CAD Modelling of the Birth Process:
A Preliminary Report

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Abstract A rational and comprehensive approach for indicating when cesarean delivery (C/S) is necessary would result in a limitation in the overall maternal risks of childbirth as well as in the cost of health care. For this purpose, we are in the process of developing a set of computer aided design (CAD) models and a systematic and flexible simulation of the birth process. Different from the volume-based approach, our system provides three dimensional *surface models* of 1) the maternal bony pelvis obtained from digital radiographic images of computed tomographic (CT) pelvimetry and 2) fetal anatomy obtained from ultrasound images. Our modelling system and initial simulations bear many similarities to the results of assembly/disassembly planning research in robotics. Our initial result on generating the detailed CAD surface models is reported in this paper.

1 Introduction

From digital radiographic images of computed tomographic (CT) pelvimetry[1] and ultrasound images of the head of the fetus, we are in the process of developing a set of three dimensional computer aided design (CAD) models of the maternal bony pelvis and fetal anatomy. The final goal of this project is to achieve a systematic and flexible three dimensional CAD simulation of the birth process, so that we can provide

- a tool with which the bony structure of the fetus and the birth canal can be generated as three dimensional CAD models from a set of static digital radiographic images, and with which these models can be further parameterized, transformed (by translations, rotations and scaling) and observed extensively on the computer;
- a testbed where the interactions of the CAD models of the fetus and the birth canal can be displayed and calculated, in particular, where simulations of the childbirth process can be examined in detail;

[1] CT pelvimetry exposes both the mother and infant to significantly lower radiation than does conventional radiographic pelvimetry [10]

- evaluations of both normal and abnormal forces during the birth process, which may cause both obvious and subtle birth injury to the infants, leading to the development of protocols that limit the risk of birth trauma.

The significance and impact of this research are many-fold. Firstly, all the analysis and simulations of the birth process can be done on computers before a clinical trial, which elucidates critical factors involved in operative obstetrics, limits risks to human subjects (mothers and the babies), and enhances the benefits of interventions or lack of interventions in parturition. Secondly, it is cost effective. A set of inexpensive, precise, reproducible and visually comprehensive models generated from radiographic/ultrasound images conveys all the critical information for the choice of techniques employed in operative obstetric procedures. As 3.8 million births occur annually in the U.S., of which approximately 800,000 are by C/S with an additional 800,000 which are operatively assisted vaginal deliveries, the potential clinical importance and saving on the cost of health care are great. Thirdly, the final product of this research can be easily converted into an educational tool, which can be used by obstetrical residents to predict the consequences of a treatment or to assist on-line decision making. Last but not the least important is that the techniques utilized in this research are borrowed from and can contribute to other research fields such as robotics. In particular, our modelling system and initial simulations bear many parallels with the methods used for assembly/disassembly planning research in robotics. On the other hand, the rigid geometric models commonly used in robotics can be enhanced by the addition of dynamics (force and other physical factors) as well as the simulation of flexible bodies.

As a first step towards our final goal, we have accomplished the transformation from a set of pelvis CT scans to a CAD *surface model* on a personal computer (PC), which is described in detail in section 3.1. Our method differs significantly from the more traditional volume-based approach as explained in the next section. Section 3.2 gives an overview of our general approach and a specific justification on using surface models. Section 4 concludes the paper with what we learned from our experiments.

2 Related Work

Modern geometric modelling systems employ computers to store, edit, and display three dimensional shapes. The system builds internal representations ("models") of objects, either through interaction with an on-line end-user or by reading in a command file, and then invokes application dependent procedures to answer geometric questions about the objects. For example, one can check whether there is any intersection between two solids that have been relocated in three dimensional Euclidean space. There is a vast amount of literature on three-dimensional computer modelling and computer graphics [3, 9, 14]. There is, however, little to be found on the computerized modelling of anatomy [1, 4, 5].

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 used as guidance in the deliveries. Despite advanced imaging techniques, the majority of obstericians use the active management of labor or a trial of labor approach to evaluating the fetal-pelvic relationship. A simple assessment method of the fetus and the maternal pelvis called the *fetal-pelvic index* [15] has achieved considerable success in predicting C/S. There are four circumferences involved in this method:

- the circumference of the fetal head (HC), which is calculated with the biparietal[2] diameter using the following simple formula:

  $$HC = (TD + APD) * \pi/2$$

  where TD is the outer-outer transverse diameter of the head and APD is the anterior-posterior diameter (APD) of the fetal head;

- the circumference of the fetal abdomen (AC), which is obtained using the transverse and anterior-posterior diameter of the abdomen, and the formula mentioned above;

- the circumference of the maternal inlet[3] (IC) obtained by using the anterior-posterior diameter and the transverse diameter of the inlet and the formula;

- the circumference of the maternal mid-pelvis (MC) obtained by using the anterior-posterior diameter and transverse diameter of the mid-pelvis, and the formula.

Since the head will have to negotiate the inlet, we must measure head minus inlet circumference: HC-IC. Then we have the head minus mid-pelvic circumference: HC-MC. We then take the abdomen minus the inlet and the mid-pelvis: AC-IC and AC-MC. When these differences are negative, it indicates that the pelvis is larger than the baby, and vice versa. The fetal-pelvic index is the sum of the two most positive numbers of those four differences. If the index is positive, it indicates fetal-pelvic disproportion, and if it is negative it indicates the absence of fetal-pelvic disproportion.

Our work is an extension along this line in the sense that we consider the spatial and geometric features of the fetus and the birth canal as one of the most important factors in delivery. Furthermore, we employ computer modelling techniques combined with modern image processing to produce a detailed, three dimensional, dynamic simulation of the birth process.

While there are a few systems in existence for forming CAD models from medical image sequences (for example, SurgiCAD from Intergraph Corporation, Huntsville, AL), they rely significantly on more expensive hardware and software than the approach presented here. While the 3-D display of medical images has been around for a long time [5] (or more recently [16]), most such products use a volume based approach which does not include a useful representation of curved surfaces suitable for the analysis of contacts between objects. We model polyhedral as well as non-polyhedral surfaces, which are most useful in the analysis of contact and relative motions among objects. This latter emphasis also has a theoretical basis developed in robotics research [6, 8], where the mathematical tool for describing symmetries, group theory, is applied to the analysis of surface contact.

[2] For a detailed, clear account of the terms used here and about childbirth in general, one can refer to [13].

[3] The maternal measurements are obtained using conventional X-ray pelvimetry techniques.

3 Computer Modelling of the Birth Process

Our approach to modelling the birth process includes the following stages in temporal order:

- the transition from a set of 2D static images to a 3D model represented as an internal entity of the CAD system;
- the manipulation of a 3D model, including the adjustment of the shape parameters of the model and transformations (translations, rotations and scaling) applied to the model;
- the formation of an articulated kinematic chain (assembly) from a set of isolated entities, and the motion of the chain (the baby's body) in contact with its environment (the birth canal);
- the simulation of the interactions (surface contact, rolling, gliding, intersection, penetration and deformations) among 3D models and the force analysis.

In this paper we report our initial result on generating the precise CAD models from a sequence of 2D digital images, with which one can describe the surfaces of bones found in CT scans within a CAD product, the AutoCAD solid modelling system [2]. AutoCAD provides three types of 3D models: *wireframe, surface* and *solid.* Our experiments used mainly the *surface models*, which can be approximated by a *polygon mesh* for further control of the modeled surface. A *surface model* in AutoCAD is an infinitely thin shell corresponding to the shape of the object (the bone structure, in our case) being modeled. This shell consists of a combination of flat and *curved* surfaces or adjoining surface elements called patches.

3.1 Formation of a CAD model from a set of CT scans: A PC based approach

Our method has been developed at Baystate Medical Center in Springfield, Massachusetts using a DEC LPx+ 66Mhz 486 personal computer, the AutoDesk AutoCAD/AutoSurf CAD products, the Aldus Photostyler image editor and a few small C++ programs. The method has been applied to the task of modelling the human bony birth canal as part of an attempt to model human parturition.

First, the image sequence (32 slices) from a CT scanner for a particular patient was obtained and transferred to the PC. An example slice is shown in Figure 1. Then the scan slice images were translated by a program into a format the Photostyler program could read. Next, Photostyler was used to touch up the images and prepare them for thresholding to produce black and white images of the bones in the images. A program was written to trace the resulting bone outlines and produce lists of coordinates. The lists were produced in a format that AutoCAD recognized as a list of '3D polylines'. The black and white images for 16 slices are shown in Figure 2.

The lists were read into the AutoCAD/AutoSurf program and each slice was placed in a separate layer to speed processing. The polylines were then approximated with cubic splines. These splines were then examined individually and modified as needed to eliminate artifacts and separate any bones that had not been separately resolved. The resulting closed spline curves were grouped according to the bone each outline resulted from. Four images of the outlines of a pelvis are shown in Figure 3: clockwise from upper left, view down the spine, view through the pelvic inlet, the side view, and the front view.

Rami of the bones were identified, and extra contours were drawn by hand between existing layers to ensure that before a single contour split, a contour existed which showed a narrow bridge between the two sections of the contour about to be split. Further, for each tube-like structure the origins of each constituent contour were aligned. This prevents twisting artifacts as surfaces are built. This preparation allowed AutoSurf to fit a surface to each tube-like structure. Gaps remain at the bifurcations and the poles (the singular points of a surface). The major tube-like structures of the bones in the CT scan are rendered in Figure 4.

A technique has been developed to interpolate between and join the tube-like structures into combined surfaces. The tubes are broken into appropriate patches, gaps are interpolated between patches, and the patches are rejoined. A similar technique is used at the poles: extra contours are drawn between slices and joined to small spherical caps. The resulting surfaces are smoothed to reduce the number of surface patches to the minimum consistent with an accurate representation.

The result is a detailed CAD model of the surfaces of the bones. The rendered image of a complete right femur is shown in Figure 5. A rendering of part of the right femur's surfaces is shown in Figure 6. The surfaces produced are suitable for the analysis of the sliding motions of bones at joints, or, in our case, for the analysis of the sliding of the fetal skull through the mother's birth canal.

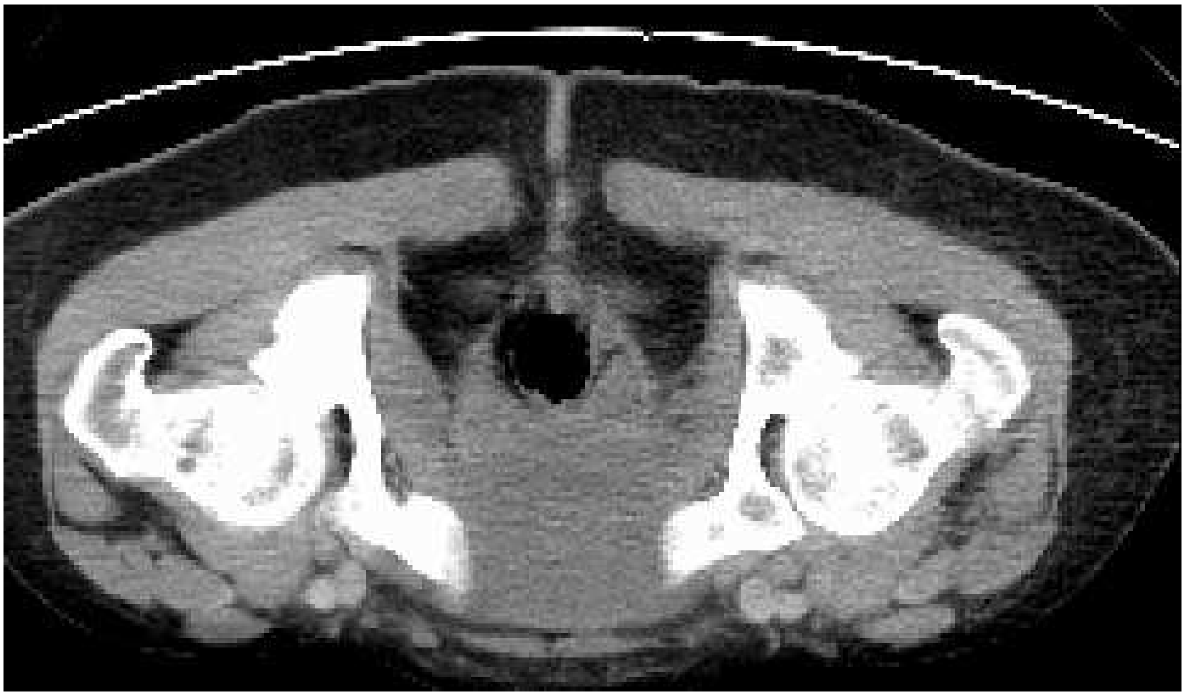

Figure 1: The seventh slice of the pelvis image

3.2 Manipulations on and interactions among the models

Averaging a variety of representative pelvic models and simulating the development of the pelvic bones [11] are two of our current subgoals. AutoCAD, as well as other

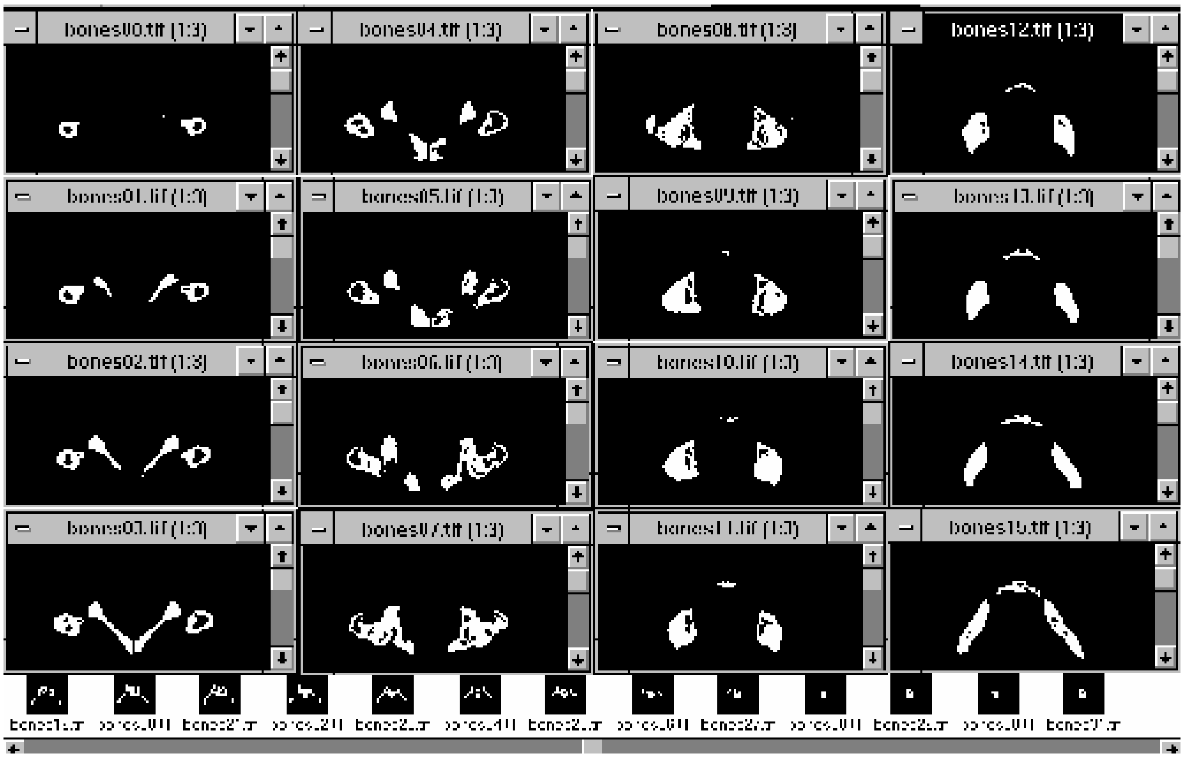

Figure 2: Sixteen slices of pelvis bone structure

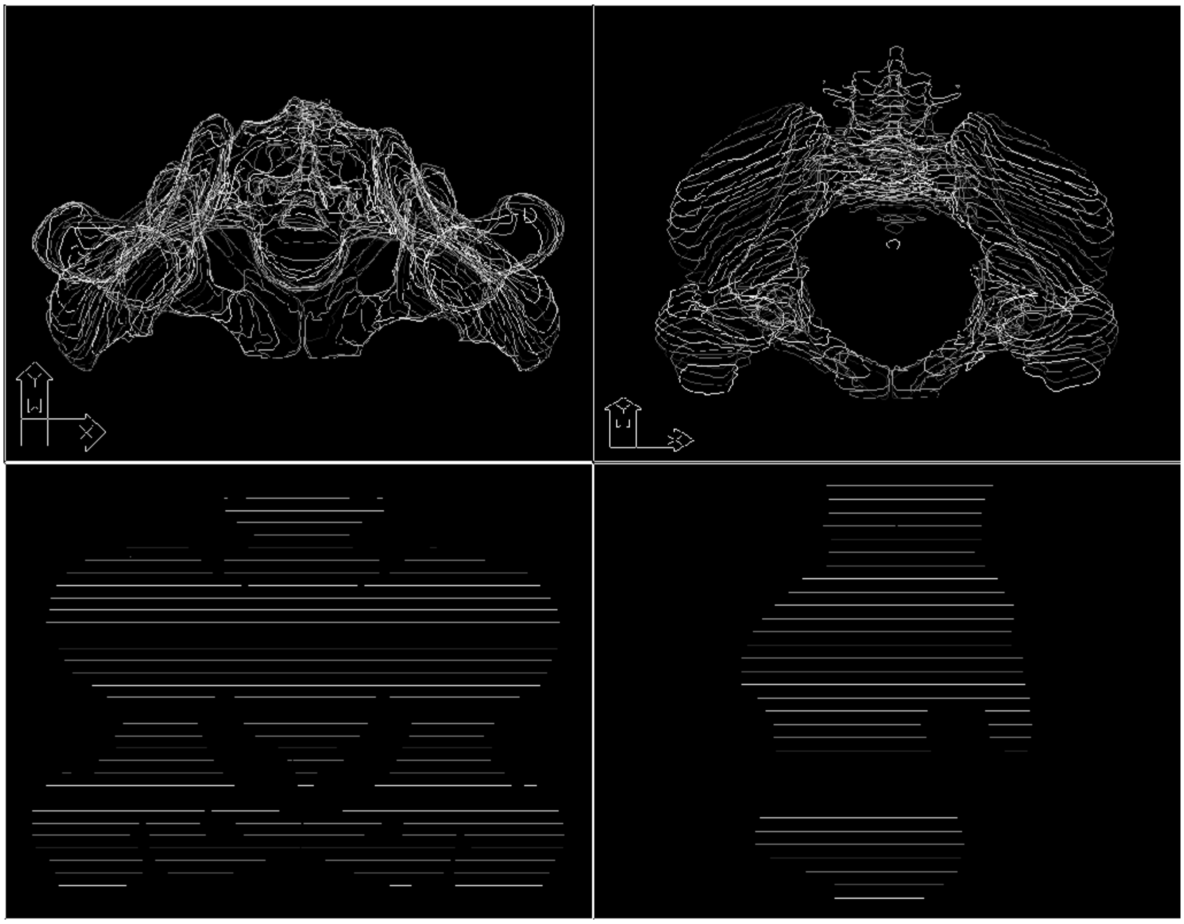

Figure 3: Four images of the outlines of a pelvis: (clockwise from upper left) view down the spine, view through the pelvic inlet, the side view and the front view.

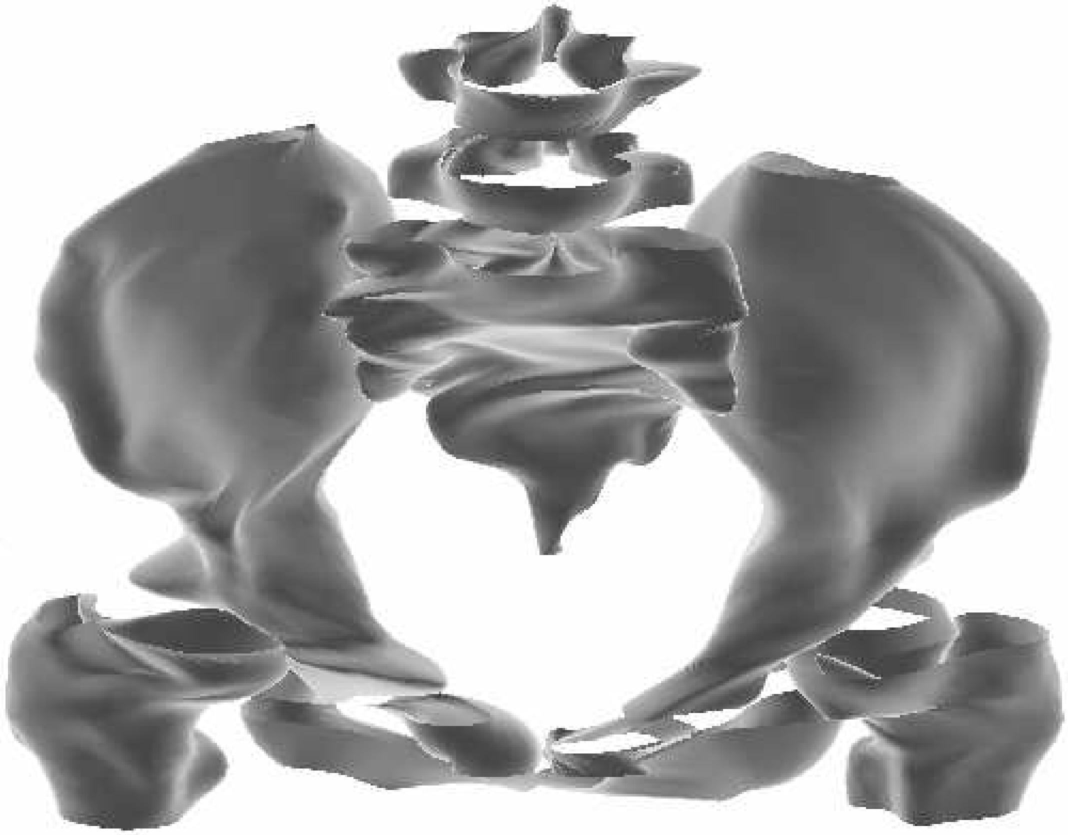

Figure 4: The major tube-like structures of the bones in the CT scan are rendered.

geometric solid modelling systems, provides the user with the ability to manipulate its geometric entities. In particular, the *surface mesh* capability of AutoCAD provides the potential for the analysis of force directly from our surface models of the maternal pelvis and that of the fetus.

The surface contacts between solids are always associated with a set of symmetries of the contacting surfaces. These symmetries form a group, known as the *symmetry group* of the surface. Relative motions between a pair of solids can be expressed precisely and completely by the symmetry groups of the contacting surfaces. A group theoretic formalization for describing surface contact between solids has been developed in [6, 8], where it is shown that the exact relative motion (position) of solids under surface contacts, which is either rigid or articulated, can be computed using the symmetry groups of contacting surfaces. A geometric representation for symmetry groups and an efficient group intersection algorithm using characteristic invariants has also been implemented [7]. This offers a rapid determination of an object's position with respect to its specified surface contacts with its environment. One advantage of this formulation is its ability to express continuous motions between two surface-contacting solids in a computational manner, and to avoid combinatorics arising from multiple relationships. A group theoretical analysis of joint movement (neck joint of the fetus) is to be applied to a simplified model of the atlas and axis of the fetal anatomy.

Like the simulation of the disassembly process in robotic assembly planning [6], the model of the fetus can be successively translated and rotated with respect to the model of the pelvis within the AutoCAD system. One can then check whether there exists any intersection between the trajectory volume swept by the fetus and the birth canal.

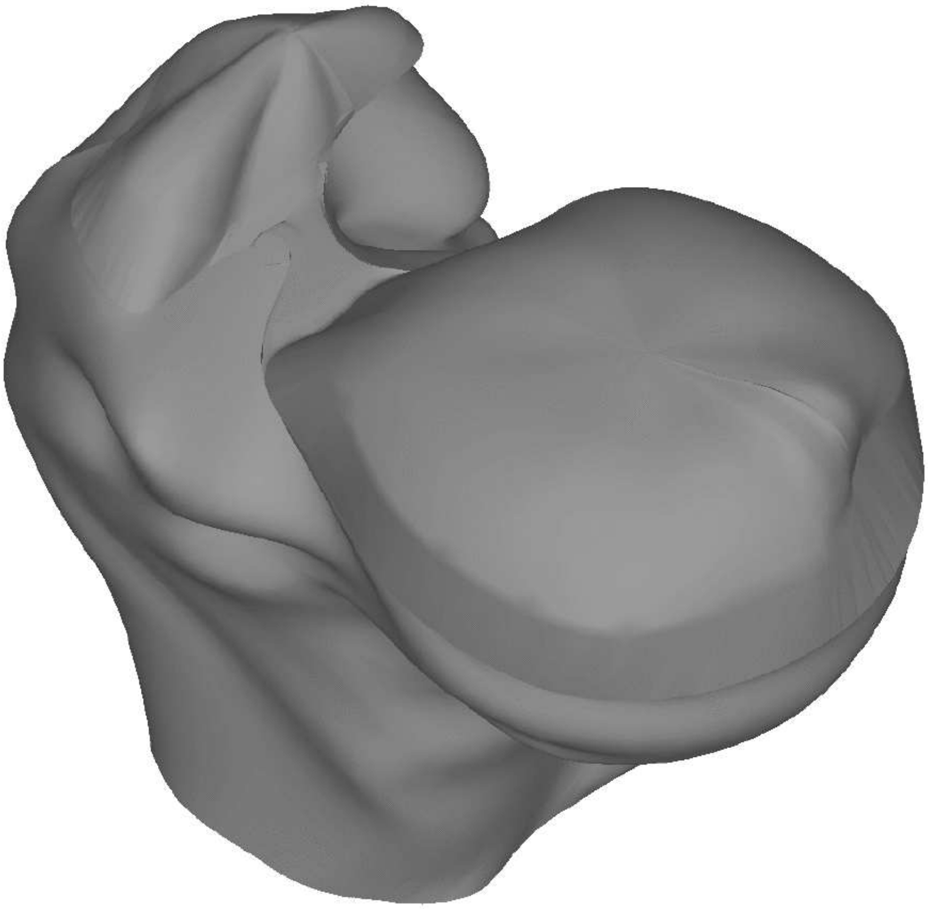

Figure 5: The rendered image of the complete right femur

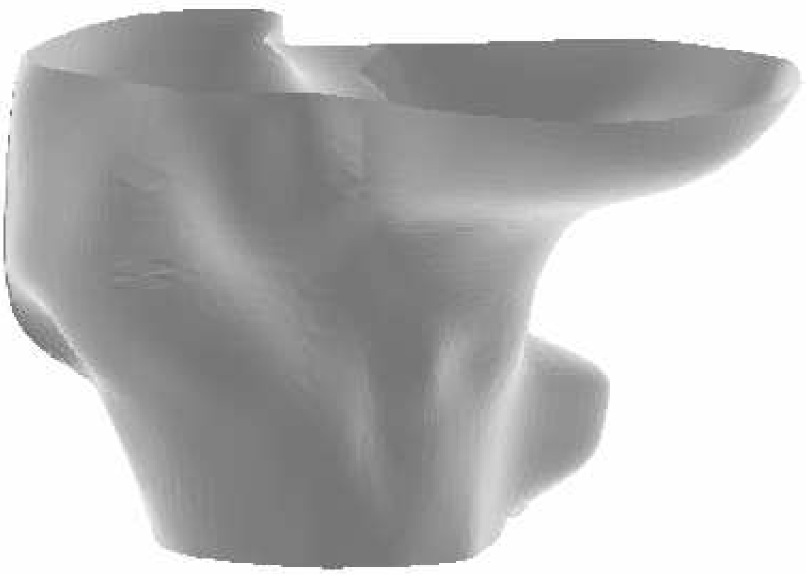

Figure 6: The rendered image of the right femur

If such intersection exists, either the trajectory can be altered to avoid the penetration or the deformation and the force can be analyzed.

4 Conclusion

What we have learned from our exercises on the CAD modelling of the birth process so far includes

- building three dimensional CAD surface models from CT scanned images can be done on PCs with limited software and hardware requirements, *and* achieve satisfactory results;

- transferring the data from a CT scanner to the PC is a non-trivial task[4] however, and special care needs to be taken on dealing with the singular points of the surface model;

- while we have been using 32 slices of CT scanned images to obtain a fairly detailed model, it yet remains to be seen what is the minimum number of slices which is sufficient for our purpose. Our guess is that any number above 10 should be enough, with more slices allowing greater accuracy and requiring more computation. Our approach should work on MRI scans as well.

- the resulting triangulated surfaces of the surface models have a computational advantage since there exists a rich pool of algorithms on dealing with such surfaces in computational geometry [12].

Though many open problems remain in our way, we can confidently say that using advanced computer modelling technique combined with the recent theoretical and algorithmic results from robotics and computational geometry is a feasible and comparatively inexpensive approach for modelling the childbirth process. Despite many years of experience and the development of new devices and techniques (e.g. vacuum extraction) in parturition, much about the birth process and the appropriate use of instrumental assistance remains unknown. The application of a scientific basis for decision-making in what has heretofore been an "art" has great potential for improvement in both the theoretical and clinical study of obstetrical management, to say nothing of the possible beneficial effects for women and their infants in childbirth.

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[4] In our case Picker Scientific was kind enough to provide us with a description of their proprietary format, and we were able to use the facilities at the University of Massachusetts at Amherst to rewrite the data on a media the PC was equipped to read.

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