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Explorable Three-Dimensional Digital Model of the Female Pelvis, Pelvic Contents, and Perineum for Anatomical Education

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The anatomy of the pelvis is complex, multilayered, and its three-dimensional organization is conceptually difficult for students to grasp. The aim of this project was to create an explorable and projectable stereoscopic, three-dimensional (3D) model of the female pelvis and pelvic contents for anatomical education. The model was created using cryosection images obtained from the Visible Human Project, in conjunction with a general-purpose three-dimensional segmentation and surface-rendering program. Anatomical areas of interest were identified and labeled on consecutive images. Each 2D slice was reassembled, forming a three-dimensional model. The model includes the pelvic girdle, organs of the pelvic cavity, surrounding musculature, the perineum, neurovascular structures, and the peritoneum. Each structure can be controlled separately (e.g. added, subtracted, made transparent) to reveal organization and/or relationships between structures. The model can be manipulated and/or projected stereoscopically to visualize structures and relationships from different angles with excellent spatial perception. Because of its ease of use and versatility, we expect this model may provide a powerful teaching tool for learning in the classroom or in the laboratory. Anat Sci Educ 3: 127–133. © 2010 American Association of Anatomists.

Key words: gross anatomy; three-dimensional models; stereoscopic models; anatomical reconstruction; female pelvis; virtual pelvis; reproductive organs; perineum; medical education; teaching tool

INTRODUCTION

The study of anatomy plays an integral role in the education of health care professionals. Many clinical tasks and procedures require a firm understanding of spatial relationships between closely associated structures (Cottam, 1999; Garg et al., 2001). However, limitations of standard educational methods become problematic when trying to learn or teach inherently complex regions of the human body, such as the female pelvis. Restrictions of traditional teaching techniques coupled with a decrease in curriculum time allocated to anatomy (Blake, 1980; Drake et al., 2002, 2009) have challenged the medical pedagogue to explore alternate teaching methods to augment those that currently exist (Nicholson et al., 2006). Dramatic advances in technology and imaging modalities, as well as the availability of cross-sectional data have afforded the development of three-dimensional (3D) anatomical models (Vernon, 2002; Bajka et al., 2004).

The Visible Human Project (VHP) is currently the most important international source of high quality images of human gross anatomy (Jastrow and Vollrath, 2003). The VHP consists of volumetric data, representative of a normal adult male (Visible Human Male, VHM) and female (Visible Human Female, VHF) (Ackerman, 1998). A comprehensive technical report on the Visible Human Male (VHM) documents how both data sets were prepared (Spitzer and Whitlock, 1998). Each set contains magnetic resonance imaging, computer tomography, and cryosection photographic data sets. Since their creation, the Visible Human data sets have

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been applied to a wide range of uses, including, but not limited to education, medicine, industry, and art (Ackerman, 1998). Not surprisingly, the Visible Human Project data finds its primary application in health care and education. A number of three-dimensional anatomical models have been created using the VHP data including lumbar vertebra (John et al., 2001), female abdomen and pelvis (Bajka et al., 2004), and male pelvis (Brook et al., 1998). Jastrow and Vollrath provided a compilation of anatomy projects, including those available online, in CD-ROM form, or in print that focus on teaching three-dimensional anatomy using digitized sections from the Visible Human Project (Jastrow and Vollrath, 2003).

The aim of this project is to create an explorable, three-dimensional (3D) model of the female pelvis and perineum for anatomical education using full resolution cryosection images obtained from the Visible Human.

METHODS

Cryosection images were chosen for this pelvis reconstruction. In total, 753 slices were chosen for reconstruction: from the level of the superior border of the iliac crests, superiorly, to the level distal to the lesser trochanter of the femur, inferiorly (slice numbers avf1703a-avf1953c). Before model construction, the color images were checked for sequential alignment, converted to black and white images, and cropped to a size that encompassed the largest structures in the section of data used for this reconstruction (Adobe Photoshop, San José, CA). This image stack was then imported into a general purpose, three-dimensional segmentation and surface rendering program, Amira 4.1 (Mercury Computer System, Chemsford, MA).

The general process of model generation is described by Brenton et al. (2007) and Nguyen et al. (2009). The first step in creating 3D reconstructions is a process termed segmentation. Simply, segmentation involves digitally identifying and labeling regions of interest on individual 2D slices. The process must be completed on all slices in which the region of interest is present in order for accurate representation. The majority of the segmentation occurred in the axial plane; however, for torturous structures, such as blood vessels, many planes of view were required in order to segment them completely. The model could then undergo further processing, such as smoothing, to become more presentable and portable. The smoothing process takes the form of a digital filter. As 2D slices are stacked together, the software produces a 3D mesh with several million polygons forming the surface of each digital component of the model. By reducing the number of polygons the model surface interpolates between polygon intersections thus smoothing the surface visually and economizes computing power to allow the model to be represented without high end graphic processors. Care is taken not to reduce the number of polygons so far that the surface becomes distorted.

Generally, segmentation for the pelvis proceeded from the largest to the smallest structures. Bones were segmented first because of their ease of recognition; they appeared as the whitest structures in the cryosection images. These were followed by the upper limits of lower limb muscles. Each muscle was recognized by its anatomical position and size, as well as its attachment and insertion to the surrounding structures. This strategy of identification worked efficiently for the muscles of the pelvic floor as well. The next group of structures to be segmented was organs of the pelvic cavity, the rectum, uterus, and bladder, in conjunction with their associating structures, the anal canal, vagina, and urethra. The most delicate structures, including components of the perineum, blood vessels, and peritoneum, were last to be segmented. Throughout the segmentation of these latter structures, orientation, position, and surrounding structures were constantly consulted to ensure anatomical accuracy.

RESULTS

A three-dimensional model of the female pelvis, pelvic contents, and perineum was created using thin section human cryosections and digital segmentation. The surrounding musculature of the trunk and lower limb was also segmented, resulting in 60 reconstructed structures (Table 1).

The pelvis model created here includes the anatomical details required for undergraduate and medical education. Individual structures of the 3D model are displayed in a variety of alterable colors. The colors presented in the illustrations here were assigned to the structures during the segmentation process, and by no means represent realistic hue or texture. Bright colors were chosen to provide contrast and differentiation for closely opposed anatomical structures. To project all components of the model simultaneously would not offer optimal visualization and learning opportunities for the student viewer. Users, however, can create countless permutations of the model by changing the colors, or adding anatomical structures in combinations from the list described in Table 1. Once a subset of anatomical detail is chosen for projection, users can manipulate the 3D model from any angle (Fig. 1) and magnification. This model allows for significant magnification and, given that the model is a 3-dimenstional volume, users can enter and/or orient structures to explore the anatomy from previously unseen aspects, for example, viewing the abdominal cavity from within the pelvic cavity. Additionally, the model allows for individual structures to be added and removed independently, enabling students to participate in "virtual" dissection or syncretion, the process of putting things back together (Fig. 2A–2D) (Miller, 2000). Furthermore, any structure in the model can be made semitransparent, allowing for deeper relationships to be observed (Fig. 3). Anatomical structures can be labeled at any orientation or magnification for of the purposes of self-study or for defining anatomical landmarks. The labeling feature can also be applied to a 3D view such that the leader line follows the anatomical landmark in any plane the viewer defines. Finally, a unique feature of the virtual pelvis model is that it allows for the simultaneous display of one or more of the Visible Human's high resolution cryosection images in conjunction with the 3D model (Fig. 4). These images can be displayed in any plane, and allow for the correlation between the two-dimensional images and the three-dimensional model.

The resultant model can be displayed in four ways. First, two-dimensional images or snapshots of the model can be captured and displayed elsewhere, for example a lecture presentation. Second, the 3D model can be viewed at a computer workstation, enabling the observer to both manipulate the model utilizing features previously described. Third, preprogrammed digital videos of the model can be made and incor-

Table 1.

Summary of Three-Dimensional Reconstructed Structures of the Female Pelvis

Bones:	**Urinary viscera:**	**Back muscles:**
Pelvic bone	Ureter	Erector spinae
Sacrum	Bladder	**Lower limb muscles:**
Coccyx	Urethra	Gluteus maximus
Lumbar vertebra (L5)	**Perineum:**	Gluteus medius
Femur (proximal)	External urethral sphincter	Gluteus minimus
Supporting structures:	External anal sphincter	Obturator externus
Intervertebral disc (L5/S1)	Crus of clitoris	Gemellus superior
Round ligament of uterus	Bulb of vestibule	Gemellus inferior
Ligament of ovary	Ischiocavernosus	Quadratus femoris
Suspensory ligament of ovary	Bulbospongiosus	Adductor longus
Peritoneum	**Neurovascular structures:**	Adductor brevis
Pelvic floor/wall muscles:	Common iliac vessels	Adductor magnus
Piriformis	External iliac vessels	Pectineus
Obturator internus	Internal iliac vessels	Gracilis
Levator ani	Obturator nerve	Sartorius
Coccygeus	Sacral plexus	Rectus femoris
Gastrointestinal viscera:	**Abdominal muscles:**	Vastus lateralis
Rectum/anal canal	Iliopsoas	Vastus medialis
Reproductive viscera:	Quadratus lumborum	Vastus intermedius
Ovary	Rectus abdominis	Tensor fasciae latae
Uterine tube	External oblique	Biceps femoris
Uterus	Internal oblique	Semitendinosus
Vagina	Transversus abdominis	Semimembranosus

porated into lectures, online learning modules, or portable visualization devices (CRIPT, 2009). In these videos, important anatomical structures can be labeled, the model can rotate and allow different perspectives, and the 2D cryosection images can be superimposed to allow visualization of spatial relationships. Finally, the model can be viewed in a stereoscopic 3D mode using passive projection systems. This method allows for maximal manipulation of, and immersive interaction with, the pelvis.

The passive stereoscopic system comprises dual projectors (InFocus IN36, Wilsonville, OR) with one projector displaying a left eye image and the other displaying a right eye image, two linearly polarized lenses, polarized glasses (with matching polarized lenses), and a single silver screen. To achieve the stereo effect, Amira's passive stereo output functionality is used to project the model from the projectors through linearly polarized lenses. The lenses are placed such that the polarization planes run perpendicular to each other. With this arrangement, only vertically-polarized light can pass through one lens, and only horizontally-polarized light can pass through the other lens. Light rays that pass through the filters project the images onto a nondepolarizing silver screen. Observers wearing polarized glasses will unknowingly see two independent images: one eye sees the vertically-polarized image and the other eye sees the horizontally-polarized image. When viewed simultaneously, the brain interprets the

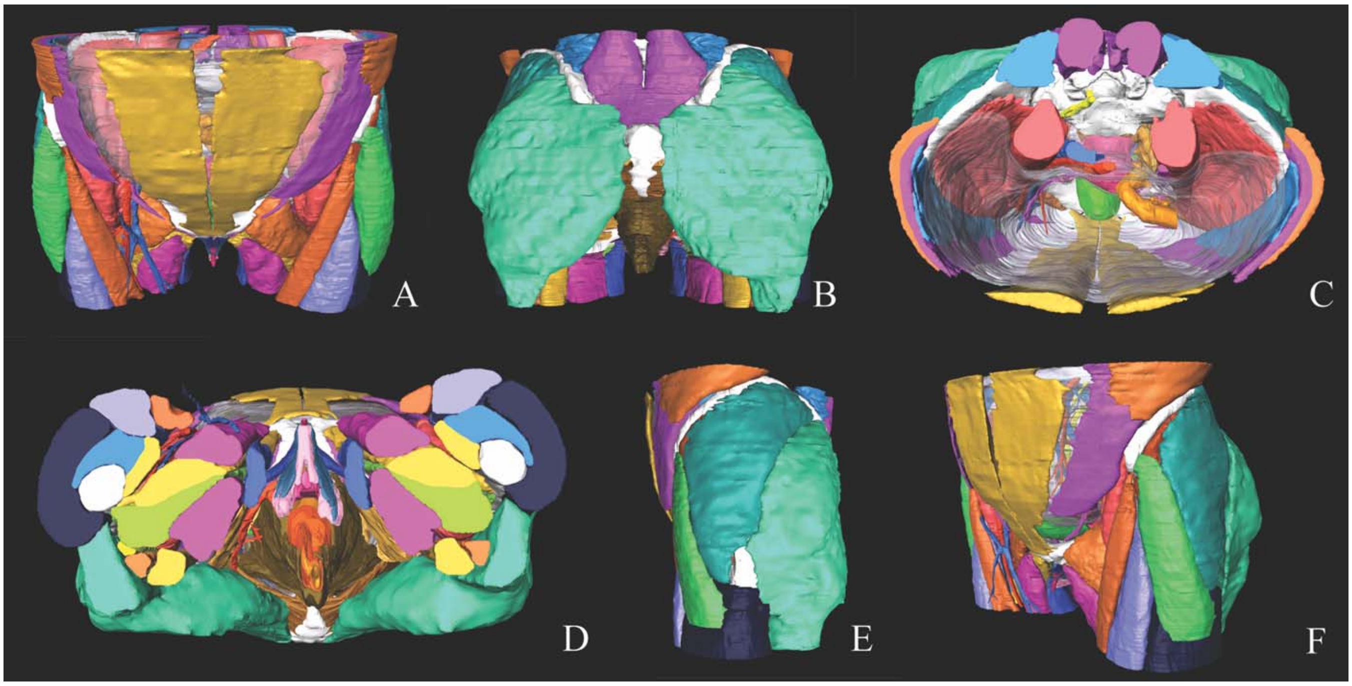

Figure 1.

Female pelvis, pelvic contents, and perineum. All reconstructed anatomical structures from different views: anterior (**A**), posterior (**B**), superior (**C**), inferior (**D**), lateral (**E**), and oblique (**F**).

disparity between the two retinal images and reconstructs the depth dimension in the observers' visual world (Poggio and Poggio, 1984).

DISCUSSION

To our knowledge, this is the first electronic model of the female pelvis created using the VHF cryosection data at its full resolution, thus making it the most detailed volume-based digital representation of its kind. Other models of the female pelvis have been created using a variety of cross-sectional data (Pearl et al., 1999; Beyersdorff et al., 2001; Parikh et al., 2004). However, these models focus primarily on the muscles of the pelvic floor, and do not acknowledge surrounding structures, for example the perineum. Lack of detail, complexity, and completeness may offer educators limited usage of such models. Most similar to the model created in this project was one that was created by Bajka et al. (2004) also utilizing cryosection images from the VHF. Their reconstruction, detailed the abdomen and pelvis, showing pertinent organs, blood vessels, bones, muscles, and ligaments. One limitation to their model however, was the inability to completely segment the vestibule of the vagina and the perineum, due likely, to their methodology incorporating only a subset of cryosection images. In their reconstruction, every other, or essentially half the cryosection images were omitted. Furthermore, the remaining images were down-sampled to half the original resolution. Bajka and coworkers (2004) report those responsible for structure segmentation found it difficult to differentiate the edges of organs and tissues; this may be the result of the decreased image resolution. The applications of their model as a teaching/learning tool or surgical simulator were not discussed; therefore, the key features and potential limitations of that model are unknown.

Two other examples of pelvic digital models are present in the literature. A male pelvis model was created from coregistered CT and MR for educational purposes (Holubar et al., 2009). Pilot surveys suggest a high level of user preference for their model and although some participants felt a greater level of detail was required, the tool was well received (Hassinger et al., 2010). Hassinger and his collaborators suggests further testing is warranted to understand the incremental impacts the model affords to anatomical education as it pertains to surgery. Finally, another male pelvis was created from high resolution CT scan data. Interestingly, an air enema and CT angiographic methods aided the differentiation of pelvic viscera and vasculature (Yu et al., 2008). The authors, like the current study, plan to incorporate their model into surgical education training scenarios to provide validation of novel training regimes.

Several other anatomical models have been created for anatomical education, including the bones of the wrist (Garg et al., 1999), the inner ear (Nicholson et al., 2006), the skull base and cranial nerves (Kakizawa et al., 2007), the abdomen (Luursema et al., 2006), the shoulder (Hariri et al., 2004), and the male pelvis (Brooks et al., 1998; Venuti et al., 2004). The effectiveness of these computer generated models as a viable and effective teaching tool is still under great debate. Some reports suggest that interactive 3D models are a benefi-

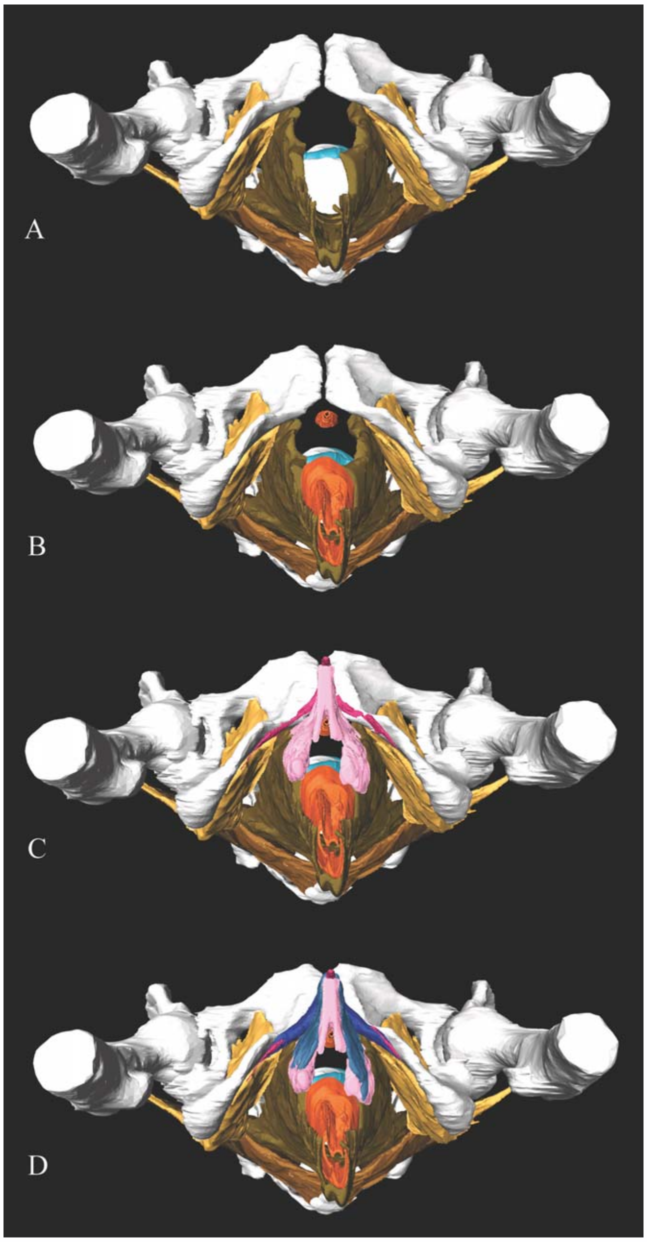

Figure 2.

Structures of the female perineum. An inferior view of the structures of the female perineum depicting the add and/or remove capabilities of the model beginning with the pelvic floor (**A**) and adding the external urethral and anal sphincters (**B**), erectile tissues (**C**), and their associating muscles (**D**).

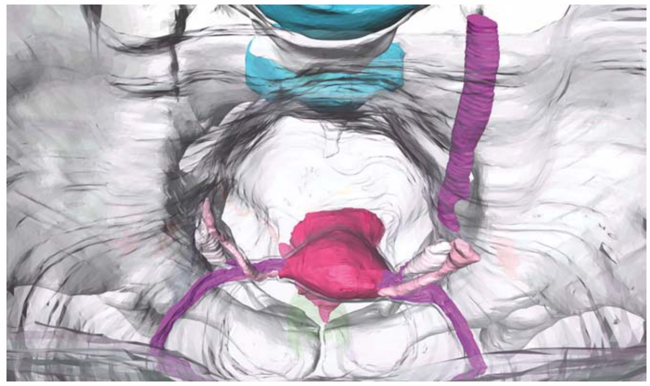

Figure 3.

Female pelvic peritoneum. An antero-superior view of the semitransparent pelvic peritoneum as it drapes over the uterus and uterine tubes.

cial aid to student's comprehension of specific anatomical material (Luursema et al., 2006; Nicholson et al., 2006). Other studies suggest there is no advantage to 3D models, as they do not enhance student learning or performance on tests (Garg et al., 2002; Hariri et al., 2004), and may actually handicap those students with poor spatial ability (Garg et al., 1999). However, those who found negative results investigated the effectiveness of 3D models using a model of the wrist. The bones of the wrist naturally fall into two planes, anterior and posterior, are all relatively the same size, and do not consist of much spatial information. It would be interesting and informative if the same results were found using a model of a more visually complex area, such as the female pelvis.

Patel and Moxham's review of the literature indicates that many institutions tend to implement teaching techniques, including 3D models, without first investigating their effectiveness as a teaching tool (Patel and Moxham, 2008). Future projects will involve assessing the effectiveness of the female pelvic model as a teaching/learning tool before introducing it into the laboratory or classroom. The versatility of the model allows for several different types of studies to be conducted. For example, the effect of manipulation of and interaction

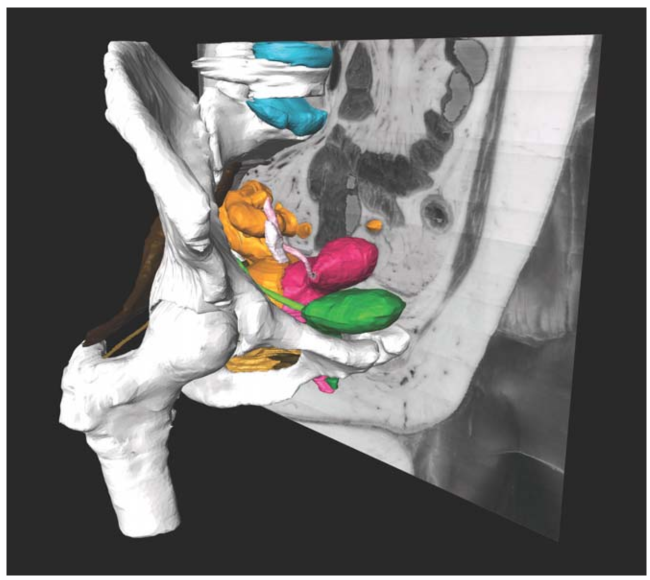

Figure 4.

Organs of the female pelvic girdle. An oblique view of 3D pelvic girdle and viscera accompanied by superimposed sagittal slice of Visible Human Female (VHF) cryosection image.

with the model on student learning could be analyzed, or its effectiveness compared with cadaveric dissection or the use of prosections could be assessed. By addressing these basic research questions, instructors will be able to better plan educational approaches that maximize learning in the evolving anatomy classroom.

Taking advantage of the flexibility of the model described here, it will be possible to approach the pelvic anatomy through virtual dissection as well as through "syncretion" (Miller, 2000). Miller coined this term to identify an alternate approach to dissection that involves "putting things back together again." In other words, students would start with an empty body cavity to which careful sequences of structures are added to produce a more complex and realistic anatomical cavity. He further suggests that learning gross anatomy, particularly of the visually complex body cavities, would be easier if students utilized a "syncretion" approach, as this approach to learning may be perceptually preferable compared with that of gross dissection. Studies to confirm whether the "syncretion" approach is effective when learning gross anatomy still need to be conducted and the virtual realm might be the most appropriate venue; thus, the female pelvic model could be used as an instrument to investigate this suggestion.

Once established as an appropriate teaching tool, other virtual models allowing deep user control may be introduced in the health care education curricula. Currently, medical school curricula in North America are being altered to include more emphasis on imaging techniques, clinical correlations, and cross-sectional data. To deliver this type of material, instructors are relying less on lecture and dissection, and more on case studies, problem-based learning, and computer learning (Collins et al., 1994; Cottam, 1999). This trend may afford investigations examining the effects of inclusion of digital models into the evolving medical curricula.

CONCLUSIONS

The female pelvis is a challenging region of human anatomy to conceptualize using traditional teaching modalities. A three-dimensional model of the female pelvis, pelvic contents, and perineum was created through segmentation of full resolution cryosection images from the Visible Human Female. Interaction with, and modification and manipulation of the model allows for the visualization of the dimensionality and spatial relationships that exist in the living female pelvis. This model provides a platform from which digital anatomical teaching tools for the classroom or the laboratory can be born.

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