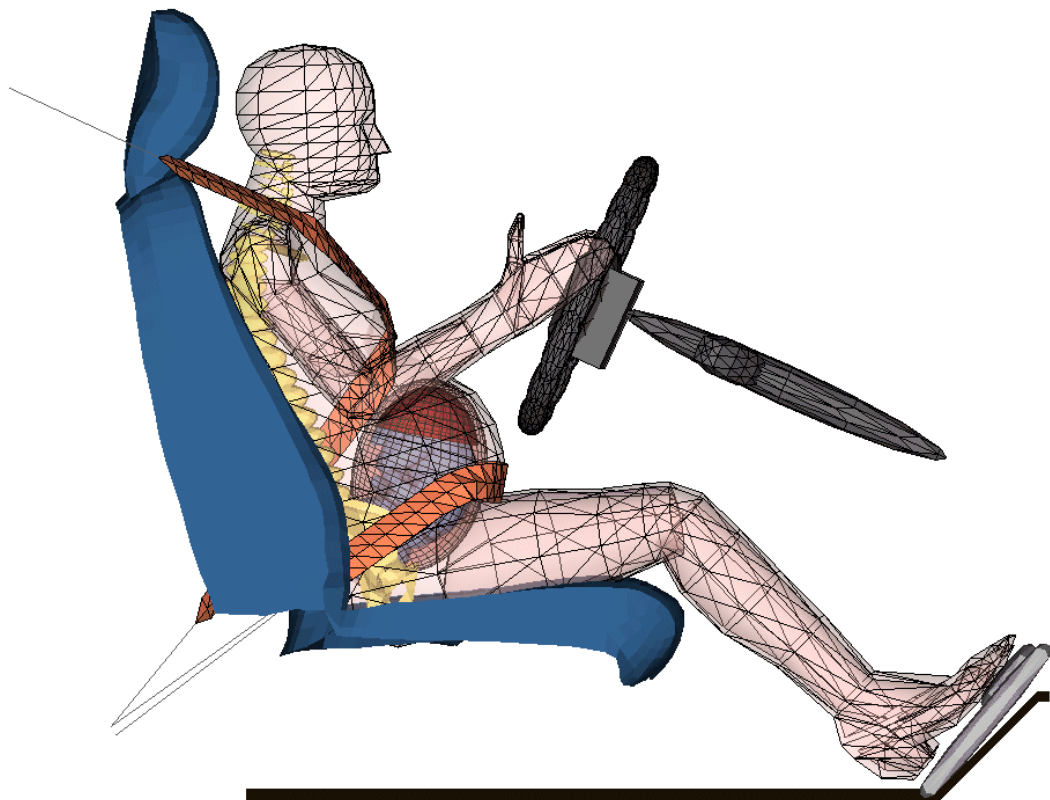
Figure 5. 38th week pregnant female occupant model 'Expecting' in vehicle interior from Acar and Van Lopik [30].

Rigid bar impact and belt loading tests were performed by earlier researchers and the force-deflection abdominal corridors were developed for the 50th

percentile male [32]. As no other data is available these corridors are scaled and used in the development and validation of the 5th percentile pregnant female physical and computational models, including 'Expecting'. The comparison of a number of crash simulations and predictions by using 'Expecting' and earlier pregnant woman models are reported in [30]. Various other scenarios are simulated to investigate the fetus and pregnant woman's safety in [33-36]. Simulations and analysis indicate that taking unborn occupant into consideration is much more realistic modelling. For example, Figure 6 demonstrates the von Mises stress distribution in the uterus at 60 ms of a frontal crash with Δv=25kph. Pregnant occupant is restrained by a three-point seatbelt, the fetus continues to move forwards due to inertia and is forced against the anterior wall of the uterus, causing stress concentration points from loading of the head, shoulder and pelvic regions. Further observations of these movements and calculation of strains at the utero-placental interface can suggest placental abruption based on an accepted strain thresholds.
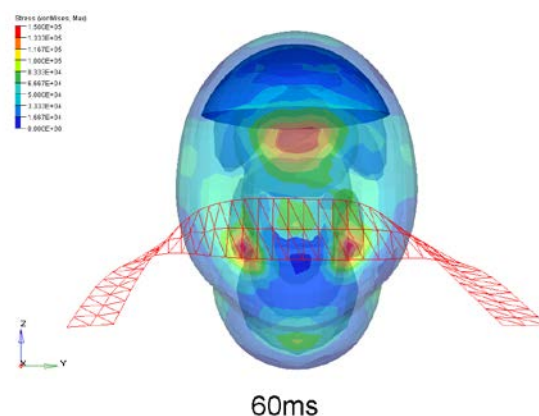
60ms

Fig 6 Frontal view of fetus and uterus demonstrating stress concentration points from loading of the head, shoulder and pelvic of the fetus at 60 ms of Δv=25kph 3-point belt test.

5. DISCUSSION

Earlier physical and computational models of pregnant woman in her third trimester do not carry a fetus in them. The fetus fills the uterus almost completely towards the end of pregnancy. It is considerably solid, has approximately 3.3 kg of mass and is relatively free to move within the uterus. It is essential to include a fetus model within a uterus model for a realistic pregnant woman model. Placental abruption is the main cause of fetal mortality in road traffic accidents and it can be predicted by the strains at the utero-placental interface and it is the only quantifiable injury criterion for the fetus. Even if the fetus itself does not physically impact the placenta and directly cause placental abruption during an impact, its existence alone has the potential to affect the dynamic response of the pregnant occupant and the strain levels at the utero-placental interface.

'Expecting' is the only known pregnant occupant model in the world which incorporates a detailed fetus model. In this article, generating a multibody model of a fetus is explained in detail for the first time. The authors acknowledge the fact that the unborn occupant model cannot be validated in the traditional sense. However, 'Expecting' is used in predicting fetus safety in real-life accidents case studies and full agreement is achieved between the predicted and accident outcomes.

The fetus model presents an opportunity to predict fetal movements as opposed to 'no fetal movements' in earlier pregnant woman models. During an accident, inertial effects on the fetus cause it to move forwards relative to the pregnant occupant as the restraint systems restrict the expectant mother's motions. The

fetus model provides an opportunity to observe the stress concentration points. There is a very good indication that the unborn occupant model truly represents an unborn occupant within the model of an expectant mother. Despite the limitations, the first multibody fetus model is generated and reported here starts the life for future generation of research on unborn occupant modelling.

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