'Expecting': occupant model incorporating anthropometric details of pregnant women

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Abstract: This study reports the research for a design tool related to pregnant women's safety during car travel. Anthropometric measurements are taken to generate an occupant model incorporating pregnancy related changes. These anthropometric changes mean that a pregnant occupant may be excluded by the designs, based upon non-pregnant female anthropometry. The paper explains the generation of a comprehensive parametric computer aided model of a pregnant occupant, 'Expecting'. The model can represent different size pregnant occupants as well as the size differences occurring in standing and seated postures. This model can be used as a design tool for automotive designers to help ensure that vehicle designs can accommodate the anthropometric needs of the pregnant occupants.

Keywords: pregnant; occupant; model; driver; safety; comfort; anthropometry; design.

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1 Introduction

Every year, there are approximately 670,000 pregnant women in the UK (Office for National Statistics, 2000), the majority of whom are likely to be car occupants during some or all stages of their pregnancy. More women are driving today and driving longer distances than ever before (Haapaniemi, 1996) and subsequently, increasing number of pregnant women are being exposed to automobile accidents. It has been estimated that around 130,000 women in the second half of pregnancy are involved in car crashes annually in the USA (Klinich et al., 1999). Of these, around 30,000 will sustain treatable injuries, while approximately 160 will die. Of those that survive, between 300–3,800 will experience a fetal loss (Klinich et al., 1999) making motor vehicle crashes the leading cause of traumatic fetal mortality (Weiss et al., 2001). Placental abruption, uterine rupture, direct fetal injury and maternal mortality have been identified as the main causes of immediate fetal death. Placental abruption has been shown to account for 50% to 70% of all fetal losses following motor vehicle crashes (Pearlman et al., 1990). Little is known about the delayed effects of car accidents on pregnant women and on adverse fetal outcomes.

The safety of pregnant women can be compromised due to the body size and shape changes that occur during pregnancy. Anthropometric changes occur throughout the body and are not limited to the abdominal region (Acar and Weekes, 2005). Changes in the abdomen, chest and hip regions are particularly important because they can influence the fit and positioning of the seat belt during pregnancy (Acar and Weekes, 2005). The correct position for the seat belt has been established so that the shoulder section passes between the breasts and around the abdomen and the lap section passes across the hips and underneath the bump (Crosby et al., 1972). This position has been adopted by governmental safety guidelines, both in the UK (DFT, 2003) and the USA (NHTSA, 2002). However, only 13% of pregnant women are actually able to position their seat belt correctly (Acar and Weekes, 2005, 2003). Some pregnant women do not use the seat belt due to safety concerns and discomfort and others may take unsafe actions such as holding the belt away from the body during car travel, which may prevent it from functioning correctly (Acar and Weekes, 2003). Pregnant women and their fetuses may not be adequately protected by their seat belt if it is incorrectly positioned or not used.

Another cause of concern in pregnancy is increased abdominal protrusion toward the steering wheel. Acar and Weekes (2005) found that 11% of pregnant women were seated with less than 2.5 cm between the abdomen and the steering wheel or with their bump actually in contact with the steering wheel. This proximity to the steering wheel may put the placenta at increased risk of abruption from direct impact with the steering wheel (Aschkenazi et al., 1998). Abdominal depth is defined as the ‘maximum horizontal distance from the vertical reference plane to the front of the abdomen in standard sitting position’ (Pheasant, 1996). The abdominal depth data can be used to define the clearance between the steering wheel and the occupant. Pheasant (1996) suggests that adequate clearance is defined by lower limb length and abdominal depth. He states that 95th percentile abdominal depth with the seat in the foremost position should be used, but states that it is even better to use abdominal depth of a pregnant woman (Pheasant, 1996). However, Pheasant only provides abdominal depth and forward grip reach data for pregnant women, without providing data for the rest of the body, making it difficult to accurately represent the needs of the pregnant occupant since the size of the fetus and hence the abdomen is not necessarily related to pregnant woman’s stature.

It is important for automotive designers to consider the changed shape and size of pregnant women to ensure that the pregnant occupant is not excluded from designs. This is particularly imperative if the type of car is designed and marketed for women of child-bearing age. Acar and Weekes (2004a) introduced an anthropometry website for use by automotive designers, so that pregnant occupant anthropometry can be incorporated into vehicle design. This anthropometric data has been collected as part of the ‘Automotive Design: Incorporating the Needs of Pregnant Women’ project based at Loughborough University. The pregnant anthropometry has been used to generate the pregnant occupant model presented in this paper. The model is a design tool for automotive designers to help ensure that vehicle designs can accommodate the anthropometric needs of the pregnant occupant.

2 Method

In this study, 48 anthropometric measurements were taken from 100 pregnant women. The details of this sample of pregnant women are provided in Table 1. The measurements recorded were adapted by the authors for pregnant women based on standard anthropometric postures (Pheasant, 1996). Women were recruited in two locations in the UK: Loughborough University and the Luton & Dunstable Hospital National Health Service Trust. Volunteers removed their shoes and wore light clothing. The equipment used included weight scales, an anthropometer, a digital vernier calliper, a stadiometer and a tape measure.

Table 1 Pregnancy and driving details of the sample of pregnant women

	Second trimester (Weeks 13–28)	*Third trimester (Weeks 29–40+)*
Number of volunteers	35 women	65 women
Mean week of pregnancy	21.6 weeks	35.5 weeks
Std. dev. week of pregnancy	4.5 weeks	2.8 weeks
Driver	34 women	52 women
Non-driver and unknown	0 and 1 women	4 and 9 women

The first comprehensive analysis of the anthropometry of pregnant women throughout the entire body, specifically for the automotive industry, is presented in an *International Journal of Vehicle Design* paper by Acar and Weekes (2006). The paper classified the measurements in four groups: weight and stature, head and shoulders region, trunk region and limbs. The analysis of every parameter is given in detail in the paper and it was concluded that the whole body measurements provide an insight to the changes, however, the most significant changes during pregnancy occur in the chest, abdominal and thigh areas.

The relevant trunk region measurements (i.e., chest, abdominal and thigh area) which are illustrated in Figure 1 are incorporated in the generation of ‘Expecting’: the Pregnant Occupant Model.

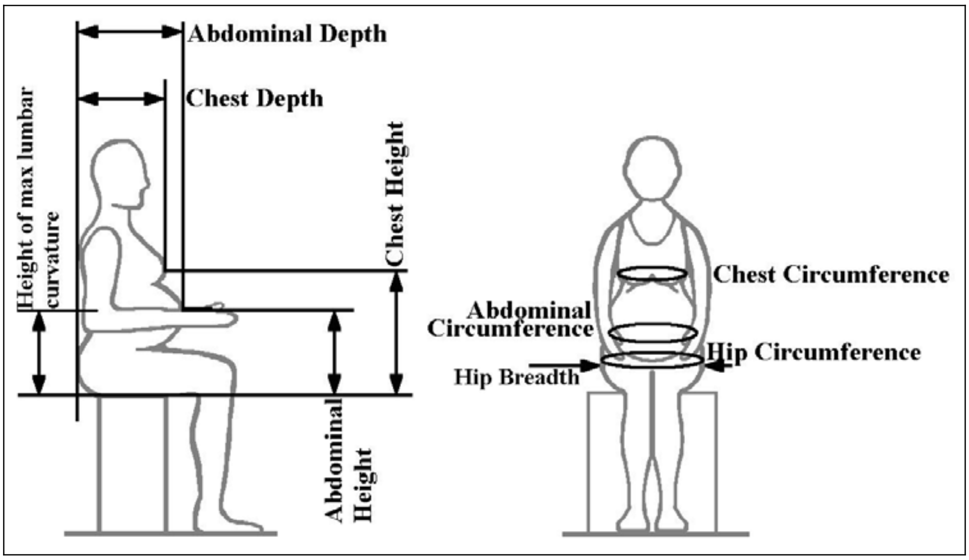

Figure 1 An illustration of the trunk region anthropometric measurements

3 Exclusion from design

The typical engineering practice involves producing designs to accommodate 90% of the population by accommodating people between the 5th and 95th percentiles. However, the anthropometric data available for UK females in Adultdata by DTI (1998) does not include measurements of pregnant women. If this data for non-pregnant women is used in a design and no consideration of pregnant women is made, then the design will not accommodate the changed anthropometry of pregnant women. For example, the abdominal depth of pregnant women is greatly increased by pregnancy. The mean abdominal depth of pregnant women measured in the third trimester is 359.5 mm. This is significantly ($p<0.03$) larger than the mean abdominal depth for non-pregnant women given by Acar and Weekes (2006) of 269.9 mm. The impact of this difference between the abdominal depths of pregnant and non-pregnant women is clearly illustrated by the difference of the two curves in Figure 1. The mean abdominal depth of non-pregnant females corresponds to the 1st percentile for pregnant women in the third trimester. This means that 99% of third trimester pregnant women might be excluded by a design based on the 50th percentile non-pregnant female anthropometric data, as shown in Figure 2.

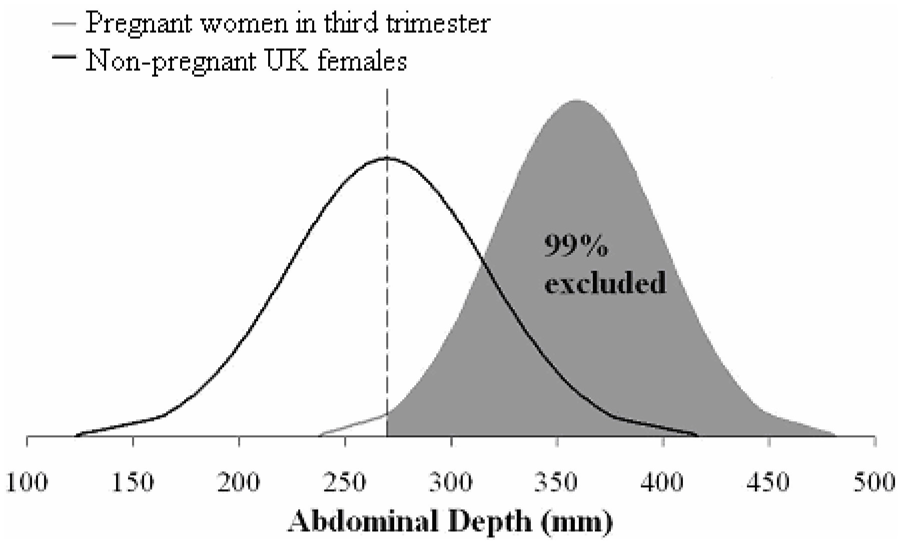

Figure 2 Abdominal depth distribution of non-pregnant UK female data* and that of pregnant women in third trimester**
Source: *DTI, Adultdata, London (1998) and **measurements from this study

Even if a design is produced to accommodate the 95th percentile large female, it still may not accommodate up to 62% of pregnant women in the third trimester, as shown in Figure 3.

Furthermore a design produced to accommodate a large 95th percentile male might not accommodate 65% of pregnant women in the third trimester, as shown in Figure 4. Using the 95th percentile male anthropometry as the upper limit might be inadequate for accommodating pregnant women because the women are so physically altered by pregnancy.

Abdominal depth is not the only example of analysed anthropometric data. Similar to the abdominal differences, a change in the chest circumferences and chest depth give an understanding of how much the breasts enlargement can potentially affect the comfort and safety of pregnant women. The increasing size of the breasts can affect how the seat belt fits around the breasts and stays in position to avoid cutting into the neck during car travel. The increasing chest depth also means that the breasts are closer to the steering wheel. The exclusion rate for a design that accommodates up to the 95th percentile male is 49% in seated posture. Using the non-pregnant female 95th percentile data as the limit for accommodation might still exclude 36% of pregnant women.

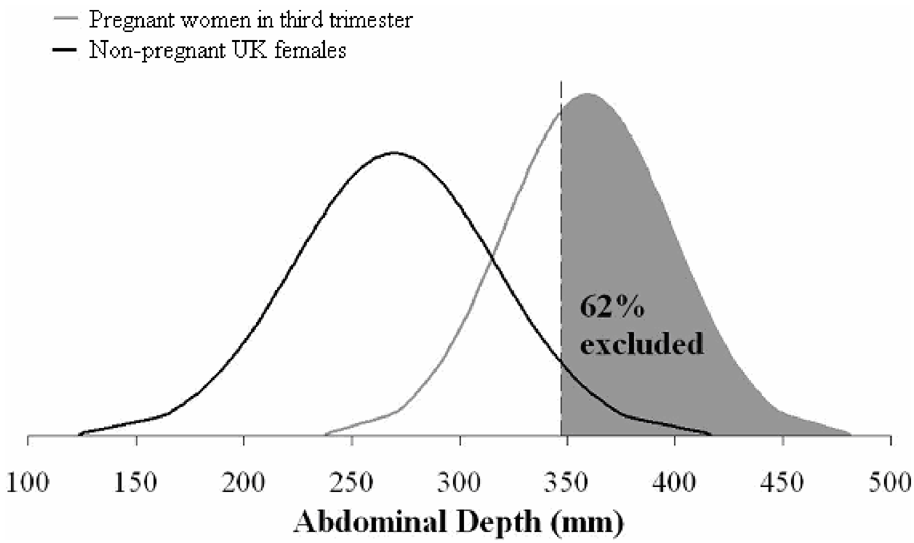

Figure 3 Abdominal depth distribution of non-pregnant UK female data* and that of pregnant women in third trimester**

Source: *DTI, Adultdata, London (1998) and **measurements from this study

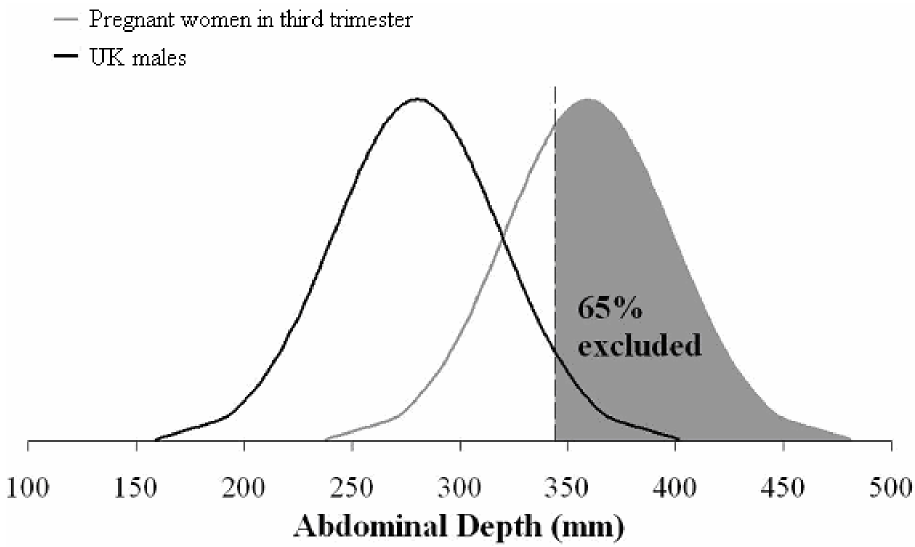

Figure 4 Abdominal depth distribution of UK male data* and that of pregnant women in third trimester**

Source: *DTI, Adultdata, London (1998) and **measurements from this study

Automotive designers can avoid excluding pregnant women from designs by incorporating pregnant occupant anthropometry into the designs. Detailed description of the generation of ‘Expecting’, Loughborough University Pregnant Occupant Model is given in the following sections.

4 Pregnant occupant model

The unique anthropometric measurements from pregnant women, collected in the first stage of this research, are used to develop a parametric model of the pregnant female occupant. The aim is to produce a tool that will facilitate the production of a three-dimensional model of a pregnant woman of any size and at any stage of gestation.

The underlying structure of the model is based on the kinematic linkage model of the MADYMO 5th percentile female facet occupant, developed by TNO Automotive (2003). The positions of the various kinematic joint centres, representative of actual joints in the human body, are positioned relative to the hip joint centre or ‘H’ point. Corresponding joint centres are connected by a rigid link, which can be thought of as the ‘bones’ of the model. The basic arrangement of the linkage model is depicted in Figure 5 showing how the joint centres are connected to form the body.

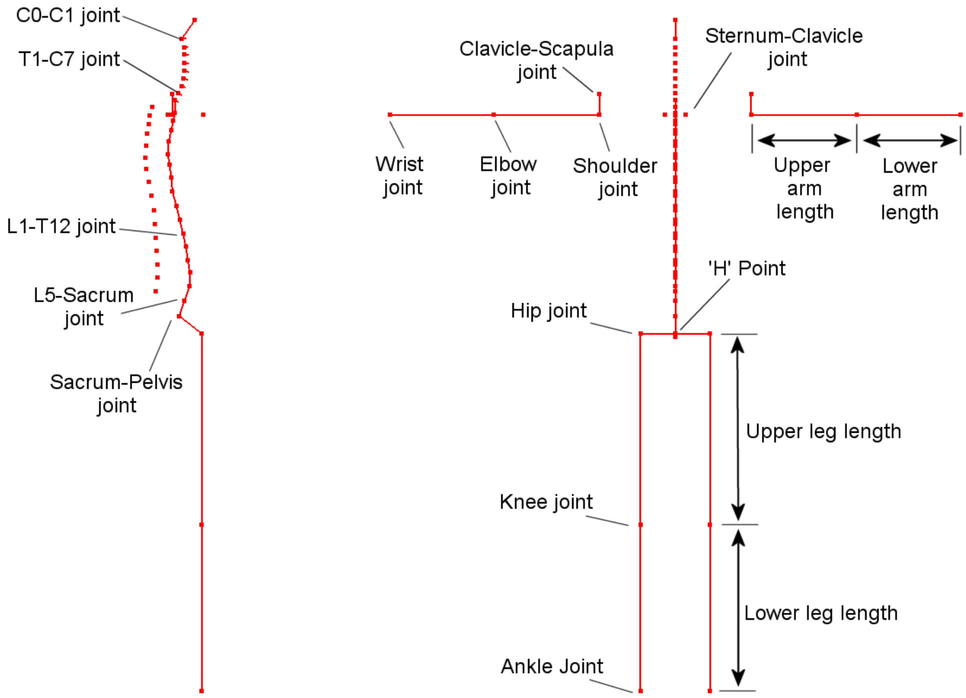

Figure 5 Kinematic linkage model of the MADYMO 5th percentile female facet occupant model

The three-dimensional geometric surface of the model is constructed from a series of cross sections that are positioned relative to their parent ‘bone’ linkage and derived from the anthropometric measurements of pregnant women. For example, the cross section of the knee, positioned at the knee joint, has a width equal to half the measured knee to knee breadth and a depth equal to the difference between the measured sitting distance for buttock to the front of the knee and buttock to the back of the knee. The model has been developed in an upright standing position with arms horizontal and out to the sides, allowing for easy application of standard anthropometric measurements and enabling all the body cross sections to be orientated either horizontally or vertically.

To describe the pregnant abdomen, the sagittal plane abdomen contour is defined by three points positioned relative to the ‘H’ point, they are: the pubic symphysis, the point of maximum abdominal height and depth, and the xiphoid process (bottom of sternum). For the initial model, the point of maximum abdominal height and depth representative of a 5th percentile woman in her 30th week of pregnancy has been used. Figure 6 shows the model; all the cross sections used to define the geometric surface are shown along with the underlying segment linkages.

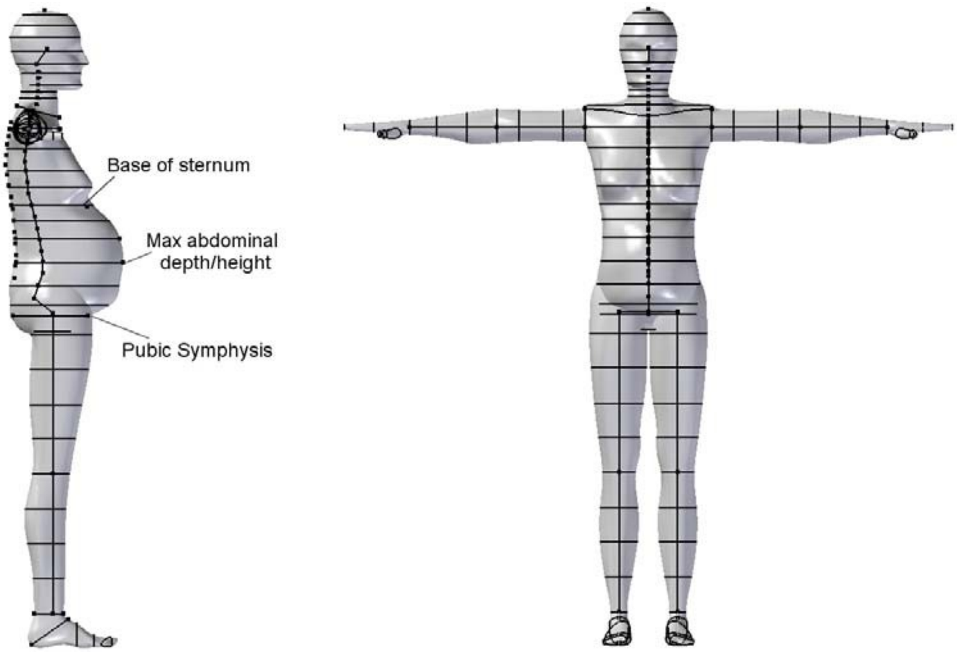

Figure 6 Side and front view of the pregnant female model

Note: In the side view, the points defining the abdomen contour are labelled.

The pregnant female model can be easily scaled to represent women of different statures and to embody the unique changes experienced at any stage of the gestational period. A second anthropometric study measuring a series of bony landmarks of pregnant women in driving postures is undertaken to enable the scaling of the current model. Calculation methods as presented by Reed et al. (1999) are used to determine joint locations from measured exterior landmarks. For the legs, the positions of the lateral femoral condyle (bony surface on the outside of the knee) and the lateral malleolus (bony surface on the outside of the ankle) are recorded, along with pelvic width and depth, to allow the positions of the knee, ankle and hip joints be calculated. The positions of these joints in the model can be adjusted to change the lengths of the upper and lower parts of the legs accordingly. Similarly, the positions of the joints of the upper extremity can be determined from the measured positions of the wrist, lateral humeral condyle (bony surface on the outside of the elbow), and acromion landmarks and used to adjust lengths of the upper and lower parts of the arm of the model.

To adjust the length of the spine, a series of measurements are required to determine the positions of important transitional joints as shown in Figure 5. The position of the upper neck joint, C0-C1, also known as the atlanto-occipital joint, can be determined from two measured landmarks on the head. The lower neck joint, C7-T1 is calculated using the measured positions of the suprasternale and C7 spinous process surface landmarks. The relative positions of these two joints thus define the length of the neck. The length of the thorax is defined as the distance between the lower neck joint, C7-T1, and the upper lumbar joint, T12-L1. The position of the upper lumbar joint can be found by using the measured position of the spinous processes of T8 and T12. Finally, the lower lumbar joint, L5-Sacrum can be calculated using the measured pelvis width and depth. Pelvis width is defined as the distance between the left and right anterior superior iliac spines (ASIS) and pelvic depth as the distance between the left (right) ASIS and the left (right) posterior superior iliac spine.

In order to take into account the various size changes experienced during pregnancy, the individual cross sections of the model can be scaled to change the circumferences of any body element as required. In particular, the size and shape of the abdomen can be altered by moving the point of maximum abdominal height and depth accordingly.

5 Sitting and standing

Pregnant women may be inappropriately represented if the anthropometric data is taken from an unrepresentative posture. For example, for pregnant women in the third trimester, the mean 'seated hip circumference' is 1,249.8 mm, which is 94.6 mm larger than the 'standing hip circumference'. It is important to use anthropometric data measurements taken from the seated posture in designs where the user will be seated. The abdominal and chest sizes are also greater in seated position than in standing, which reinforces the importance of using the appropriate anthropometry from a relevant position.

The difference in standing and seated anthropometry occurs because the soft tissue spreads outward from the body in the seated position. The seat applies pressure to the buttocks causing the hip tissues to spread. The thighs make contact with the base of the abdomen in the seated posture (Acar and Weekes, 2005), which reduces the space available for the abdomen and causes the abdomen to spread outward from the body. The abdomen is pushed upward and outward from the body, which applies pressure on the breasts and causes the soft tissue around the chest region to spread. Pregnancy exaggerates this spreading effect in seated position and using the anthropometric data recorded from a relevant position is even more important when the subjects are pregnant.

Automotive designers can accommodate the difference between seated and standing sizes by using the anthropometric data of the pregnant occupant in the appropriate positions. For example, only the seated anthropometry should be used in the design process of vehicle interiors.

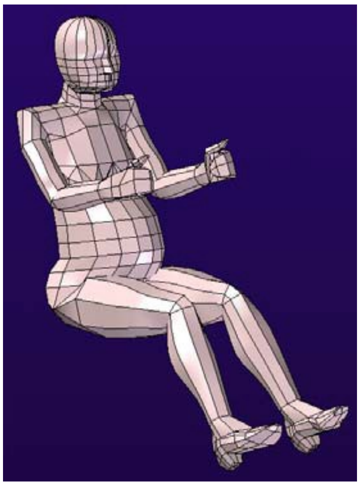

Figure 7 Pregnant occupant model in driver position

Note: Dimensions are changed according to the seated anthropometric data of pregnant women.

Acar and Weekes (2004b) analysed 450 questionnaire responses filled in by pregnant women and concluded that the restricted movement that women experience during pregnancy causes them to alter their method of vehicle entry and egress. For example, when women are getting in to the car, they tend to separate the movement into two stages. The two separate motions are first to sit down on the seat whilst facing laterally out of the door opening, then secondly, to swivel to face the front of the car whilst lifting their legs in. This is a different technique compared to before pregnancy, when women would normally move from standing to seated in the car in one fluid motion. The reverse of the two-stage entry method is used for vehicle egress.

Hence, during entry into the vehicle and egress out of the vehicle, the occupant moves between the standing and seated postures so the body undergoes transition between sizes. This transition between postures should be accommodated during the design of door openings and for determining the clearance between the seat and the steering wheel. The cross sections in the model can be altered to take into account the size changes between standing and sitting postures and the deformation of the buttocks when sitting.

6 Discussions and conclusions

This paper presents the importance of considering pregnant occupant anthropometry for vehicle designers. Using anthropometric data for males or non-pregnant females might exclude pregnant women from being accommodated in the automotive interior designs. Even using large male (95th percentile) data can be inadequate for this purpose. It is also important to consider the difference in size for seated and standing positions that occurs during pregnancy.

The most important recommendation to automotive designers and motor manufacturers is using appropriate anthropometric and geometric models of pregnant women, which incorporate anthropometric data taken from the relevant positions, if they would like to include pregnant occupants in their design. General recommendations such as availability of adaptable integrated seat belts, adjustable pedals, retractable steering wheels including the pregnant population as discussed by authors in detail (Acar and Weeks, 2005) would not exclude the non-pregnant and male populations and may also include further populations such as overweight occupants whose numbers are increasing all over the world and also small-stature occupants.

Furthermore, cars are usually the second most expensive items bought by families. Considering the comfort and safety issues for pregnant occupants without affecting the comfort and safety of non-pregnant occupants might be expected as a bonus and a selling point of family-friendly cars since more women are travelling today and travelling longer distances than ever before and a subsequently increasing number of pregnant women are being exposed to automobile accidents.

A comprehensive parametric pregnant occupant model representing pregnancy is presented as a design tool that can be used to evaluate vehicle safety systems and interiors to help improve the pregnant occupants' safety.

The model has the ability to be scaled between the standing and seated posture sizes of the pregnant occupant. This is particularly advantageous to designers to help meet the anthropometric needs of the pregnant women in both positions. Other examples of specific safety concerns that can be addressed using the pregnant occupant model include the seat belt positioning, steering wheel clearance and head restraint geometry.

The work described in this paper is part of a comprehensive research program at Loughborough University to improve pregnant occupant safety using a computational pregnant occupant model for crash protection. The overall aim is to produce a pregnant occupant model capable of simulating the dynamic response to impact and predict the risk of injury in automobile crashes.

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