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COMPUTER GRAPHICS MODELING OF ANATOMY: FROM 2D DATA ACQUISITION TO 3D SCULPTING

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ABSTRACT

This paper describes a process which is used to generate three-dimensional computer graphics surface models of gross anatomical structures. Key steps in the generation of these models include acquiring 2D cross-sectional data from macrocryotome slicing, generating 2D cross section contours from edge detection and region segmentation, generating a polygonal mesh surface model by triangulating between the 2D contours, and interactive sculpting of the 3D surface for editing and changing the appearance of the model. The algorithms and development involved with these steps are briefly described here and several images resulting from the process are presented. The main purpose of the paper is not to present the details of implementation of the various algorithms, but rather to present the overall methodology and illustrate the results. Implementation details can be found in other papers referenced here. The most recent results of our efforts, which are presented here, are 3D surface models of the complete human thorax. These models have numerous applications in anatomy and biomechanics visualization and teaching.

INTRODUCTION

The Vesalius Project at Colorado State University is developing a computer-based system to supplement cadaver study and serve as an innovative low-cost substitute at facilities where it is not practical to use cadavers [McCracken and Spurgeon, 1991a; McCracken and Spurgeon, 1991b; Alciatore and Miranda, 1992]. The project is named after Vesalius who was a 15th century pioneer in the dissection of cadavers. The project was originally funded by a grant from the Department of Education Fund for Improvement of Post Secondary Education (FIPSE) and is currently under private funding. The focus of the Vesalius Project is production of interactive anatomy educational software based on 3D computer graphics surface models of gross anatomy of the human body. The software would lead the student through an electronic dissection laboratory of realistic three-dimensional images of human anatomy. This will prove to be an extremely useful tool for biomedical student training. The images the student interacts with are stored on CD-ROM, CDI, and/or video laser disk and queried by multimedia interactive software running on PCs and Macintoshes.

Currently, we are working on a project to model the entire male and female bodies starting with complete models of the human thorax. This project is called the Glaxo Virtual Anatomy Project [Webster, 1994; http://www.vis.colostate.edu/library/gva/gva.html] and is funded by Glaxo Inc, a large pharmaceutical and health care research company. Applications of these models include biomechanics and anatomy visualization and education, cadaver dissection and surgery simulation, and medical condition and treatment plan illustration for medical doctors and their patients.

The remainder of this paper summarizes the entire process used to generate the 3D surface models of anatomical structures. Steps in the process include acquiring 2D cross-sectional data, performing edge detection on the 2D cross sections to obtain contours, triangulating between the contours to create a 3D surface model, and sculpting the resulting surface in 3D. Several of the resulting models, including those of the human thorax, are also presented.

ACQUIRING 2D CROSS-SECTIONAL DATA

Traditional data sources for human gross anatomy cross sections include computed tomography (CT), magnetic resonance imaging (MRI), and positron emission tomography (PET). These techniques are powerful tools for medical diagnosis, but in general lack the soft tissue resolution to be useful for constructing complete and accurate 3D models.

The most useful source of cross-section data for our project is color photographs of cadaver sections. Whitlock and

Spitzer [1989, 1990, 1991] at the University of Colorado Health Sciences Center (Denver, CO) have developed a process called macrocryotoming where they freeze cadaver specimens in blocks of gelatin and successively shave off 0.5 mm thicknesses with a stiff saw exposing cross sections. They store color photographs of these sections on video laser disks for easy perusal and acquisition through video frame grabbing hardware. An example image of a dog head section from this process is shown in Figure 1. Once these cross-sectional images are loaded into our editing software (as TIFF images) they can be interactively hand traced by a user and/or automatically segmented with edge detection algorithms (see next section). The result of this process is a set of vector-based contours (i.e., line strings) which surround the perimeters of anatomical structures of interest (e.g., bones, muscles, nerves, arteries).

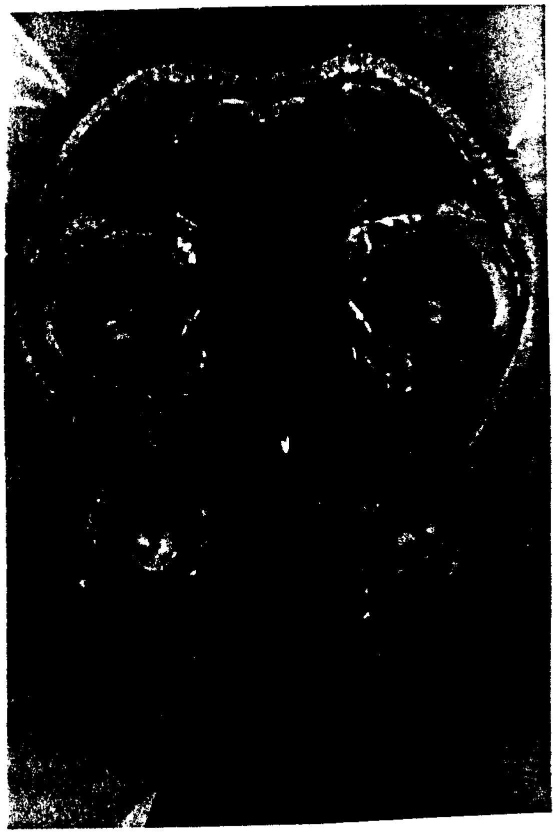

FIGURE 1 PHOTOGRAPH FROM MACROCRYOTOME SLICE THROUGH A DOG'S HEAD

Another source of contour data is the Digibot laser ranging surface scanner [Koch, 1991]. This scanning technology, based on single point triangulation ranging, was developed at Colorado State University as part of the Vesalius Project and is now commercially available through Digibotics (Austin, TX). There are also many other surface scanners available on the market which can digitize object surfaces [Wohlers, 1994; Wohlers, 1992]. The Digibot outputs successive vector-based planar contours of the external surface of physical specimen directly, one for each circular horizontal scan of the ranging laser. An example scan and rendering of part of a human femur is illustrated in Figure 2. Advantages of this system include its high resolution and the fact that it is completely automated resulting in the desired set of cross section vector-based contours (see next section). The disadvantage with this system for our application is its inability to scan interior features – only visible outside surfaces can be digitized. The Digibot or other digitizer can scan the surfaces of bones and plasticized organs beautifully, but the structures must first be removed from the specimen, cleaned, and prepared (e.g., dried, plasticized, sometimes painted), scanned, and then registered with surrounding 3D models once the 3D surfaces are created.

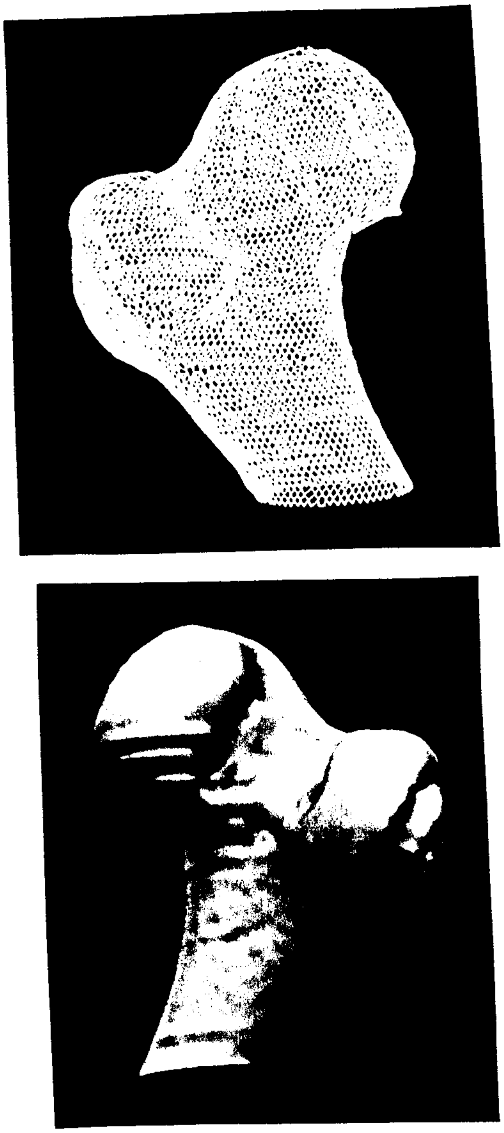

FIGURE 2 DIGIBOT-SCANNED FEMUR

CONTOUR GENERATION AND AUTOMATIC EDGE DETECTION

Once suitable cross section images are acquired, the next step is generating cross-sectional vector-based contours of the individual anatomical structures. These planar contours define the perimeters of the structures within each of the sections. The contours, which consist of ordered sequences of points connected by straight line segments (see Figure 4), are used by the surface-generating triangulation algorithms described in the next section.

Ideally, contours would be acquired from the cross section images automatically. There is an abundance of literature available on edge detection research and developments which addresses this problem – good representative articles are Ivins and Porril [1994], Boyer and Sarkar [1992], Bersen [1991], Cohen [1991], Kaabi et al. [1991], Kass, et al. [1987], and Davis [1975]. However, although the general processing techniques presented are well understood, they are usually only valuable with relatively clean (noise-free, simple) images. These techniques are not easily and robustly applied to the complicated images found in our application. Anatomy cross-sections possess complex, poorly defined geometry with noisy and poorly delineated segmented regions representative of the structure of interest. The general procedure we are currently using to help detect the edges of the anatomical structures within the 2D cross-sectional images is described below:

1.) Filter the image with modified pixel neighborhood averaging to eliminate noise and non useful region textures.
2.) Use the filtered image histogram (pixel frequency vs. color intensity) to suggest color intensity thresholds between which the pixels are assumed to have constant color intensity.
3.) Apply a local Laplacian or Sobel operator to isolate areas (bands of pixels) of large color intensity gradient.
4.) Create vector-based contours through the pixel bands of large gradients where, theoretically, there are edges in the image.
5.) Have a user with anatomical training interactively touch up or trace over edge detection results.

An example of the results of steps 1 through 3 of this process applied to an MRI cross section through a human thigh is shown in Figure 3. The output image containing the pixel bands is the result of filtering, histogram thresholding, and Laplacian differentiation and rate thresholding. As is obvious in this image, the result is only an approximation of the desired structure perimeters, and subsequent processing and user interaction is still required to produce vector-based contours.

We are currently investigating use of active snakes [Kass, et al., 1987; Cohen, 1991; Ivins and Porril, 1994] in improving our edge detection capabilities. Active snakes are closed energy minimizing splines which are numerically shaped to enclose similar regions and locate edge features. Statistical measures are commonly used to characterize the enclosing regions and traditional edge detection measures are commonly used to help lock the snake onto edges. The snake or spine is also given tension and bending stiffness properties to help maintain a natural shape. Active snake edge detection and region segmentation are much more promising than more traditional image procession methods, especially for medical imaging applications. We are also currently investigating applying the active snake method in conjunction with neural network methods for characterizing regions [Crawford, 1994].

FIGURE 3 EDGE DETECTION IN AN MRI IMAGE (MRI COURTESY OF OTSUKA, FORT COLLINS, CO)

SURFACE MODEL TRIANGULATION

Planar vector-based contour data is ideal for generating triangulations of 3D anatomical surfaces between successive contour levels (see Figure 4) which when assembled form the complete surface model representation of the anatomical structure (see Figure 5).

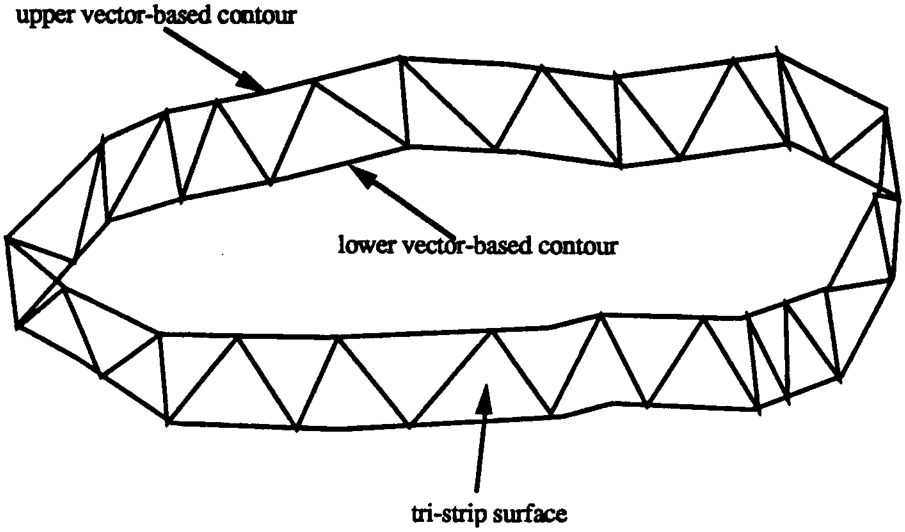

FIGURE 4 CONTOUR-TO-CONTOUR TRIANGULATED SURFACE

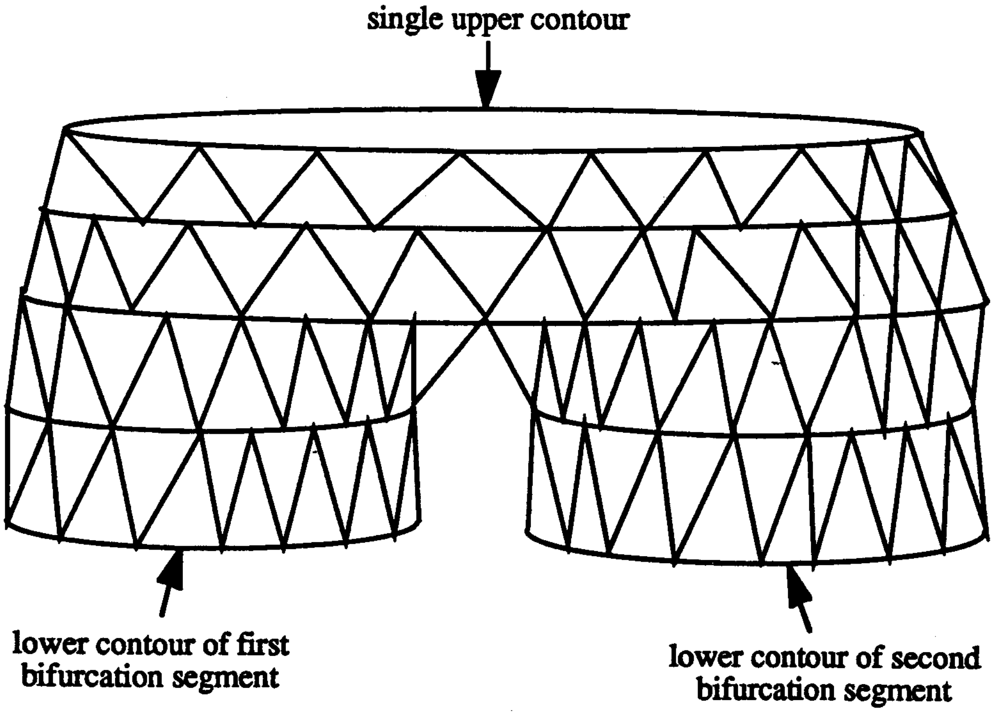

FIGURE 5 TRIANGULATED SURFACE

To generate 3D triangulated surfaces, contour connectivity across all cross-sectional levels must be determined. Our method of performing this uses an overlap criteria which can deal with surface splitting or other anomalies such as the bifurcation illustrated in Figure 5 [Miranda et al., 1990]. After the contour connectivity has been determined, any number of triangulation algorithms may be invoked. There are many successful instances of the development of such triangulators in the literature [Goldwasser et al., 1988; Schlusselberg et al., 1988; Lorensen and Cline, 1987; Kehtarnavaz et al., 1988; Kehtarnavaz and DeFigueiredo, 1988; Miranda et al., 1990]. One such triangulator has been developed during the course of the Vesalius Project at Colorado State University [Miranda et al., 1990]. This particular triangulator is capable of generating surfaces which bifurcate, even with multiple splittings (e.g., the flesh of the human hand bifurcating into five fingers). The Vesalius triangulator can also handle surfaces which are not closed (e.g., the orbit of the eye sockets in the human skull).

IMAGE RENDERING

The triangulated anatomical structure surfaces are rendered into realistic computer graphics images using standard surface imaging techniques. The surface vertices, normal vectors, and material properties such as color and reflectivity are used to perform Gouraud shading calculations and z-buffer hidden surface removal resulting in realistic color-shaded images of the modeled anatomical structures. An example image of a rendered dog head model is shown in Figure 6. Cross-sectional data for this model was acquired from CT images of a live dog under anesthesia (courtesy of the Colorado State University Veterinary Hospital).

FIGURE 6 RENDERED DOG HEAD MODEL FROM CT DATA

3D SCULPTING OF THE TRIANGULATED SURFACE MODEL

Once a structure's triangulated (polygonal) surface mesh has been constructed and rendered, often artifacts (i.e., features which are not supposed to be there) appear in the model images. These missing or aberrant features are usually the result of problems or error in the cross-section contour generation phase. Sometimes, the edge detector and/or the user's hand tracings miss features and/or add features due to poor interpretation of the cross-section images. Interactive 3D polygonal mesh sculpting (editing) software has been developed to facilitate correction of these problems. The user easily performs interactive sculpting operations on the 3D surface according to the following procedure:

1.) the user interactively define an area of influence (a 3D closed polygon) on the surface with the mouse.
2.) the user interactively defines a spine (3D line string) in the interior of the area of influence which defines the high points (ridge) of the stretched surface. The software can also automatically define this based on determining the interior points farthest from the area perimeter.
3.) the software assumes that the surface will be stretched normal to the center point on the spine but the user can interactively adjust this direction with the mouse.
4.) the user interactively stretches the surface until the desired shape change is achieved. The surface is deformed in a cubic fashion where C^1 (position, and slope) continuity is maintained at the influence area perimeter and at the spine.

The details of this implementation are presented elsewhere [Alciatore, 1995], and include algorithms and techniques for determining surface geodesics, determining the interior of a closed surface polygon, and applying surface mesh refinement and decimation techniques. The power and ease of this interactive sculpting is illustrated in Figure 7 where an inexperienced user was able to totally transform the appearance of a scanned face with about 30 minutes of interactive editing. Even an experience clay sculptor would not be capable of performing such transformations as quickly working with a clay model. The polygonal mesh for this face was acquired from a plaster impression scanned with a Digibot laser digitizing system (courtesy of Digibotics, Austin, TX).

In addition to removing erroneous features on the anatomy models, the computer-aided sculpting tool can also be used to deform the models to represent organ or tissue abnormalities (e.g., cancerous growths or inflammation). Also, a dynamic structure such as the heart could be sculpted into the different shapes representing the beating cycles, and then and animation of the complete beating cycle could be easily created by interpolating between the cycle shapes.

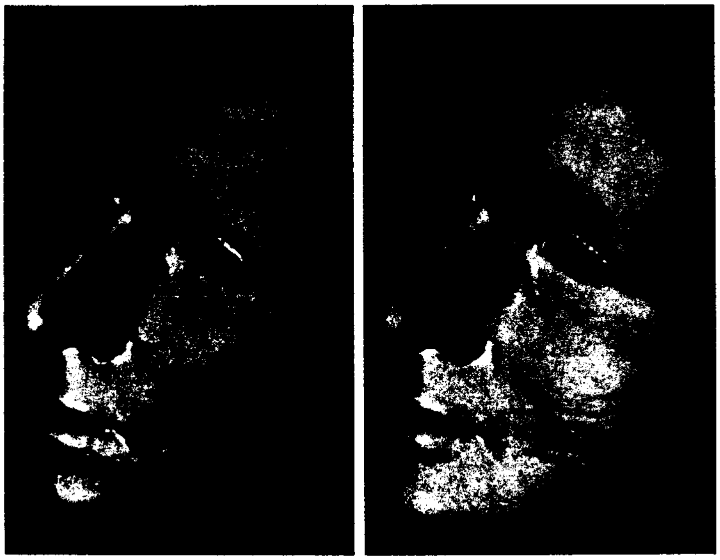

FIGURE 7 FACE SURFACE TRANSFORMED WITH INTERACTIVE SCULPTING SOFTWARE

HUMAN BODY MODELING RESULTS

The thorax models we have created to date for the Glaxo Virtual Anatomy Project include all of the bones, most of the muscles, major veins and arteries, the heart, the lungs, and the trachea and bronchi. Input for these models was macrocryotome slices of a cadaver's thorax taken at 0.5 mm separation. Each section is stored as a 2000 by 3000 24-bit RGB digital image. Approximately 650 sections were cut and photographed for the entire thorax. Custom developed software [Gulden, 1994] was used to perform edge detection and to allow interactive computer-assisted manual tracing of structures within each of the sections. The custom developed triangulation software [Miranda, 1990] was then used to develop surfaces between the section contours. The resulting polygonal mesh surfaces were then rendered with realistic colors and texture maps using Wavefront's Advanced Visualizer. Texture images were acquired from photographs of live dog organs and tissues during surgeries at Colorado State University's Veterinary Hospital. The textures from the dog tissues are similar to that of humans, but in the future we will attempt to acquire live human textures with consent from open heart surgery photographs. Rendered images of our current human thorax models are shown in Figures 8.

CONCLUSIONS AND FUTURE WORK

In our efforts to generate computer graphics surface models we have developed algorithms and software capable of detecting edges and generating vector-based contours in cross-sectional images (from MRI, CT, or macrocryotome photographs), triangulating 3D polygonal mesh surfaces between the 2D contours, rendering these surfaces, and editing the surfaces through 3D interactive sculpting. All of these algorithms and software have been implemented on Silicon Graphics IRIS (SGI) workstations using C and the SGI GL graphics library. The purpose of this paper was to present an overview of the entire process and show the results of our recent work. Implementation details and related work can be found in the references cited for each of the steps in the process.

The next major task in our development is to improve and automate the contour generation phase of data entry. Our present edge detection algorithms are promising but much work still remains before the results will be truly useful. The operator (a trained anatomist) is still required to do a significant amount of on-screen hand tracing to compensate for failures and ambiguities from the edge detector.

Our long term goal is to generate a complete anatomically correct polygonal surface-based models of the entire human male and female bodies. We are currently being supported by Glaxo, Inc to pursue this goal [Webster, 1994]. The most useful engineering-related application for these models is biomechanics visualization and teaching where students could visualize, in 3D, operating organs such as a pumping heart or breathing lung, and operating joints such as a flexing knee complete with muscle contractions. Other applications for the models include anatomy education, surgery illustration, and medical illustration.

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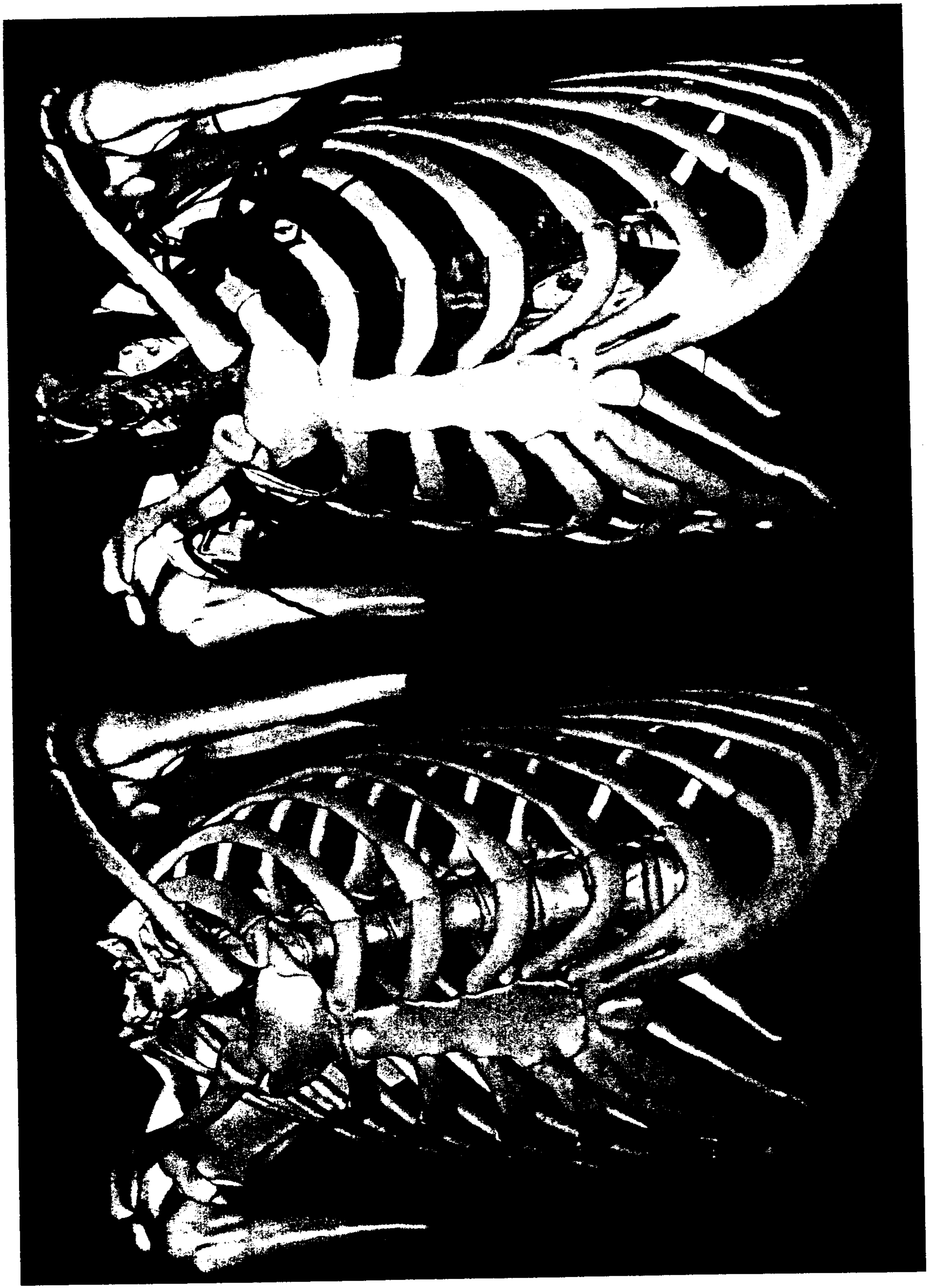

(i)

FIGURE 8 HUMAN THORAX SURFACE MODELS CREATED FOR GLAXO VIRTUAL ANATOMY PROJECT

(ii)

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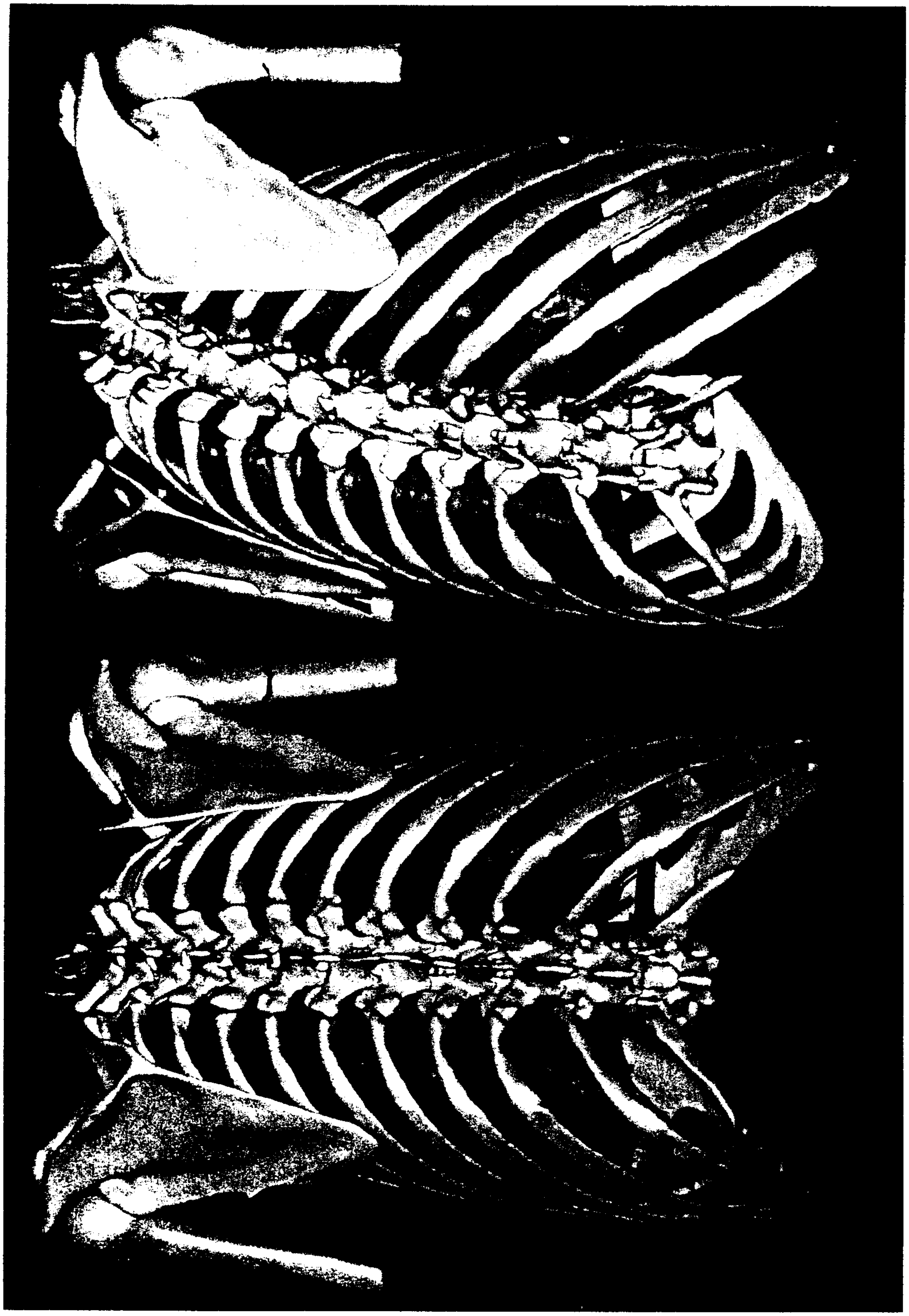

(iii)

FIGURE 8 HUMAN THORAX SURFACE MODELS CREATED FOR GLAXO VIRTUAL ANATOMY PROJECT