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Pregnant Female Anthropometry from CT Scans for Finite Element Model Development

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ABSTRACT

Approximately 800 fetal losses occur each year in the United States due to motor vehicle crashes. Changes during pregnancy drastically alter the abdominal anatomy of the pregnant female. Pregnant occupants involved in motor vehicle crashes are at risk for pregnancy-specific injuries, such as placental abruption. In this study, anthropometry data is collected from an abdominal CT scan of a pregnant woman at 32 weeks gestation. A scan most representative of a fifth percentile female in the early 3rd trimester with a healthy fetus and no abdominal injury was selected for analysis from available abdominal computed tomography (CT) scans taken over the past ten years. Using medical image analysis software, masks of the fetus, uterus, placenta, and each of the maternal abdominal organs are created by segmentation of the CT slices. The volume and Hounsfield unit ranges for the masks of each abdominal organ are calculated. The total volume of the uterus is 3378 cm^3. The total volume of the placenta is 687.7 cm^3. The masks are used to render three-dimensional volumes of each of the organs. By measuring the length of seven different sets of bones on the fetal skeleton from the CT slices and the 3D rendering, the gestational age of the fetus is estimated to be 32.2 ± 1.9 weeks by comparison with literature values, which matches the estimated gestational age of 32 weeks predicted by emergency room staff. Anthropometric measurements confirm the woman is within one standard deviation of 5th percentile. Measurements of each of the abdominal organs are obtained from the 3D rendering to create a blueprint of the pregnant anatomy. The uterine wall thickness is found to differ in the superior-inferior direction, with average uterine wall thickness 6.80 ±0.72 mm. The placenta thickness varies along its attachment at the UPI and is thickest at the fundus. After creating an accurate FE model of the UPI, improved geometry may help to predict the occurrence of placental abruption. The masks created and the anthropometric measurements taken will be used to develop a more accurate FE model of the pregnant female for use in research and development in academia, industry, and government.

INTRODUCTION

Motor vehicle crashes (MVCs) caused 42,642 deaths in the United States in 2006 (NHTSA 2007). MVC's involving pregnant mothers are reported as causing a minimum estimated 856 fetal losses each year in the United States (Manoogian and Duma, 2008). This data demonstrates the need for an accurate crash test model of the pregnant female at different stages of pregnancy. This paper introduces methods and data for creating an anthropometrically correct pregnant female to incorporate into a finite element model of the female for use with virtual crash tests.

In the latter stages of pregnancy, the gravid uterus causes obvious changes in the anthropometry of the abdomen, potentially predisposing the abdomen to trauma during MVC. Common injuries to a pregnant female after a MVC include: excessive bleeding, placental abruption, uterine rupture, and premature delivery (Hyde et al., 2003). When the mother does not receive serious injury from MVC, the fetus can receive fatal injuries (Agran et al., 1987; Bunai et al., 2000; Farmer et al., 1990). The most common fatal injury for the fetus when the mother survives blunt force trauma, such as that sometimes experienced in a MVC, is abruptio placentae (Crosby and Costiloe, 1971). This is caused by a shearing effect between the placenta and the uterus during rapid impact and deceleration (Crosby and Costiloe, 1971). The uterus can be torn from the placenta due to the rebound of the uterus after the impact has occurred. Often, this injury is not evident until it is too late to save the fetus (Connolly et al., 1997).

An accurate pregnant model could be used to research the protective effect of current restraint systems and could be used to develop new restraint system advancements to protect mother and unborn child. It has been suggested in the literature that pregnant females should turn off their airbags during the late stages of pregnancy. Researchers have hypothesized that inflation of the airbag could cause higher contact forces on the abdomen with a gravid uterus because the abdomen is closer to the steering wheel (Aschkenazi et al., 1998). An anthropometrically correct model with detailed anatomy would be helpful to determine the results of airbag deployment in MVC involving pregnant females. An accurate pregnant female model could test some of the common proposed injury mechanisms to make public health recommendations on the best methods for travelling safely in a vehicle while pregnant.

Changes during pregnancy drastically alter the abdominal anatomy of the pregnant female. In this study, a CT scan from an early 3rd trimester pregnant female is segmented using medical imaging software, and 3D models of the pregnant abdomen are created. This study investigates the anatomy of a pregnant female and seeks to determine gestational age by measuring 3D renderings of the fetus from CT scan data.

METHODS

A scan most representative of a fifth percentile female in the 3rd trimester with a healthy fetus and no abdominal injury was selected for analysis from available abdominal computed tomography (CT) scans taken over the past ten years. Scans were acquired due to trauma suffered by the mother, but not included if abdominal or pelvic trauma affecting the anatomy was identified. Scans were reviewed by a radiologist (EY Anthony) for inclusion in the study. Our final candidate was a 22 year old who was estimated by Emergency Department personnel to be 32 weeks gestation. The selected scan was imported into a medical image analysis program (Mimics) as a compressed CT scan using the program's automatic file import feature. The 3D medical image processing and editing software was used to segment the CT scan into masks to create 3D models of the uterus, placenta, volume inside the uterus, fetus, fetal skeleton, maternal skeleton, and maternal internal organs.

The masks of the pregnant subject were created using a combination of automatic functions available in the software and manual editing with the aid of a touch screen monitor. After the fetal skeletal mask was created, the gestational age of the fetus was estimated using a 3D measurement tool provided by the software. The fetal skeleton 3D rendering was used to measure the crown-to-heel length, foot length, femur length, and humerus length. A combination of the 3D rendering and fetal brain CT slices were used to measure the occipitofrontal and biparietal skull measurements. For accuracy, the crown-to-rump length measurement and rump-to-heel length measurement were added together to get the total crown-to-heel length measurement. The foot length was measured from toe to heel on each foot, and these measurements were averaged. Each femur, humerus, and foot length was measured for each side of the body and averaged. The measurements were compared with literature values to estimate gestational age (Chatterjee et al., 1994; Fetus Growth Charts, 2007; The Medical Algorithms Project, 2007). At this stage of gestation, clinicians estimate that all gestational approximations are ±3 weeks accuracy.

The placental mask was created differently than the other masks in order to ensure a correct uteroplacental interface exact fit. The placental surface adjoining the uterine wall mask was defined using a Boolean operation to subtract the uterine wall from the placental mask. This allowed for a uniform assessment of the uterus-placental attachment. A mask was next created to define the volume inside the uterus and placenta. This mask was created using the cavity fill function. A single layer cavity fill was performed on each slice of the uterine wall and placenta mask so that a new mask defining the inner volume of the uterus was created. A Boolean operation was performed to subtract the placenta from the volume mask. The resulting mask was the volume interior to the uterine wall and placenta.

Once initial masks and 3D objects were created, the smoothed uterine wall 3D object was used to create a smoothed uterine wall mask. Coordinates for mask pixels were exported as a text file and imported into Matlab using export gray values function available in Mimics. Uterine wall coordinates were exported and placed into a coordinate matrix using Matlab (The MathWorks, Natick, MA). This coordinate matrix was converted to an image file and was cropped based on a given range and stored in a cell. These cells were retrieved by a second file that found the outer region of the image using the *bwlabel* function in Matlab. The area, outer perimeter, and inner perimeter of the region were calculated and cavities in the mask were filled. Average thickness values for each slice were calculated by dividing the area by the average perimeter. In this way, the average uterine wall thickness was calculated for each serial slice.

The smoothed placental mask was exported into Matlab and thickness values were obtained for portions of placenta attached to anterior and posterior walls of the uterus. For the inferior placenta, where only the anterior portion of the placenta can be seen on the slice, the anterior side was region one. For the superior placenta slices, where anterior and posterior portions of the placenta were present, there were two regions. A thickness subfunction calculated the maximum of the y-coordinate as the starting point as each of the regions were read. The boundary was traced clockwise for the anterior side (region 1) and counterclockwise for the posterior side (region 2). Smoothing was used to average the number of points and regress into a tangent line. The perpendicular line to this tangent line was found through the simple slope reciprocal. Each perpendicular was cut off using the binary image as a mask and resulting line lengths were calculated. These calculations were then exported to Microsoft Excel where they were put into a table format and a plot was created with the data. Placental thicknesses were displayed in Matlab in serial slices to visually depict superior to interior variation in the thickness of the structure.

From volume renderings, measurements were taken for each region of the pregnant female using the 3D measurement tool. Measurements were used to find length, height, width, and depth in each anatomical plane for each region. These provide an anthropometric blueprint of the pregnant female's abdomen.

RESULTS

The following results were found by creating masks of a pregnant female abdomen and all internal structures from transverse slices of a CT scan. All of the results are from the same individual in her 3rd trimester without any anatomical irregularities.

By measuring the distance between T8 and T12 on the female's spine in the CT scans, it is estimated that she is a 5th percentile female in stature, as shown in Table 1 (Schneider et al., 1983). The T8-T12 distance of 101.51 mm is in the range listed for a female of this size. Her size had to be estimated using T8-T12 height from the CT scan because her height and weight were not available in medical records. She appeared to be of normal to low weight as evidenced by the subcutaneous fat in the abdomen.

Table 1. Female T8-T12 size, based on ranges for a 5th percentile female.

Small Female Measurement	
Description	**T8-T12 Measurement (mm)**
Pregnant subject	101.51
Literature mean	128.88
Literature low	94.82
Literature high	135.37

Figure 1 shows how the uterus is positioned within the abdomen. This shows how crowded the abdomen has become in this stage of pregnancy. The intestines and other abdominal organs have been displaced superiorly by the enlarged uterus. Figure 2 shows crowding of the fetus within the uterus and placenta location in the fundus.

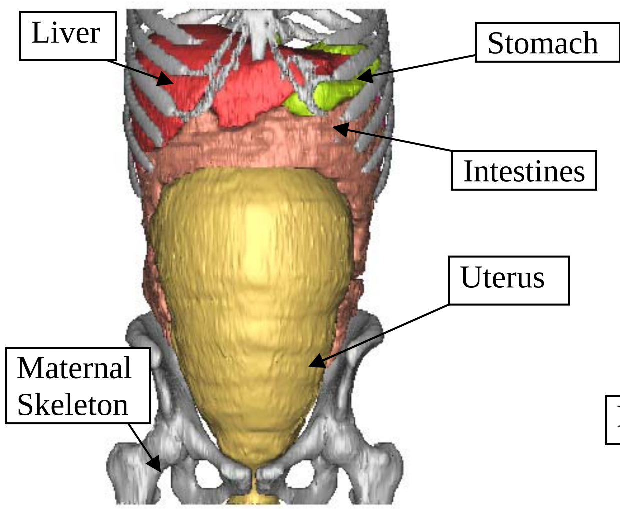

Figure 1: Anterior view of pregnant female masks with fat, skin, and muscles removed.

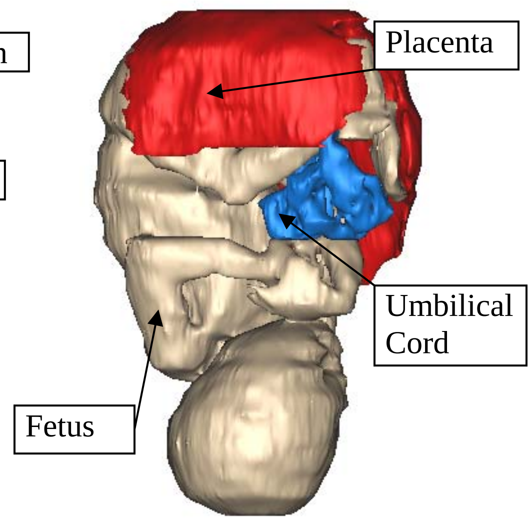

Figure 2: Posterior view of fetus, placenta, and umbilical cord.

Table 2 shows volume and threshold averages and low/high values from individual masks. Using these volume measurements, the 3rd trimester uterus and all its contents have a volume of 3377.74 cm^3.

Table 2. Mask data.

Mask Name	Volume (cm^3)	Final Thresholds (HU)			Details
		Low	High	Average	
Uterine Volume	2579.03	-150	1177	42	Interior mask of uterus (exc. placenta)
Skin	329.20	-1024	60	-444	Automatic mask of skin
Pancreas	84.64	-134	222	113	Pancreas mask
Uterine Wall	111.04	-1024	578	62	Uterus mask
Fat	6082.02	-199	141	-96	Automatic mask of body fat under skin
Maternal Skeleton	1953.77	-328	1582	382	Maternal skeleton
Gallbladder	36.22	-134	174	42	Gallbladder Mask
Stomach	455.80	-1024	417	-35	Stomach and duodenum mask
Placenta	687.67	-69	271	102	Placenta mask
Abdominal Muscles	1018.88	-150	174	29	Abdominal muscles mask
Fetal Skeleton	197.12	109	1177	250	Fetal skeleton mask
Liver	1769.73	-555	433	129	Liver mask
Intestines	1800.64	-1024	595	-50	Intestines mask
Fetus	1697.66	-150	3071	59	Fetal mask
Kidneys	401.98	-101	287	169	Kidney mask
Spleen	180.65	-134	287	143	Spleen mask
Umbilical Cord	95.00	-69	3071	33	Umbilical cord mask

Uterine wall thickness values ranged from about 5.5 mm to 7.75 mm. The most superior and inferior slices were not used because they contained error due to the angle of the uterine wall when imaged with transverse slices.

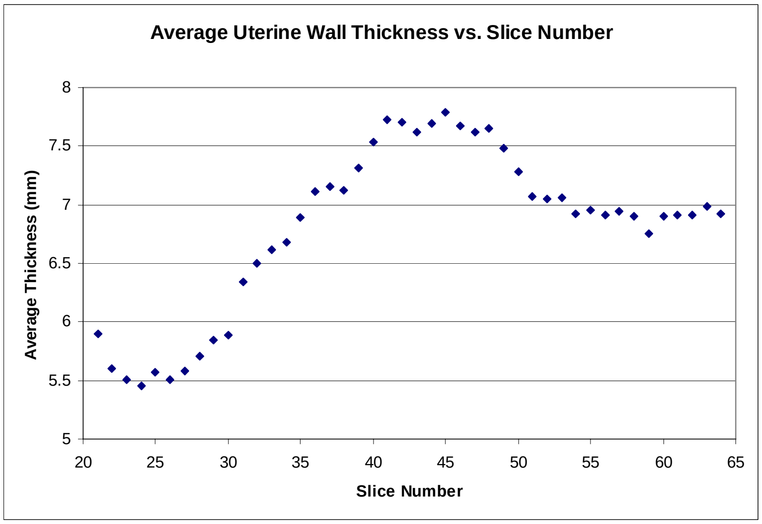

Figure 3: Average Uterine Wall Thickness Results.

The slice on the left in Figure 4 is slice 23 which is near the cervix at the inferior uterus. The slice on the right is slice 65, which is superior, near the fundus of the uterus.

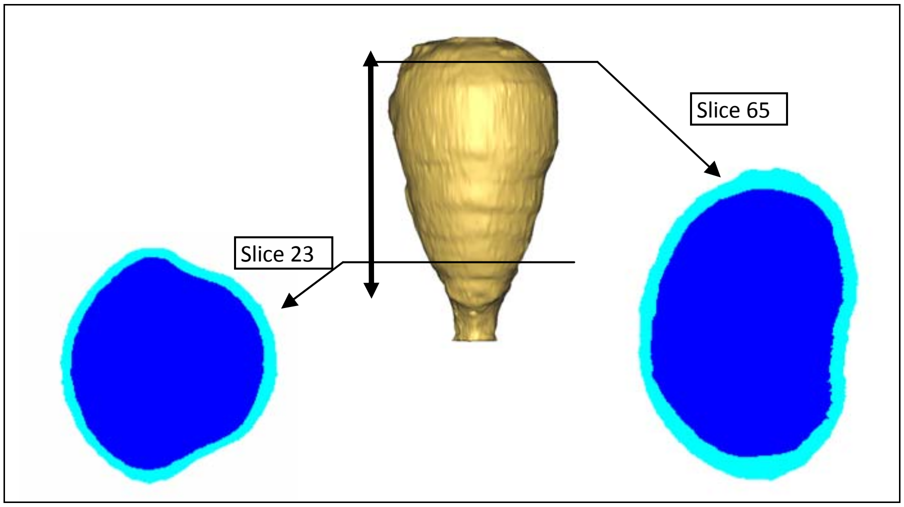

Figure 4: Uterine wall slice thickness images.

Placental thicknesses are shown in Figure 5. Values ranged from about 20 mm to 65 mm for the anterior portion, and about 5 mm to 45 mm for the posterior portion.

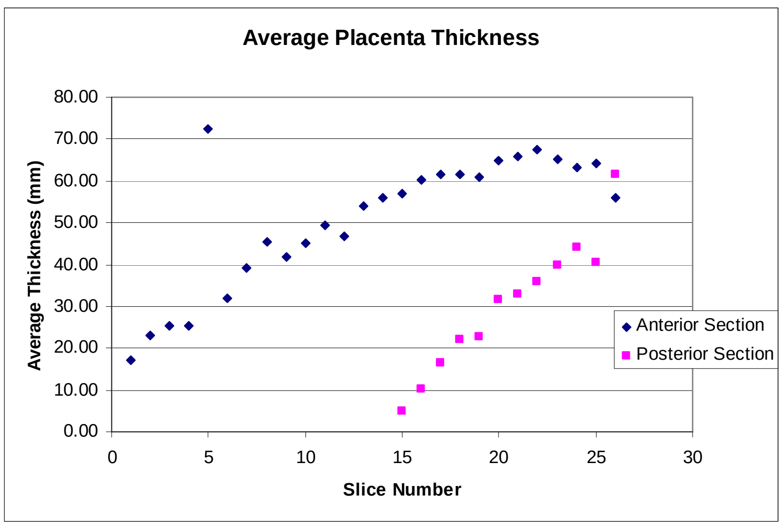

Figure 5: Average placenta thickness results.

Figure 6 shows two different slice thickness images from the placenta. The slice on the left is from the anterior, inferior portion of the placenta. The slice on the right contains the anterior and posterior, superior portion of the placenta, closer to the fundus of the uterus. These black and white images are the result of the serial slices that visually depict superior to inferior variation in the thickness of the placenta.

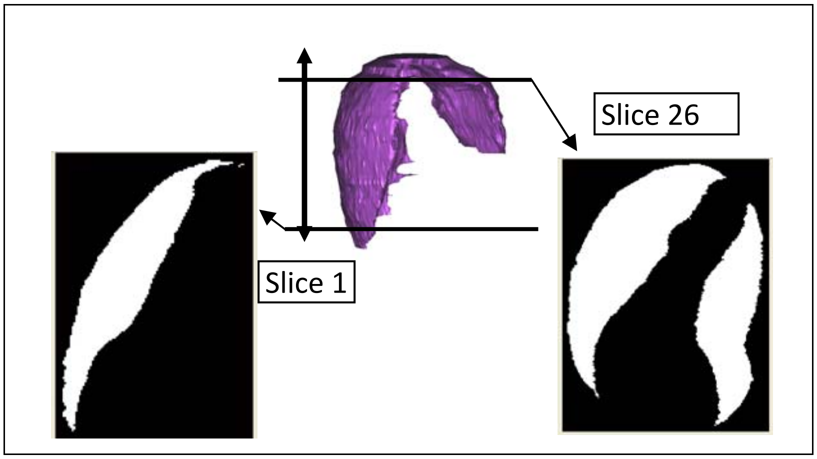

Figure 6: Placenta slice thickness images.

Bone length measurements of the fetus were taken from 3D renderings and compared to literature data to estimate gestational age of the fetus (Table 3). Approximate gestational age predicted by crown-to-heel measurement in CT may be incorrectly estimated, because the measurement is usually not performed *in utero*.

Table 3. Table of measurements used in determination of gestational age.

Approximate Gestational Age		
Measurement	**Data (mm)**	**Age (weeks)**
Crown to heel (The Medical Algorithms Project, 2007)	360.91	29.5
Avg. foot length (Chatterjee et al., 1994)	58.13	30.1
Avg. femur length (Fetus Growth Charts, 2007)	63.87	32.5
Avg. humerus length	58.94	33.9
Occipitofrontal diameter	101.84	32.0
Biparietal diameter	87.83	34.9
Head circumference	297.78	32.7
Average approximate gestational age		32.2

DISCUSSION

This study has been successful in generating quantitative data on the geometry of the pregnant female and fetus and has resulted in masks of the early 3rd trimester pregnant abdomen. Medical image analysis allowed for segmentation and creation of 3D objects representing the pregnant abdomen. By measuring the height of T8-T12 on the CT scan, the female is considered to be a 5th percentile with an estimated height of 4’ 11” and estimated weight of 104 lbs (Schneider et al., 1983). Uterine and placental aspects of abdominal geometry are probably applicable to more than just the 5th percentile female at this stage of gestation, because in the 3rd trimester fetus size largely determines uterine size. Masks of the fetus, uterus, placenta, liver, kidneys, gallbladder, pancreas, stomach, and spleen are representative volume calculations for this individual in the 3rd trimester. A brief description of each mask can be found in Table 2. These measurements provide a starting point for creating an accurate Finite Element model of the pregnant female for use with crash tests for the automotive industry and academia.

Many measurements of the fetus were taken as a means of confirming the gestational age and to record the dimensions of a fetus in the proper stage of development. Gestational age estimations are usually made from the brain and skull anatomy using ultrasound (Woo, 2007). Using CT, it was difficult to locate the specific brain landmarks where these skull measurements were to be taken because of slice spacing and low brain resolution. Upon measurement, the biparietal diameter was slightly large and the occipitofrontal diameter was small in comparison to literature values. The head circumference calculation averaged the two measurements and allowed for a measurement independent of the shape of the head (Creighton University Medical Center 2007). The approximate gestational age predicted by crown-to-heel measurement could be underestimated, because at this gestational stage it is difficult to perform this measurement due to the size and position of the fetus. Measurements were compared with data in the literature (Table 3) to estimate the gestational age to be 32 weeks. The reported emergency department medical record listed a gestational age of 32 weeks, so this method of measuring the fetus at multiple locations using CT slices and 3D renderings is accurate.

The computerized analysis process may introduce some human error, and this contributed to the placement of the markers for measurement within Mimics and the creation of masks for 3D volumes. Much manual error was reduced by viewing correct threshold levels for each type of soft and hard tissue within the CT scan when creating the masks.

Uterine wall and placental thickness measurements showed the uterine wall was thicker near the fundus than the cervix. This could be due to the placement of the placenta. The placenta was much thicker than the uterine wall, and was thickest near the fundus. It was thicker more anteriorly than posteriorly. There was one outlier in the placental data at slice number 5, which was believed to be an error in the creation of the vector normal to measure the thickness values. This error was not seen in any other slices. The thickness values at the apex of the placenta are not accurate because of the horizontal slices and the horizontal plane of the superior placenta over the fundus of the uterus, which caused the measurement slices to be parallel to these anatomical planes. These techniques and measurements will be useful for guiding the development of pregnant FE models and for creating finite element models of the utero-placental interface in the future.

Further studies need to be conducted using a larger sample to validate results of this study. This study focuses on one pregnant female, and placental attachment and individual anatomical variation will differ for different women. Studies of women at different periods of gestation would be useful for creating scaled models at any stage of pregnancy. As in this work, data obtained from CT's would be obtained retrospectively because it is impossible to do a prospective CT study of the pregnant female. Future studies might make better use of MRI for obtaining these measurements, and this effort is ongoing as well.

In the future, the calculation methods demonstrated here will be applied to more studies at different gestational ages. Average uterus area for each slice could be calculated and used to create an accurate representation of the amount of amniotic fluid that is present. This could be incorporated into the pregnant female model in order to predict how the amount of incompressible fluid within the uterus affects the fetus during blunt force trauma. After creating an accurate model of the utero-placental interface and studying the relationship between assumed deformation and outcome in patients, it may be possible to predict where abruption may occur. This prediction technique would be helpful in formulating injury metrics and criteria for placental abruption and other mechanisms with risk of fetal loss.

CONCLUSIONS

Using a CT scan from a pregnant female, masks and 3D volume renderings were created for each maternal abdominal organ. These were used to calculate organ volumes, fetal gestational age, and anthropomorphic measurements. Uterine wall thickness was found to differ by anatomic location. The placenta thickness varied anteriorly and posteriorly and was thicker at the fundus. Gestational age was determined to be 32 weeks, by comparing fetal skeleton measurements to literature values. Lastly, anthropometric measurements were taken for the pregnant female and fetus, in order to create a blueprint for modeling. These methods and measurements will aid in creating a more correct anatomical model of the pregnant female and fetus.

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DISCUSSION

PAPER: **Pregnant Female Anthropometry from CT Scans for Finite Element Model Development**

PRESENTER: ***Kathryn Loftis, Virginia Tech - Wake Forest University Center for Injury Biomechanics***

QUESTION: *Costin Untaroiu, University of Virginia*
I'm wondering if you checked somehow, because you played with house-field numbers and house-field numbers are sometimes hard tissue for bone, you know, to detect when it's bone or it's not bone. So soft tissue, I know, is more difficult. Did you try somehow to apply a metal to verify accuracy? With what accuracy did you determine thickness? Because what you show there, it involved a lot of manual work and of **_____** and operations. This is in milliseconds, right?

ANSWER: Yes, sir.

Q: Okay. So, did you try, somehow, to verify your accuracy?

A: We did not do that with this study; but by starting the Hineswall unit value and then manually segmenting from that we were able to -- visually able to verify that what we were selecting was correct.

Q: How did you verify?

A: By looking at the CT scan, we could tell which points we had selected within the mask that we had chosen.

Q: *Jeff Crandall, University of Virginia*
What you could do is take materials of a known thickness of **_____** with the same properties**,** measure them physically, and then go through sensitivity analysis, which was what they did for the pelvis. So that might be a way where you could follow-up and verify, in a more quantitative fashion.

A: Okay. Thank you.

Q: *Guy Nusholtz, Daimler Chrysler*
This is for one geometric initial position. Are you planning to look at how the thicknesses and everything changes as you change, say, from sitting to standing in different areas?

A: We do hope to look into that in the future.

Q: Do you expect that there will be a big difference or that you'll get basically the same material characteristics, in terms of geometry, as you would for the one spatial?

A: I'm not sure about that.

Q: Okay. Thank you.

Q: *Erik Takhounts, NHTSA*
I have a question. I wonder when you finish up your study, since this is for a finite element analysis, are you going to give the modelers an average geometry of 50th percentile population of pregnant women? Or, what's the final goal because you will have more females signed up for it, right? That's the way I understand it.

A: Hopefully. We chose the 5th percentile female because that's what currently is being used in the dummy, so we were hoping that we could get the geometry incorporated into the existing models to fit accurately.

Q: Okay.