CAD Modeling of the Birth Process: II[1]

Y. Liu, Ph.D. (liu@cs.umass.edu)
M. Scudder (scudder@cs.umass.edu)

Computer Science Department, University of Massachusetts, MA 01003

M.L. Gimovsky, MD. (mgimovsky@BHS.org)

Tufts University, School of Medicine
Department of Obstetrics and Gynecology
Baystate Medical Center, 759 Chestnut Street, Springfield, MA 01199

ABSTRACT

We are engaged in studying the process of human birth by developing a computer-based dynamic model that can be adapted to specific birth scenarios. The individual characteristics of a given pregnant woman and fetus, embedded in their clinical measurements and CT and MRI images, are captured in the model. One can thereby predict adverse events that might happen during labor and delivery. Based on our findings from a preliminary design and execution of this model, we believe it holds great promise as an accurate, cost-effective diagnostic and teaching tool that will help predict conditions during individual labor scenarios that might cause traumatic birth injuries, and thereby enable us to make the most informed clinical decisions possible.

[1] This paper is to appear in the proceedings of *Medicine Meets Virtual Reality IV* Conference, January 1996, San Diego.

1 Introduction

We are engaged in studying the process of human birth by developing a computer-based dynamic model. Our final goal is to apply this computer model to the prognosis of labor. It has been previously shown that traumatic birth injuries can be lessened by a clinically available approach to pelvis-fetal size and shape relationships, as evidenced by our understanding of the process of delivering the fetus whose birth is complicated by malposition, such as breech presentation [11, 13, 9, 10, 12, 7, 8, 6] and the small and/or preterm infant. The critical factors of a successful labor are often identified as the three P's:

1. **P**assage — the size and shape of the pelvis;

2. **P**assenger — the size and shape of the fetal head, the presentation and position of the fetus and the moldability of the head;

3. **P**ower — the force of the uterine contractions and possible external help.

Our aim is to capture the three P's on computers by providing a rational and comprehensive approach using a non-invasive computer-based tool *in vitro* to 'manipulate' the fetus and foresee the forces applied. We have reported on constructing a customized CAD model of a pelvis from CT images [23] (the passage). Our continuing work on improving this model, building the fetus model (the passenger) and simulating interactions between the fetus and the birth canal is reported here. The final goal is to use this computer model to evaluate the forces (the power) involved in childbirth and their dispersal, especially to those structures frequently injured during difficult or premature labor. This evaluation cannot be replaced by retrospective correlation of the delivery process and the Apgar values [24] nor can it be 'visualized' by standard imagery-based diagnostics [31].

We hypothesize that the availability of such a computer-based modeling and simulation system will

- reduce birth injuries to both the infant and the mother,
- promote the design of better birthing instruments,
- contribute to obstetrics education, and
- decrease the cost of health care.

2 Relevant background studies

2.1 Cephalopelvic versus fetal-pelvic disproportion

Cephalopelvic disproportion denotes a disproportion between the pelvis and the fetal head. In the 70s, Jagani [17] and Joyce [18] put forth the concept that it is the <u>overall</u> pelvic size with respect to the <u>overall</u> fetal size that is the problem in the active management of labor. Thus the term *fetal-pelvic disproportion* was coined. It has been re-recognized that one very important dimension of labor that has been neglected is the relation between the fetal and pelvic size and shape, which can be known before the trial of labor and used as a guide in the delivery. As 3.8 million births occur in the U.S. annually, the potential clinical importance and savings on the cost of health care that would result from developing an effective fetal-pelvic appraisal method are great. A simple assessment method for *fetal-pelvic disproportion* called the *fetal-pelvic index* [33] has achieved an overall accuracy in predicting required C/S on the order of 90 to 95%. This method has reconfirmed that the main problem during labor is not one of cephalopelvic disproportion, but of fetal-pelvic disproportion. This is especially true for a normal-sized fetal head with a rather large-sized fetal abdomen, for example, the infant of a diabetic mother. Another case is when the size of the fetus's shoulders is large compared to the birth canal, as studied in [26].

2.2 Cephalopelvic Childbirth Simulation

Dr. Bernhard Geiger did his Ph.D. thesis at INRIA Sophia Antipolis, France, on the subject of *Three-dimensional modeling of human organs and its application to diagnosis and surgical planning* [5]. His work was based on *computational geometry* (Voronoi diagram and Delaunay triangulation [28]) and robotics compliant motion planning where a simulation of delivery is demonstrated. He used 23 axial MR images of a nonpregnant woman, each pair of images separated by a distance of 0.86cm. Several diameters were measured on the pelvis-model. The fetal head was reconstructed from 16 MR scans of an adult; then the proportions were changed manually to obtain a resemblance to a newborn. The biparietal diameter was 9.4cm in the model (average size). Both models were polygonal, no consideration was given to the inner structure of the head nor to the effects of the soft tissues. One important assumption in Geiger's simulation was that the resultant of the force is applied to the center of the gravity of the head. The general idea was to determine a measurement of adequateness by passing (discretely) the head-model through the pelvis-model. If at any step the head polyhedron penetrated the pelvis polyhedron, the resulting force and the moment applied to the center of the head were calculated. According to this force and moment, a number of translations and rotations were made, hopefully to reduce the force to zero. In his simulation, the fetal head will always pass through the pelvis, even with a severe disproportion. The *adequateness value*, however, indicates the quality of the passage. Only one pelvis-head pair was tested, although the head was scaled to different sizes. The encouraging feature of his simulation is that the simulated trajectory of the fetus corresponds to that described in the literature [29].

The work reported in [34] was a three-year project (92-94) carried out in Germany by a group of MDs and engineers on a method developed to perform dynamic, biomechanical postprocessing of the static information obtained from MRI. They used scans of a 2 weeks premature child and a woman with complications. The mechanical tissue properties used in their Finite Element Analysis (FEA) were taken from published properties of biological tissue. They developed a special software where matrices of the maternal pelvis and the fetal head were color-coded and — according to the principle of equal density — line data were created. After sectional attribution of the resulting polygons, a three-dimensional mesh was created, which could then be used for deformation analysis. The simulation was carried out by running a FEA with the head only in 10 different positions along the expected process of birth. They found pressures as high as 800 kPa with respect to a line contact, showing that great force exists during labor. Their simulations were carried out on a Cray, a parallel super computer. They found that a 32bit Cray was still too slow; a 64bit Cray would be desired. Though their method is resource intensive, they argue that their system returns quite accurate data in terms of forces acting on the fetal head, and that the method cannot be replaced by retrospective correlation of the delivery and the Apgar values. For example, Ludwig et al [24] reported on their finding of intracerebral bleedings on CT of 150 unselected full-term newborns[2]. The authors also justified their work by mentioning Largo's [20] doubt on the sufficiency of the usual pre and perinatal criteria to evaluate the neurological outcome, and Schulte's [31] indication that standard imagery-based diagnostics cannot find any or can only find very insignificant morphological defects that can cause discrete brain parenchym damage.

3 Our Result

Our work is an extension of the fetal-pelvic index method in the sense that we consider the spatial and geometric constraints between the size and shape of the overall fetus and the overall birth canal to be one of the most important factors in delivery. We treat the fetus as a kind of kinematic chain instead of an isolated head only. We employ computer modeling techniques to store, edit, and display three dimensional shapes in combination with modern image processing to produce a detailed, accurate, customized 3D simulation of the birth process. We continue using AutoCAD as a computational framework to build 3D *surface models* as well as another geometric modeler ACIS to build both 3D surface and *solid models* from the existing maternal pelvis and newborn scans. Since our goal is not simply to use the computer model to predict C/S but to minimize possible birth injuries by all means, such as by a selective assisted vaginal delivery, we shall go beyond the geometric/spatial aspects and put our emphasis on analyzing the forces acting on the fetus during the birth process.

3.1 Modeling the Birth Canal

As a first step towards our final goal, we reported in [23] the development of a CAD surface model of the bones that surround the birth canal. The 3D surface models are constructed by fitting cubic nonuniform rational B-spline (NURBS) surfaces [4] through a set of bony outlines. Since then, by restricting our attention to the inner surface of the bony birth canal, which is the surface the fetus will interact with, a new representation of the topologically simple bony birth canal has been developed. A deformed tube is fitted through the inner surfaces of the bones, with a bulge at each obturator foramen. This surface can be composed of a regular mesh of quadrilateral NURBS surface patches and can be given a uniform

[2] They showed that the percentage of the newborns who had intracerebral bleedings after spontaneous delivery, vaginal operative-assisted delivery, and C/S are 38%, 35% and 18% respectively.

Figure 1: The pelvis model — after fitting a deformed tube to its inner bony surface

parameterization. Consistent smoothing and deformations can be applied to it, within the AutoCAD/AutoSurf CAD program, without opening gaps. The data structure is also relatively small and easy to compute intersections with. Such a tube is shown in figure 1.

3.2 Acquisition of the Fetal Head Model

A CT or MRI scan of the entire body of a newborn or a near term fetus is rarely performed. While we wait for such a data set to become available, we have pursued a few other avenues: atlases, partial scans, and a plastic model.

We have used a flat-bed scanner to acquire three series of sections of the fetal head and neck from [16]. Spontaneously or therapeutically aborted fetuses were frozen, sectioned and then each section was thawed and photographed. For our purposes the most useful is the third series, 12 axial sections through the head and neck of a 30 week old stillbirth. Unfortunately, even this series has too few slices to resolve three-dimensional detail such as the neck joint bone shapes. Further, there are some processing artifacts due to the freezing, and the boundaries of bones are difficult to discern.

We have obtained a partial MRI scan of the head of a 2-day old infant. The slices

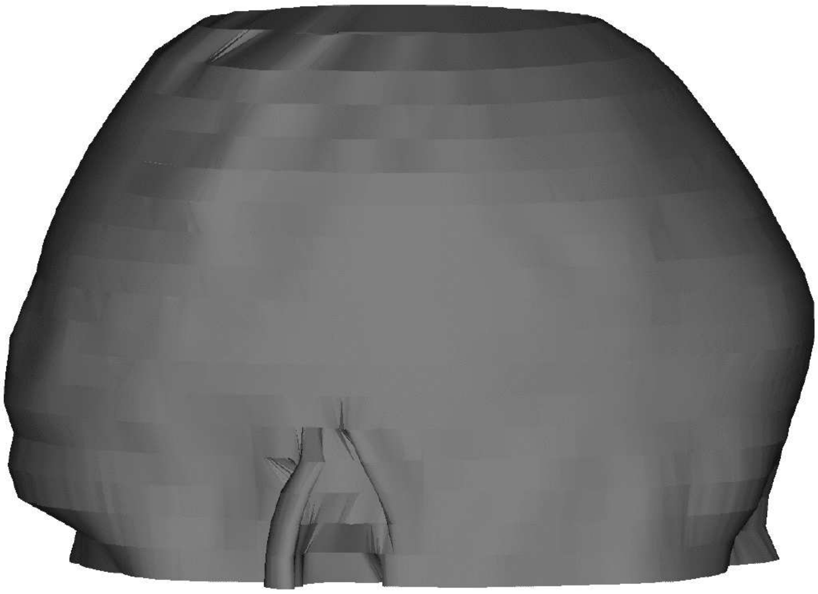

Figure 2: The CAD surface model of a two-day old baby head (top portion)

were 5mm apart and each pixel corresponded to a voxel of size 0.3516x0.3516x5.0 mm^3 produced by a Picker CT scanner at the Baystate Medical Center Radiology department. There were total of 20 images, each with 512x512 12 bit pixels. Two of these images were pilot images and 18 were axial slices spanning the brain of the young patient. The reconstruction of the outer surface of the MRI scans is shown in Figure 2. While the scan is not complete for our purposes, it does include the critical fetal head biparietal and occipito-frontal diameters, and allows us to conduct a simulation with clinical data. The process itself confirms that our approach works for both CT and MRI.

A plastic teaching model of a fetal skull was CT scanned for us with a pixel size of 0.25x0.25 mm^2 and a slice thickness of 2mm. A total of 46 slices covered the entire plastic model. While some streaking artifacts were introduced by a metal nut inside the model, the detail and accuracy available were good. At this small slice separation the construction of interpolating slices did not seem needed, although manual intervention was used in merging irrelevant detail, particularly around the jaw. Results are shown in Figure 3 and Table 1.

3.3 Modeling of the Neck Joint

The various bones of which the skeleton consists are connected together at different parts of their surfaces, and such a connection is designated by the name of *Joint* or *Articulation* [14]. Bones constitute the fundamental element of all the joints. In mechanical design, the *lower pairs* are those kinematic joints which are composed

Table 1: Plastic Fetal Head Model Measurements : Physical model v. Computer model

Diameter	Calipers	AutoCAD
occipito-frontal	9.9cm	9.9cm
vertico-mental	10.6cm	10.4cm
subocciptio-bregmatic	7.4cm	7.4cm
biparietal	8.3cm	8.3cm
bitemporal	7.1cm	7.0cm

Figure 3: The CAD model of a fetal skull from the CT scans of a plastic teaching model

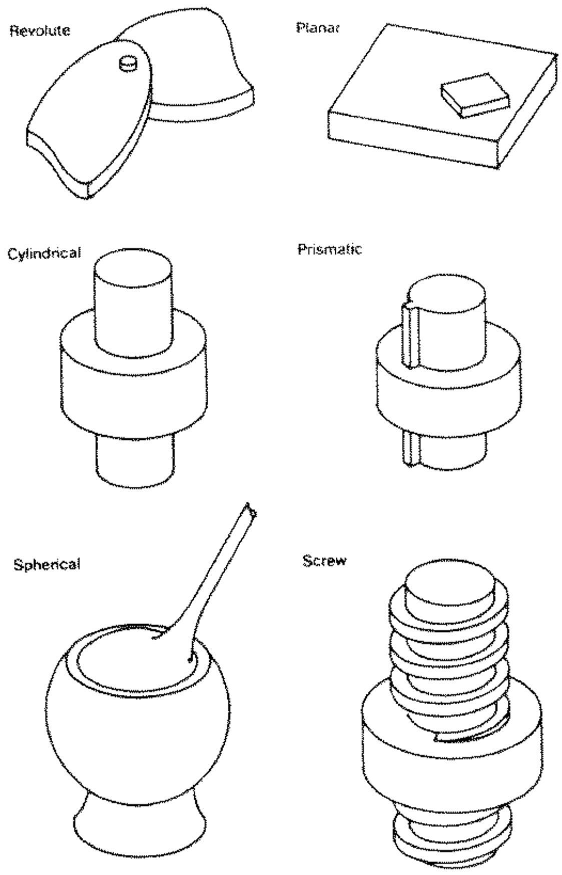

Figure 4: The six lower pairs — joints with surface contact

of two solids with surface contact. The only six lower pairs (Figure 4) and their corresponding degrees of freedom (DOF) are listed in Table 2.

As a first step to model the neck joint, the mobility effect of the neck joint is approximated as that of a spherical joint with its range of motion limited by further contact, as shown exactly in Figure 4. A solid model of the neck joint (composed of two solids with surface contact) is constructed using ACIS, where we can *group* the inner solid of the neck joint with the head surface model, and the outer solid of the neck joint with the rest of the body. The relative locations under such a surface contact can be determined using algorithms developed in [21, 22]. Volumetric or surface intersections can be checked using readily available ACIS routines. We use such an approximation of the neck joint to realize an articulated kinematic chain. Further detailed model of the neck in terms of its biomechanical structure and stress model for FEM analysis is under construction using information provided in [2, 26].

Table 2: Six Lower Pairs and Their Corresponding Degrees of Freedom

Name	Type of Motion	DOF
Prismatic	translation	1
Revolute	rotation	1
Screw	screw motion	1
Cylindrical	translation and rotation	2
Planar	translation and rotation	3
Spherical	rotation	3

3.4 Interactions between the fetus and the birth canal

The CAD models for the fetal skull and the birth canal are shown together in figure 5. In Figure 6 an intersection of the two surfaces is highlighted. It should be noted that the fetal skull easily fits through the modeled pelvis. This is due to the relatively small size of the plastic fetal model, which is 1-3 cm smaller than the average diameters of the fetal skull cited in [29], and due to the absence of any soft tissues in the renderings. In Figure 6 the fetal head model is scaled to be too large to fit through the birth canal.

Given data structures representing the fetus and the birth canal, we are able to detect and characterize intersections. AutoCAD allows us to calculate the curves of intersection between two surfaces, but not the distance between separated surfaces nor their depth of inter-penetration. Eventually we need to simulate a contact and its resulting deformations. The ACIS software package provides us with the data structures and function calls for manipulating solids bounded by stitched together NURBS surface patches and for determining the distance between features of different surfaces.

4 On-going and Future Research

4.1 Method of Simulation

Due to the intensive computation required by the Finite Element Method (FEM) [34] and the proportion of the fetal head with respect to the birth canal being a *necessary* condition for a possible successful vaginal delivery, a two-step simulation process will be adopted:

- Step one:

  a geometric phase determining optimal paths/positions of the fetal head going through the birth canal, while estimating contacting forces using an approximate function based on volume intersection with the depth of interpenetration as an important indicator [5]

- Step two:

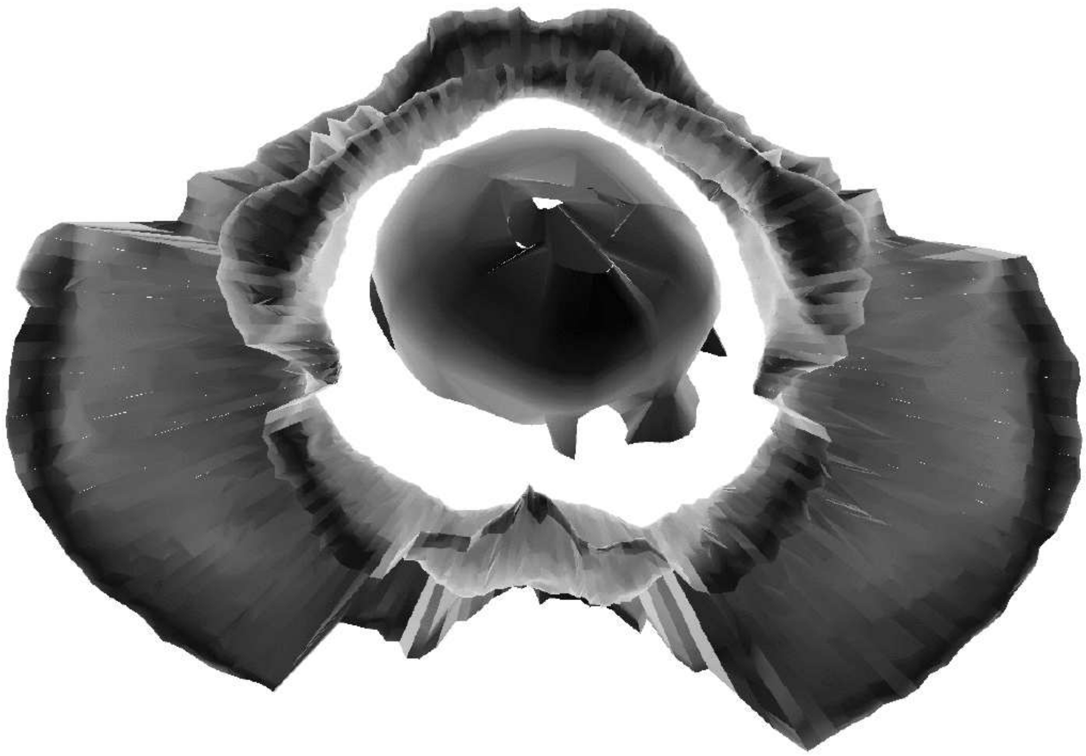

Figure 5: The fetal head in the birth canal

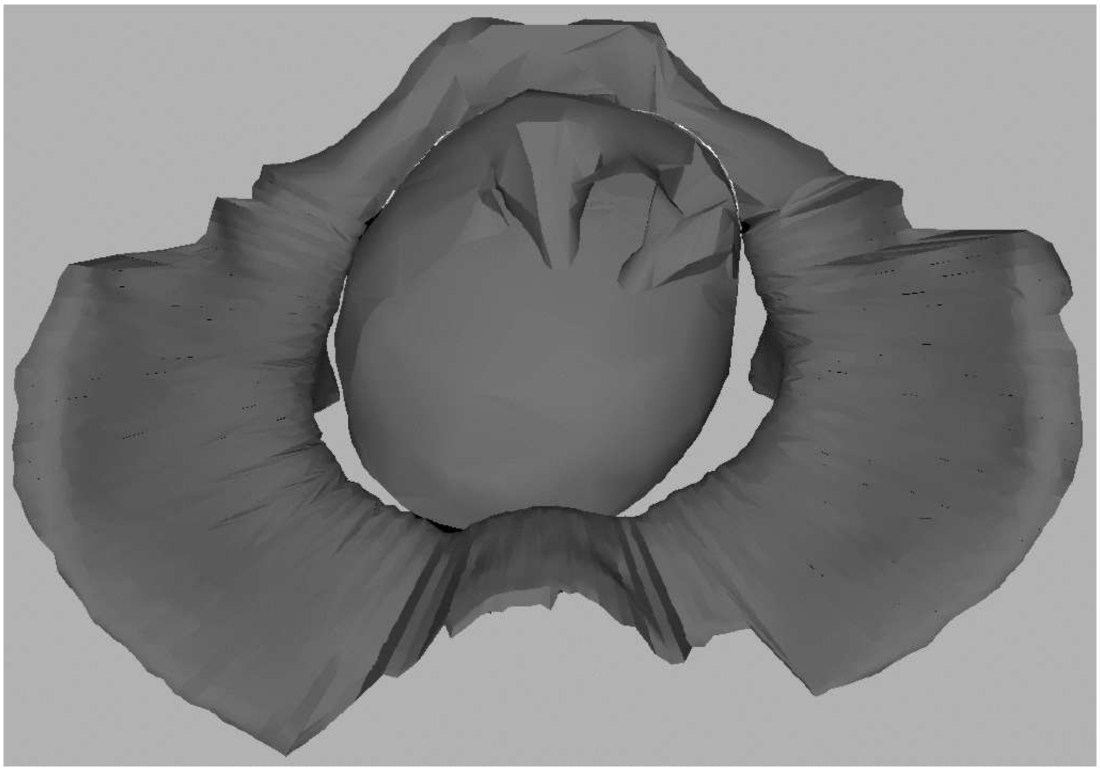

Figure 6: The intersection between the head and the pelvis surface models is shown

a physical phase determining the precise forces on the fetus using the FEM at those positions where high pressure is expected based on the approximate calculation in the geometric phase.

The 3D surface models constructed are especially suitable for the analysis of the surface contact, and the rolling and sliding motions between the fetal skull and the mother's birth canal. We are in the process of developing a first degree approximation of the birth process in which the fetus is represented with the neck joint mobile. Techniques from robotic compliant and multi-linkage motion planning are used to analyze the forces and direct the fetus along a path with minimal force applied. We are using both the AutoCAD/AutoSurf and ACIS software, since AutoCAD offers a straightforward user interface while ACIS provides a richer variety of geometric representations and operations required.

4.2 Method of evaluation

A crucial concern is validating the CAD model. Since we are using techniques similar to ones used and validated in creating computer models of the heart [3] and brain [19], we have good reason to expect our validation to succeed. Three types of checks will be made: for consistency, comparisons of scanned objects with models created from the scans, and comparisons with results in the literature.

Individual CAD models are built from a series of slices from archived CT or MRI scans. The first time a particular biological shape (such as a pelvis) is turned into a CAD model, much manual work is required. Subsequently, the existing CAD model can be used to guide the creation of other individualized CAD models. The quality of this process can be checked by performing it on subsets of slices (for example the odd and even slices) and comparing the results with the model created from the full set of slices. Moreover, where more than one scan has been taken for a single patient, the models constructed from the scans can be compared. These are checks of internal consistency.

We have a pelvis model from a skeleton which we can scan and measure with calipers, and the hospital has a variety of medical models which can be both scanned and measured. The measurements can then be checked against computer models created from the scans.

A number of studies have been done to attempt to calculate or measure the forces the fetal head undergoes during labor, including [15, 32, 1, 25, 34, 30]. We will compare our results with these published results as a further check on the validity of our models. The Library of Congress Visible Human Project [27] is scheduled to have detailed scans and pictures of a sectioned female human cadaver available in the Fall of 1995. This detailed data set will allow us to comprehensively check the accuracy of our birth canal modeling technique as well as provide a standard reference model.

5 Conclusion

Our model will have the capability to construct a customized description of labor, capturing critical factors related to (1) the passage and (2) the passenger, from imaging data. The model will be used to simulate the forces (critical factor (3) the power) applied during labor to the fetus, especially to those structures frequently injured during difficult (breech or other malpositions) or premature labor.

In summary, the unique features of our method include:

- starting from real medical imaging data;
- building accurate, detailed, computationally efficient computer models of the maternal pelvis and the fetus which will eventually be a joint-connected head-neck-body model (an articulated kinematic linkage);
- performing a two-phase computationally efficient birth simulation;
- validating both the anatomical CAD models and the simulation process using existing data.

Based on our findings from a preliminary design and execution of this model, we believe it holds great promise as an accurate, cost-effective diagnostic and teaching tool that will help us predict conditions during individual labor scenarios that might cause traumatic birth injuries, and thereby enable us to make the most informed clinical decisions possible and to take remedial action before labor-related damage occurs.

6 Acknowledgement

We thank Dr. P. O'Grady of the Baystate Medical Center Obstetrics and Gynecology Department for the loan of the plastic fetal skull model. The Baystate Radiology Department, particularly Dr. F. Hampf and the technicians J. Deane and J. Mazurowski helpfully provided the CT scans used. We would also like to thank the VISIONS and Robotics groups in the computer science department of the University of Massachusetts for their hardware and software support under the grant numbers NSF IRI-9208920 and NSF CDA-8922572.

References

[1] F. Bell. *Biomechanics of Human Parturition.* PhD thesis, The University of Strathclyde, Glasgow, 1972.

[2] E.S. Crelin. *Anatomy of the newborn: an atlas.* Lea & Febiger, Philadelphia, 1969.

[3] Lawrence L. Creswell, Stephan G. Wyers, John S. Pirolo, William H. Perman, Michael W. Vannier, and Michael K. Pasque. Mathematical modeling of the heart using magnetic resonance imaging. *IEEE Transactions on Medical Imaging*, 11(4):581–589, December 1992.

[4] G. Farin. *Curves and Surfaces for Computer Aided Design: A Practical Guide.* Academic Press Inc., San Diego, 1993.

[5] Bernhard Geiger. *Three-dimensional modeling of human organs and its application to diagnosis and surgical planning.* PhD thesis, INRIA, Sophia Antipolis, France, April 1993.

[6] M Gimovsky and C Hennigan. Abnormal fetal presentations. *Current Opinion in Obstetrics and Gynecology*, 7(6):In Press, 1995.

[7] M Gimovsky, J O'Grady, and E Keroack. Immediate neonatal outcome of vaginal breech delivery at term in oxytocin stimulated labor (abs). *American Journal of Obstetrics & Gynecology*, 168:463, 1993.

[8] M Gimovsky, J O'Grady, and B Morris. Assessment of computed tomographic pelvimetry within a selective breech presentation management protocol. *Journal of Reproductive Medicine*, 39(7):489–491, 1994.

[9] M Gimovsky and R Petrie. Optimal method of delivery of the low birth weight breech fetus: an unresolved issue. *Journal of Perinatology*, 8(2):141–144, 1988.

[10] M Gimovsky and R Petrie. The intrapartum management of the breech presentation. *Clinics in Perinatology*, 16(4):975–986, 1989.

[11] M Gimovsky, R Petrie, and Todd W. Neonatal performance of the selected term vaginal breech delivery. *Obstetrics & Gynecology*, 56(6):687–691, Dec 1980.

[12] M Gimovsky and B Schifrin. Breech management. *Journal of Perinatology*, 12(2):143–151, Jun 1992.

[13] M Gimovsky, K Willard, M Neglio, T Howard, and S Zerne. X-ray pelvimetry in a breech protocol: a comparison of digital radiography and conventional methods. *American Journal of Obstetrics & Gynecology*, 53(8):887–888, Dec 1985.

[14] Henry Gray. *Anatomy, descriptive and surgical.* Bounty Books, New York, 1901.

[15] Eardley Holland. Cranial stress in the foetus during labour and on the effects of excessive stress on the intracranial contents; with an analysis of eighty-one cases of torn tentorium cerebelli and subdural cerebral haemorrhage. *The Journal of Obstetrics and Gynaecology of the British Empire*, 29(4):549–571, Winter 1922.

[16] Glenn Isaacson, Marshall C. Minta, and Edumnd S. Crelin. *Atlas of Fetal Sectional Anatomy with Ultrasound and Magnetic Resonance Imaging.* Springer-Verlag, New York, 1986.

[17] N. Jagani, H. Schulman, P. Chandra, and *et al.* The predictability of labor outcome from a comparison of birth weight and x-ray pelvimetry. *Am. J. Obstet. Gynecol.*, 139(507), 1981.

[18] D.N. Joyce, F. Giwa-Osagie, and G.W. Stevenson. Role of pelvimetry in active management of labour. *Br. Med. J.*, 4(505), 1975.

[19] I. Kapouleas. *Model Based Interpretation of Magnetic Resonance Human Brain Scans.* PhD thesis, Rutgers University, New Brunswick, New Jersey, January 1990.

[20] R.H. Largo. Frühkindliche zerebralparese:epidemiologische und klinische aspekte. *Dt. Ärztebl*, 88(25), 1991.

[21] Y. Liu. *Symmetry Groups in Robotic Assembly Planning.* PhD thesis, University of Massachusetts, Amherst, MA., September 1990.

[22] Y. Liu. A Geometric Approach for Denoting and Intersecting TR Subgroups of the Euclidean Group. *DIMACS Technical Report, Rutgers University*, 93-82(sumitted for journal publication):1–52, 1993.

[23] Y. Liu, M. Scudder, and M.L. Gimovsky. CAD modelling of the birth process: A preliminary report. In *Proceedings of Medicine Meets Virtual Reality Conference III: Interactive Technology & Healthcare*, pages 211–220, San Diego, CA, January 1995.

[24] B. Ludwig, M. Brand, and P. Brockerhoff. Postpartum ct examination of the heads of full term infants. *Neuroradiology*, 20:145, 1980.

[25] G.K. McPherson and T.J. Kriewall. Fetal head molding: An investigation utilizing a finite element model of the fetal parietal bone. *Journal of Biomechanics*, 13:17–26, 1980.

[26] A. Meghdari, R. Davoodi, and F. Mesbah. Engineering analysis of shoulder dystocia in the human birth process by the finite element method. *Journal of Engineering in Medicine*, 206:243,250, 1992.

[27] National Library of Medicine (U.S.) Board of Regents. Electronic imaging: Report of the board of regents. Technical Report NIH Publication 90-2197, U.S. Department of Health and Human Services, Public Health Service, National Institutes of Health, 1990.

[28] J. O'Rourke. Computational geometry. *Ann. Rev. Comput. Sci.*, 3:389,411, 1980.

[29] Harry Oxorn. *Human Labor & Birth.* Appleton-Century-Crofts, Norwalk, Connecticut, 1989.

[30] A. Rempen. Pressure on the fetal head in vacuum extraction. *Geburtshilfe und Frauenheilkunde*, 53(5):337–341, May 1993.

[31] F.J. Schulte. Perinatale hirnschäden. *Gynäkologe*, 25(169), 1992.

[32] R. L. Schwarcz, G. Strada-Saenz, O. Althabe, J. Fernandes-Funes, L.O. Alvares, and R. Caldyro-Barcia. Compression received by the head of the human fetus during labor. In *Physical Trauma as an Etiological Agent in Mental Retardation*, pages 133–143, Washington D.C., 1970. U.S. Department of Health, Education and Welfare.

[33] G.R. Thurnau, K.A. Hales, and Morgan M.A. Evaluation of the fetal-pelvic relationship [review]. *Clinical Obstetrics & Gynecology*, 35(3):570–81, September 1992.

[34] A. Wischnik, E. Nalepa, K.J. Lehmann, K.U. Wentz, M. Georgi, and F. Mechert. The prevention of human birth trauma 1st communication: Computer aided simulation of delivery by means of magnetic resonance imaging and finite element analysis. *Geburtsh. u. Frauenheilk.*, 53(1993):35–41, 1993.