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MEDICAL EDUCATION

New Views of Male Pelvic Anatomy: Role of Computer-Generated 3D Images

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There is considerable controversy concerning the role of cadaveric dissection in teaching gross anatomy and the potential of using 3D computer-generated images to substitute for actual laboratory dissections. There are currently few high-quality 3D virtual models of anatomy available to evaluate the utility of computer-generated images. Existing 3D models are frequently of structures that are easily examined in three dimensions by removal from the cadaver, i.e., the heart, skull, and brain. We have focused on developing a 3D model of the pelvis, a region that is conceptually difficult and relatively inaccessible for student dissection. We feel students will benefit tremendously from 3D views of the pelvic anatomy. We generated 3D models of the male pelvic anatomy from hand-segmented color Visible Human Male cryosection data, reconstructed and visualized by Columbia University's in-house 3D Vesalius™ Visualizer.[1] These 3D models depict the anatomy of the region in a realistic true-to-life color and texture. They can be used to create 3D anatomical scenes, with arbitrary complexity, where the component anatomical structures are displayed in correct 3D anatomical relationships. Moreover, a sequence of 3D scenes can be defined to simulate actual dissection. Structures can be added in a layered sequence from the bony framework to build from the "inside-out" or disassembled much like a true laboratory dissection from the "outside-in." These 3D reconstructed anatomical models can provide views of the structures from new perspectives and have the potential to improve understanding of the anatomical relationships of the pelvic region (http://www.cellbiology.lsuhsc.edu/People/Faculty/Venuti_Figures/movie_index.html). Clin. Anat. 17:261–271, 2004. © 2004 Wiley-Liss, Inc.

Key words: 3D anatomy; visible human; pelvis and perineum; computer models

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INTRODUCTION

Over the last few decades there has been considerable discussion concerning the demise of human anatomy courses and the possibility of eliminating anatomical dissection as part of the basic science curriculum (Collins et al., 1994; Utting and Willan, 1995; Newell, 1995; Skidmore, 1995; Dinsmore et al., 1999). This concern derives in part from a shift in emphasis in the medical school curriculum coupled with a significant decrease in the number of trained anatomists to teach the anatomical sciences (Collins et al., 1994; Woolliscroft, 1995). Less time is allotted for students to learn anatomy despite the rapid development of computer-based diagnostic imaging and virtual reality surgical techniques, which will require an even greater understanding of the 3D relationships that are the basis of human anatomy (Marks, 1996; Neider et al., 2000; Marks, 2000). With fewer anatomists being trained in this ancient profession, it is clear that new ways of teaching anatomy must be considered.

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[1] Trademark held by Columbia University. The Vesalius Project™ is named after Andreas Vesalius, a 16th century anatomist whose work laid the foundation for all subsequent anatomical research. Columbia University trademarked the name Vesalius in 1997 for use in the production of educational software.

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Rapid progress in the development of computer graphics, 3D medical visualization, and interactive multi-media has allowed the development of computer-based applications. These applications can provide new views of the human anatomy and new approaches for teaching and learning (Hohne et al., 1995; Marks, 1996, 2000). Although the importance of dissection in human anatomical teaching has been hotly debated, there is little concrete evidence to support the argument that computer programs can supplant dissection and traditional approaches for learning anatomy. Few studies have examined the pros and cons of using computer-based images to illustrate and learn anatomy. In part, this is because the few programs available continue to use the paradigm of a printed textbook where static images are combined with text. The true interactivity that the computer can provide has not been fully developed in these programs. Computers offer the potential for anatomy to be organized in a more compact and logical way. Students can view the anatomy by starting with simple relationships and structures and build more complex anatomical relationships (Miller, 2000). Knowledge engineering can structure the symbolic information of anatomy more consistently and flexibly than conventional textbooks and atlases (Rosse, 1995; Wacholder et al., 1998, 2000a,b).

The Visible Human (VH) Project data sets were designed to serve as a common reference point for the study of human anatomy by providing data for testing medical imaging algorithms and to construct image libraries (Spitzer et al., 1996; Ackerman, 1998). The ultimate goal of the VH Project for the National Library of Medicine is to "link functional-physiological knowledge with an image library of structural-anatomical knowledge into one unified health information resource" (VH Fact Sheet, http://www.nlm.nih.gov/pubs/factsheets/visible_human.html). One consequence of creating image libraries using the VH data is the ability to generate 3D images that can be viewed from any angle and in varying degrees of complexity.

Our goal is to use 3D *maximal* models (Imielinska and Molholt, 2002) of anatomical structures generated from the VH data to develop resources to supplement those currently available for teaching human anatomy. This effort is part of a larger project that involves research on medical image processing and 3D visualization (Imielinska et al., 1996a,b, 1998, 2000a,b; Thumann et al., 2002), knowledge-base (ontology) development (Bean et al., 1996; Wacholder et al., 1998, 2000a,b), and curriculum development (Molholt et al., 1998; Venuti et al., 1998, 2000; Imielinska and Molholt, 2002). The ultimate objective is to develop cross-platform, innovative, and integrated computer resources for students learning anatomy. The approach we employed was to develop a "curriculum-driven" resource from the VH data; the 3D models of anatomical structures and 3D scenes generated from the models provide views of the anatomy that illustrate important 3D anatomical relationships or concepts that are difficult to convey by conventional means, yet are important clinically. We also wanted to generate 3D images that illustrate anatomical concepts that would particularly benefit from the 3D reconstruction of anatomy using the VH data.

In an effort to develop application-driven segmentation and reconstruction of the VH rather than random 3D visualizations, we focused on the pelvic and perineal regions. These anatomical regions prove to be extremely difficult for students to understand and currently available anatomical models do not provide sufficient detail, nor are they designed to be used in interactive applications. Students find this portion of human anatomy particularly frustrating and often come away with only a minimal understanding of the urogenital structures and their three-dimensional relationships. Because reproductive health, urology, obstetrics, and health problems of associated pelvic structures constitute a high proportion of visits to the physician each year, development of learning tools that provide a clearer 3D view of these anatomical regions is essential. The advent of new diagnostic imaging techniques also strongly argues for an increased need for understanding the 3D anatomical relationships of this region.

Currently, relationships between pelvic structures are most frequently viewed by using laboratory models in conjunction with cadaver dissection, textbook illustrations and skeletal models; however, conventional anatomical dissection by necessity can destroy or remove clinically relevant structures. In addition, because of the compact nature of the perineal/urogenital region, certain anatomical features are difficult to find in cadavers. This difficulty is compounded by anatomical atlas illustrations that are misleading because they portray structures to be far more robust than they are in reality. We hope to provide new views of the pelvic anatomy from different perspectives and to support different learning styles. We have generated images that not only provide new perspectives but also are more accurate depictions of the male pelvic structures and their relationships, thus improving the potential for understanding the anatomy of the region.

MATERIALS AND METHODS

We used the 3D Vesalius™ Visualizer to model the 3D pelvic anatomy (Imielinska et al., 1998; Imielinska and Molholt, 2002; Thumann et al., 2002). We first generated the maximal 3D model for each anatomical structure in the region that could be displayed and labeled in separation. We call a 3D model of an anatomical structure the maximal model if its shape matches the spatial resolution of the data set and its texture inherits full color resolution from the original voxel set (Imielinska and Molholt, 2002). The maximal models are used as building blocks to create anatomical scenes of arbitrary complexity, with the component structures depicted in anatomically correct 3D spatial relationships. From the maximal models one can derive smaller 3D models via a reduction method (Thumann et al., 2002) where the shape representation is compressed and the color texture perceptually preserved. The actual segmentation was carried out by hand and guided by an anatomist, as there is currently no reliable automated segmentation method that can separate individual muscles in the pelvis/perineum. Our goal is to extract models with all the available color texture information provided by the data. We decided not to use automated segmentation methods we have developed for other medical applications (Imielinska et al., Imielinska et al., 2000a,b, 2001), because we wished to stress the extraction of the detail present in the VH data and the results from currently available automated segmentation methods are not precise enough.

The 3D Vesalius™ Visualizer reconstructs highly detailed surfaces that are rendered in the color volumetric texture provided by the VH data. These initial models can be reduced, translated into standard 3D formats, and pseudo-colored. Our models are surface-based and textured in photographic quality, fresh human tissue color that provides a uniquely realistic representation of the anatomy. Each structure is segmented separately and can be used to generate an anatomical structure in isolation or combined with other structures to create a composite.

We have segmented all of the individual muscles of the pelvis and perineum and most of the pelvic viscera from the male VH. We have not segmented neurovascular structures nor structures from the Female VH. Our analyses of the anatomy depicted in the resulting 3D reconstructed anatomical structures of the VH Male and that described by others (Brooks et al., 1998) suggest that illustrations of this region should be revised in standard textbooks and atlases. We discuss three areas where the computerized images we have generated provide a more realistic depiction of the pelvic anatomical structures and their relationships than standard illustrations in commonly used atlases and textbooks. These include the pelvic diaphragm muscles, the perineal muscles and their relationships, and the bladder–prostate relationship.

RESULTS

Bony Pelvis

We began our reconstruction of the VH male pelvis by segmenting the bony pelvis. We outlined the pelvic bones in slices that encompassed the pelvis and lower abdomen. The boundaries of the bony tissue were easily distinguished from the surrounding tissues in the color cross sections. The segmented slices were combined to generate a model of the bony pelvis as a single unit (Fig. 1A). This model serves as a framework to which we can add other structures in the region (sequences in Figs. 1,2,5) and can be viewed from any viewpoint in 3D. Although it is possible to model the individual bones that comprise the bony pelvis from these slices, for our purposes of building and dissecting the pelvic anatomy on the computer, we chose to use the bony pelvis as a composite.

The model of the bony pelvis we generated uses the color and texture of the tissue in the VH. For this reason it lacks the detail and contrast that is seen when one examines preserved bones. In the future, the 3D scenes can be enhanced by shadows, multiple light sources, and pseudo-color textures, if needed to improve the realistic appearance of the models and highlight individual structures. The relationship of the individual bones can be examined in QTVRs that allow the student to see the bony pelvis in 3D virtual space as they would if they were holding the bony pelvis out in front of them (Movie 1A–C; to view movies go to: http://www.cellbiology.lsuhsc.edu/People/Faculty/Venuti_Figures/movie_index.html).

The advantage of our reconstructed pelvis is that it can be used to add other components of the pelvic anatomy and view them in true-to-life color and their correct spatial relationships. Because the pelvis is compact and the numerous relevant structures are concentrated in a small region we propose that the perspective provided in our 3D visualization is unique and provides views that are not available to students from either textbooks or dissections. In addition the images allow for self-instruction and interactive learning.

Pelvic Wall and Floor Muscles

Once we generated the model of the bony pelvis, we wanted to add the various pelvic structures in a useful way, we began by adding the muscles in the pelvic walls. These include the muscles that form the lateral walls (obturator internus muscles), the pelvic

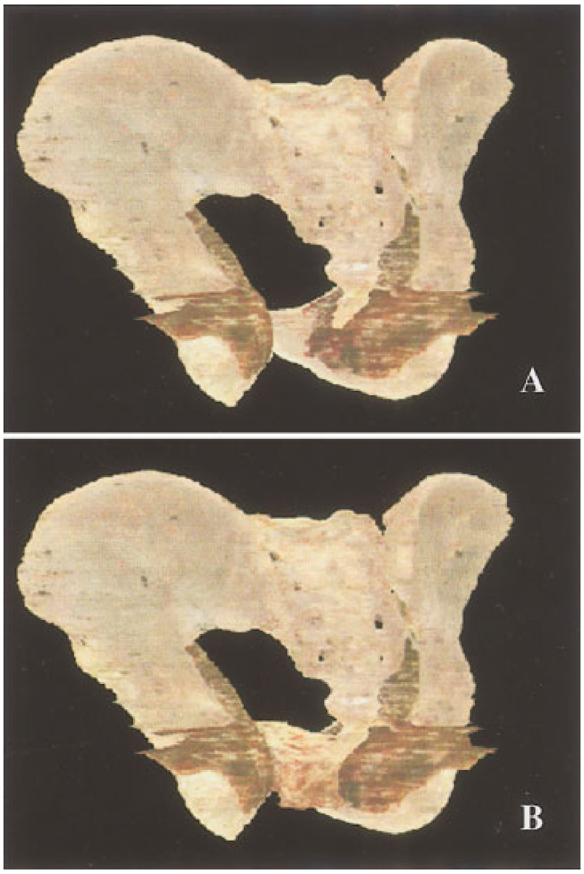

Fig. 2. Oblique (posterolateral) views of the bony pelvis showing the relationship of the levator ani muscles to the obturator internus muscles. The levator ani muscles originate laterally in part from a thickening in the fascial covering of the obturator internus muscles termed the “tendinous arch of the obturator fascia.” The ischioanal fossae are the spaces formed beneath the levator ani muscles and medial to the fascia covering the obturator internus muscles in the perineum.

floor (the levator ani and ischiococcygeus muscles), and the posterior walls (piriformis muscles). These muscles are important because they form boundaries of the pelvis and provide the framework from which the relationships of other pelvic structures can be added and visualized.

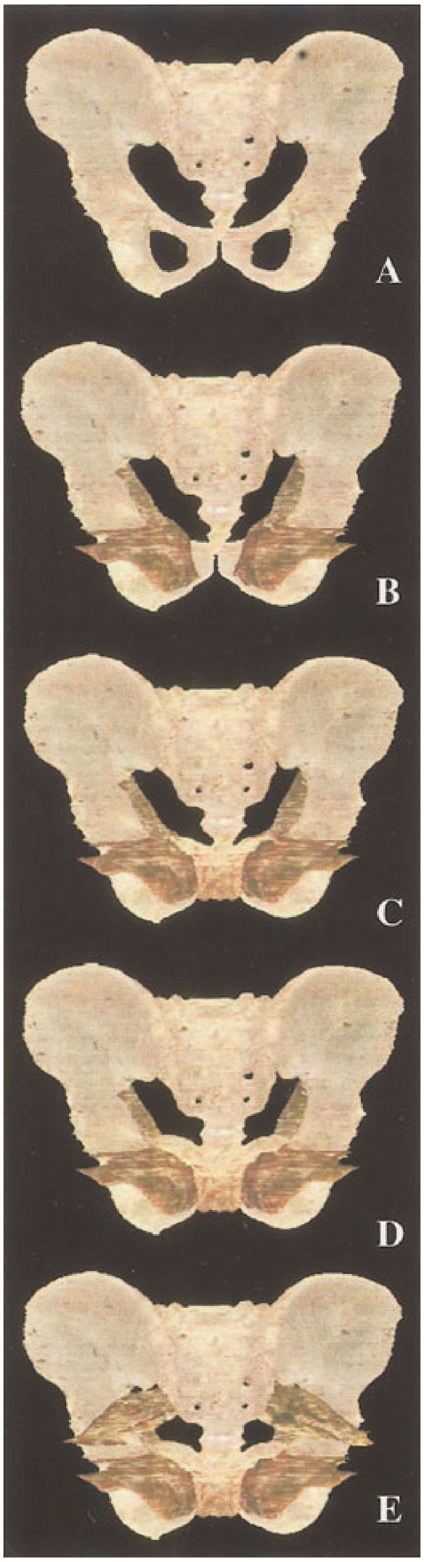

Fig. 1. Successive addition of the pelvic and related muscles to the bony pelvis to illustrate the relationship of the pelvic diaphragm muscles to other muscles in the true and false pelvis. **A:** Posterior view of the bony pelvis. **B:** Addition of the obturator internus muscles that form part of the lateral wall of the true pelvis and perineal regions. **C:** Addition of the levator ani muscles illustrates the space occupied by the ischioanal fossae. **D:** Addition of the ischiococcygeus muscles that form the posterior part of the pelvic diaphragm. **E:** Addition posterosuperiorly of the piriformis muscles, important landmarks for the exit of the sciatic nerve and gluteal neurovascular bundles from the pelvis to the gluteal region.

The pelvic floor is classically defined as the pelvic diaphragm consisting of the levator ani and ischiococcygeus muscles and the fascia covering the superior aspects of these muscles. The levator ani muscles have important dynamic functions in: supporting the abdominopelvic viscera (especially the uterus in the female); resisting intra-abdominal pressure during forced expiration (coughing, sneezing, urinating, vomiting, etc.); and in the voluntary control of urination and defecation. The pelvic diaphragm extends between the pubis anteriorly and the coccyx posteriorly, and from one lateral pelvic wall to the other. In lateral and medial views the levator ani muscles together with the ischiococcygeus muscles are classically depicted as a hammock-like structure that supports the pelvic viscera. Together these structures compose the "pelvic diaphragm" (Netter, 1997, plates 333, 334). The pelvic diaphragm also separates the pelvic cavity from the perineum and defines the roof of the ischioanal fossae where it arises from the lateral walls of the pelvis formed by the obturator internus muscles. In a classic depiction of the pelvic diaphragm the shape of the levator ani muscle and its relationship to the obturator internus muscle is difficult to discern as these muscles are often shown in different views but rarely in their entirety (Netter, 1997, plates 333–336; Agur and Lee, 1999, Figs. 3.10, 3.13, 3.21, 3.22). Most illustrations give the impression that the pelvic diaphragm is a hammock or bowl-shaped structure. Our 3D reconstructions from the VH Male data set show that the levator ani muscles are shaped very differently than depicted in classic illustrations. The 3D images we have generated show instead that the muscles are considerably more cylindrical (Fig. 1C,D, Fig. 2B, Fig. 3A–J) and have vertical walls that are in close apposition to the prostate in the male (Fig. 3C–J). The discrepancy between our illustrations and those shown in some atlases may arise from the fact that many of the atlas illustrations use the female pelvic diaphragm as a model for illustration and this may actually be less cylindrical than that of the male. However, the view of the female pelvis seen at http://summit.stanford.edu/ourwork/PROJECTS/LUCY/lucywebsite/levator.html shows a female levator ani (reconstructed from digital images of frozen sections) that is similar in size and shape to the male levator ani we have generated from the VH data. In addition, other published descriptions (Brooks et al., 1998; Shafik, 1999) and other atlas illustrations support our model of the levator ani muscles. Still, the possibility remains that the VH Male pelvis and the Stanford Female pelvis were distorted during cryopreservation or preparation for sectioning.

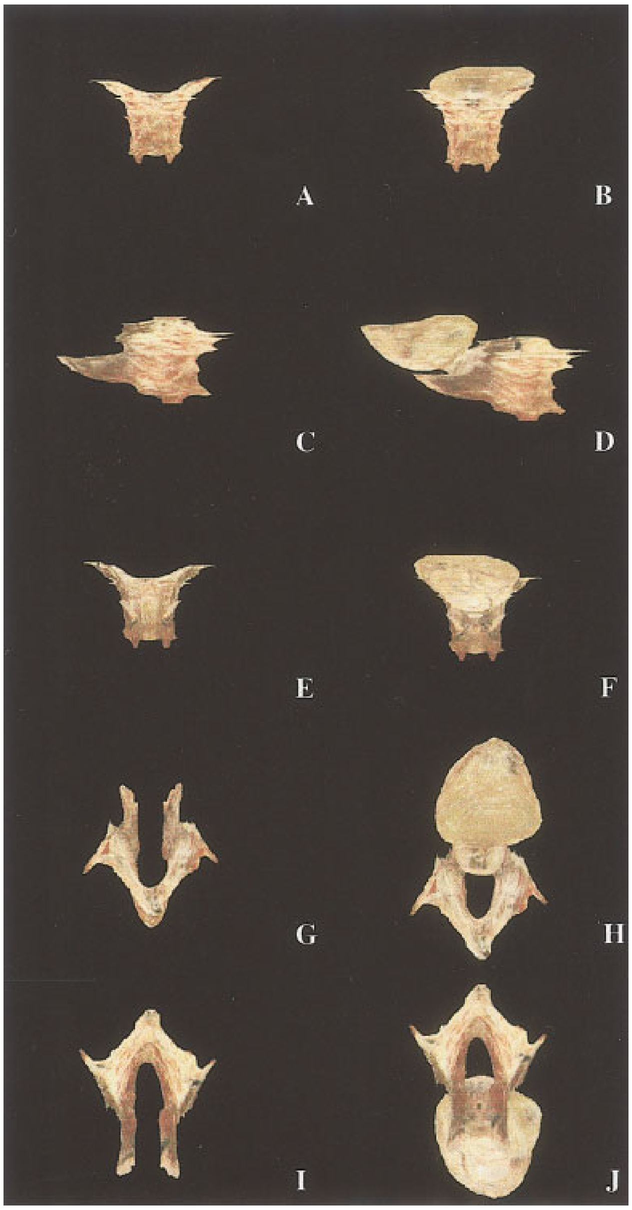

Fig. 3. The isolated levator ani muscles and the levator ani muscles in relation to the bladder and prostate from different perspectives. **A,B:** Posterior; **C,D:** lateral; **E,F:** anterior; **G,H:** superior; **I,J:** inferior views.

An advantage of our models is that we can demonstrate relationships by creating 3D scenes that show the structures individually or as composites of an arbitrary complexity. The student can move from simple combinations of structures to the more complex, allowing reconstruction of the anatomy from the "inside-out." One can also begin with complex composites of structures and disassemble them from the outside in as in conventional dissections or surgeries. By examining these structures in a movie one can view them from various perspectives, which is nearly impossible during cadaver dissection.

By adding the pelvic muscles to the bony pelvis in sequence (Fig. 1), the individual muscles can be identified and their relationships to other structures clearly discerned. This can be used as a series of 2D snapshots of the same 3D scene at different viewpoints in 3D space (compare view in Fig. 1 vs. Fig. 2 and Movie 6) or can be viewed as consecutive QTVRs (Movies 1A and 2–5). In these models the 3D relationships between the structures can be viewed clearly as one rotates the model after adding structures sequentially. Figure 2 shows the relationship of the levator ani muscles to the obturator internus muscles from an oblique view and illustrates the space occupied by the ischioanal fossae. This area can be seen better if one rotates the models in space (Movies 2, 3). Because the 3D relationships of these structures are visible, one can gain new perspectives on the structures and their relationships. Figure 3 illustrates the levator ani muscles alone (Fig. 3A,C,E,G,I) or as a composite with the bladder and prostate (Fig. 3B,D,F,H,J). In this way, the shape and extent of an individual structure can be examined in isolation and in relation to adjacent structures. To further clarify these relationships, the structures can be rotated in QTVRs (Movies 7A–C, 8A–C) and compared.

Because different combinations of structures are useful for illustrating specific relationships we can combine only certain structures and eliminate others. For example, when segmenting the levator ani from other muscles of the pelvic region we found it extremely difficult to determine where fibers of the levator ani muscles end and fibers of the external anal sphincter muscles begin. In addition, this region is highly vascularized and the true-to-life color of the VH data make it difficult to differentiate the inferior muscle fibers of the levator ani from veins and arteries that infiltrate this region. This is one of the limitations of using the VH data. We therefore excluded the inferior fibers in our illustration of the pelvic diaphragm because we wished to focus on the muscles that form the pelvic boundaries and the pelvic diaphragm (Figs. 1–3). It should be noted, however, that the lower and medial-most fibers of the levator ani insert circumferentially around the anus and blend with the muscles of the external anal sphincter posteriorly and the bulbospongiosus anteriorly. Unfortunately, this portion of the levator ani muscles, the puboperinealis muscles, are frequently neglected and overlooked. They have been segmented and reconstructed by others using MRI images (Myers et al., 1998, 2000) and can be viewed online (http://www.mayo.edu/ppmovie/pp.v.html).

Perineal Muscles

Once we generated the models of the bony pelvis and added the associated muscles of the pelvic walls, we segmented the muscles of the perineum. Our reconstruction of the muscles of the perineum, particularly the muscles of the urogenital triangle, show their relationship to the pelvic viscera is different from atlas illustrations.

The urogenital triangle contains small muscles and the erectile tissue that forms the root of the penis (Netter, 1997, plates 355–357). The structures are often illustrated as pouches so that the relationships can be studied and understood in the context of different spatial compartments (Agur, 1991, Fig. 3.59; Moore and Dalley, 1999, Fig. 3.34); however, the relationships between these structures are difficult to discern from dissections and atlas illustrations. Typically, the latter show these structures as "larger than life" making it difficult for students to relate the anatomy of their cadavers to that seen in atlases. In addition, the concept of a UG diaphragm has been questioned and is generally considered to be erroneous (Myers, 2001). A trilaminar UG diaphragm is often described as consisting of the perineal membrane inferiorly, an adjacent striated urethral sphincter muscle (deep transverse perineal muscle) and its fascia superiorly, these structures together forming a transverse plate between the ischiopubic rami. Although the long held concept of a flat "sandwich" is now considered invalid, the continuity of the striated urethral muscle and its superior fascia remain inaccurately depicted in many atlases. In most cadavers the striated urethral sphincter muscle, the principle component of the "deep pouch," does not form a transverse triangular structure because it is intimately associated with the prostate. Because it also can be infiltrated by the extensive prostatic vascular plexuses in adult males, its integrity is often lost and it is difficult to identify in cadaveric dissections (Oelrich, 1980).

To create a new perspective of the perineum we segmented and reconstructed the individual structures in 3D. Next, we created a sequence of 3D scenes, starting with the bones and sequentially adding one structure at a time to the next scene. Using a fixed 3D viewpoint, we snapped 2D views of the consecutive 3D scenes and created a movie that builds the anatomy by showing the positioning and appropriate relationship of these structures (Fig. 4; Movie 9). The layers can be combined interactively so that students can add or subtract them during study. In this way, students can better understand how the structures of this confined region come together and form the different, clinically relevant, spatial compart-

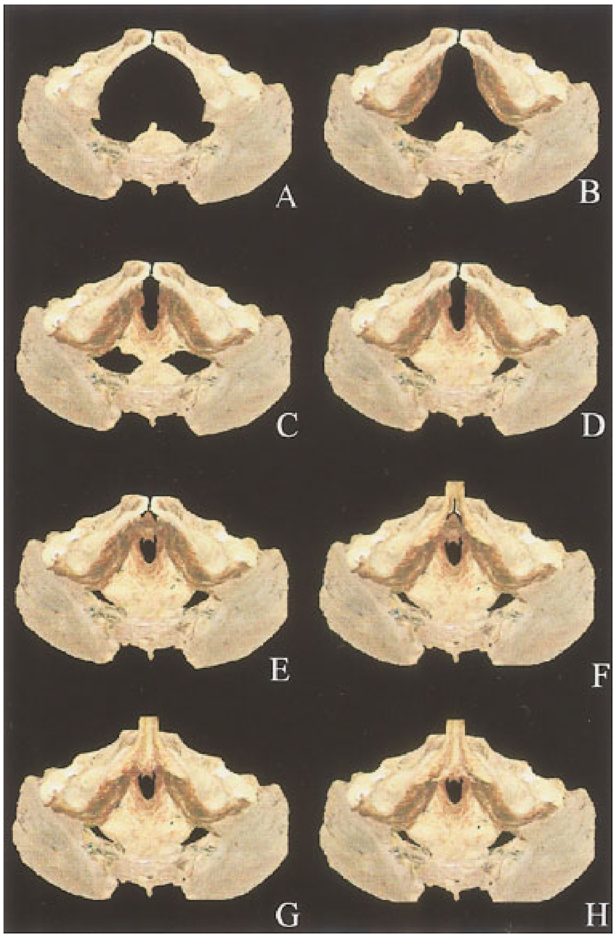

Fig. 4. Successive additions of the perineal muscles to an inferior view of the bony pelvis. **A:** An inferior view of the bones of the pelvis. **B:** The obturator internus muscles are added to (A). **C:** The levator ani muscles are added to (B). **D:** The ischiococcygeus muscles are added to (C). **E:** The sphincter urethrae muscles are added to (D). **F:** The ischiocavernosus muscles are added to (E). **G:** The bulbospongiosus muscles are added to (F). **H:** The superficial transverse perineal muscles are added to (G).

ments. In addition, structures can be added consecutively and the structures rotated to better view the relationships (Movies 10–14). Eventually, it should be possible to arbitrarily list individual structures of the pelvis that can be combined "on the fly" to illustrate specific relationships.

Bladder

We next added the pelvic viscera to the framework of the bones and muscles. We segmented the pelvic urogenital system, including the bladder, prostate, seminal vesicles, vas deferens, and urethra. We also segmented the external genitalia, including perineal structures at the root of the penis, the testes, and the penis.

Conventionally, the urinary bladder is represented as a balloon-like structure that sits directly above and on the prostate (Netter, 1997, plates 338, 343, 358; Agur and Lee, 1991, Fig. 3.11, 3.28; Olson, 1996, Fig. 345). Our reconstructed images (Figs. 3,5) show that the bladder is positioned anterior to the prostate, so that the angle between the bladder neck and the prostate is more oblique than vertical. This relationship is confirmed in photographs of dissections of the region (Rohan et al., 1998).

The reconstructions of the urogenital structures can be combined so that important relationships can be highlighted. The seminal vesicle and prostate are relatively inaccessible in an intact pelvis. Their juxtapo-

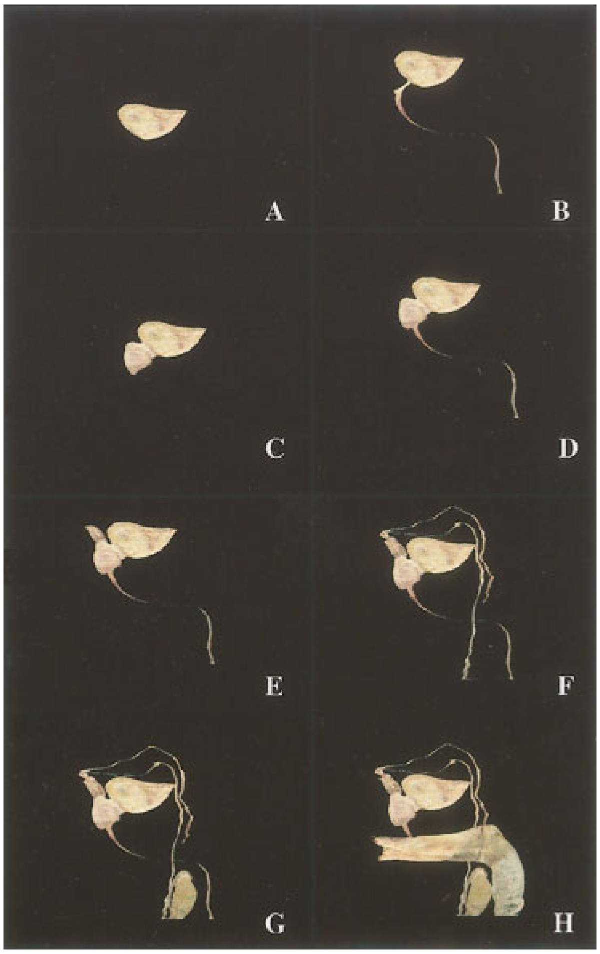

Fig. 5. Lateral views of the urinary bladder in isolation and with the successive addition of other urogenital structures. **A:** The isolated urinary bladder. **B:** Addition of the urethra to (A). **C:** Addition of the prostate gland to (A). **D:** Addition of both the urethra and prostate gland to (A). **E:** Addition of the seminal vesicle to (D). **F:** Addition of the vas deferens to (E). **G:** Addition of the epididymis and testes to (F). **H:** Addition of the penis to (G). Note that the inferior most portion of the testis and glans penis terminate abruptly. This is due to a loss of sections from this region as a consequence of transecting the VH male cadaver before cryopreservation.

sition is not clearly visible until the pelvis is hemisected. We can use our computer reconstructions to create movies to show the position of the seminal vesicle in relation to the ductus deferens, prostate and bladder from different perspectives (Fig. 5). The addition of other components of the urogenital system allows the student to view the relationships of all the structures by building or dissecting using the computer images (Movies 15A–C, 16A–C). Our 3D representation of these relationships, particularly in QTVRs, provides a more “true-to-life” representation of the anatomy than the illustrations in most traditional atlases and textbooks. Although the VH Male is missing a testis and data was lost because he was transected below his pelvis, these missing structures can be added by superimposition of computer generated illustrations of the missing structures.

Other Anatomical Features

We have not yet segmented the vasculature or neural structures of the region. A major difficulty in using images of fresh frozen tissue is an inability to resolve structures that are similar in color. The connective tissue, fat and small nerves and vessels are almost indistinguishable. The exact boundaries of muscles are sometimes difficult to discern because they blend with each other. We therefore have not attempted to segment these structures using the VH Male data. In the future, it should be possible to use illustrations to supplement the reconstructions of these structures where necessary.

SUMMARY

We have segmented the individual muscles of the pelvis and perineum and most of the pelvic viscera from the VH Male data set. Our 3D visualizations of the anatomy suggest that illustrations of this region should be re-examined in standard textbooks and atlases. The levator ani muscle, for example, which forms the majority of the pelvic diaphragm, is classically depicted as a hammock-like structure that supports the pelvic viscera, hence the term “diaphragm.” The 3D representations of this structure from the VH Male data set show the levator ani muscles to be considerably more cylindrical and to have lateral walls that are vertical and in close apposition to the prostate. Similarly, the urinary bladder is conventionally represented as a balloon-like structure that sits directly on the prostate. Our 3D visualizations show a different relationship between these structures.

DISCUSSION

The development and widespread use of new diagnostic imaging techniques argue for a renewed emphasis on understanding human anatomy (Stoker et al., 2001). Clearly, knowledge of cross-sectional anatomy is essential for the interpretation of MRI and CT patient data. As imaging techniques evolve, there will be an increased need to reconstruct 3D anatomy from these cross-sectional data and for interpretation of other modalities such as ultrasonography. Because fewer anatomists are available and less time is allotted to students to learn anatomy, new ways of presenting the anatomical relationships must be developed. We propose that 3D visualizations of anatomy can provide new views and perspectives that will aid in understanding the important relationships and structures. This will allow educators to focus on conveying clinically relevant concepts that are dependent on understanding these underlying anatomical relationships. Providing students with 3D virtual models that they can use interactively and on their own will allow them to come to the laboratory or lecture with a better appreciation of the structures involved and their relationships. This assumption is based upon the proposal that interactive manipulations will reinforce understanding through the application of the principle of learning by doing (Neider et al., 2000).

We are generating images that can be used interactively to learn anatomy. The utility of these images remains to be determined, but until now, no 3D interactive anatomical models of sufficient quality were available for analysis. Although some 3D anatomy programs exist, they are limited and frequently focus on structures that are easily removed from the cadaver and rotated in 3D space (Johnson and Whitaker, 1995; Neider et al., 2000). We focused on the anatomy of the male pelvis and perineum because the anatomy of both the male and female pelvis and perineum is conceptually difficult. Because this anatomical region is best understood when important 3D relationships are adequately represented, students should benefit from new views and perspectives of this region. For example, in the female, the pelvic floor is frequently damaged by childbirth and an appreciation of its structure and relationships is necessary for understanding how the potential consequences of this trauma, incontinence and prolapse, develop (Moore and Dalley, 1999). In the male, an accurate knowledge of prostatic relationships is essential for the prevention of impotence and urinary incontinence, which frequently follow retropubic radical prostatectomy, and to explain to patients why these complications might arise (Walsh et al., 1990; Steiner et al., 1991; Catalona and Basler, 1993; Goluboff et al., 1998; Myers, 2001).

Conventional 2D illustrations of the pelvic region in anatomical atlases and textbooks are often inadequate and sometimes erroneous. Classical cadaveric dissections do not provide a sufficient view of male pelvic anatomy because structures are concentrated in, and confined to, a small area and are relatively inaccessible. Dissection of this complex region can easily distort relationships and destroy landmarks. The visualizations we have generated provide an accurate representation of the pelvic anatomy in 3D, and allow viewing the anatomy from perspectives not available to the student from conventional textbooks and dissections.

Our 3D reconstructions of the VH Male data set differ from other reconstructions of this data because the images are generated with the true color and texture of the tissue using the 3D Vesalius™ Visualizer. Other models generated from the VH employing other modeling and rendering techniques are textured with pseudo-colors. Our 3D reconstructed models are displayed in the 3D exact spatial relationships corresponding to their locations in the VH male 3D body coordinate system, thus allowing the viewer to see structures in their appropriate positions relative to other structures in a way that has never before been possible.

There are both advantages and disadvantages to the use of the VH data over MRI imaging to generate 3D illustrations. Fixation by freezing has rendered the VH tissue stiff or cadaveric compared to the true tone and texture of the living anatomy captured in MRIs. Whereas most structures can be better resolved in the VH sections than in MRIs, segmentation of the VH data is limited because of the loss of resolution due to the "true-to-life" color of the data. In particular, connective tissue elements, tendons, ligaments, and nerves cannot be easily distinguished. Individual muscles cannot always be delineated where they are in close apposition.

Although we realize that some anatomical structures we show are incomplete, we present examples of how these anatomical models can be utilized. In the future, these 3D models of pelvic anatomical structures can be used for generating additional applications. In particular, the development of interactive applications that can be browsed, flown through and explored from any arbitrary viewpoint will enable instructors to more easily demonstrate relationships and anatomical structures.

It remains to be determined which type of visualization is more suitable for anatomy teaching: pseudocolored schematic or detailed photographic quality 3D visualizations. We believe that retention of the natural texture and color will reinforce the perceived realism of the anatomical structures. It also remains to be determined whether students learn more effectively using 3D illustrations rather than traditional methods because few studies have addressed this question. One recent study argues that students with low spatial skills may be hindered in their learning when using virtual models (Garg et al., 1999). This study used a relatively simple structure (the carpal bones) that is not necessarily viewed better in 3D than 2D (Neider et al., 2000). In addition, the students did not have navigational control over the presentation of the 3D images. More complex structures need to be tested. In this regard, another study using student controlled multiple views suggests that self-guided study from multiple perspectives can improve spatial learning, particularly among students with high spatial ability (Garg et al., 2001). We propose that more formal studies by cognitive psychologists are needed to answer these questions as there is currently no precedence in using such photographic quality color 3D visualizations to teach anatomy.

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APPENDIX

Movie 1. The bony pelvis in isolation. A: A 360° rotation around the Y-axis. B: A 180° rotation in the X-axis from posterior to anterior. C: A 180° rotation from anterior to posterior.

Movie 2. Pelvic bones as in Movie 1A with obturator internus muscles added.

Movie 3. Pelvic bones and muscles as in Movie 2 with levator ani muscles added.

Movie 4. Pelvic bones and muscles as in Movie 3 with ischiococcygeus muscles added.

Movie 5. Pelvic bones and muscles as in Movie 4 with piriformis muscles added.

Movie 6. Posterior view of the bony pelvis with the associated pelvic muscles added in succession: 1) obturator internus muscles, 2) levator ani muscles, 3) ischiococcygeus muscles, and 4) piriformis muscles.

Movie 7. The levator ani muscles at 180° rotation. A: In the Y-axis. B: From the anterior to posterior. C: From inferior to superior.

Movie 8. The levator ani muscles shown in relation to the prostate gland and urinary bladder at 180° rotation. A: In the Y-axis. B: From the anterior to posterior. C: Inferior to superior view.

Movie 9. Successive additions of the perineal structures to an inferior view of the bony pelvis.

Movie 10. Bony pelvis at 180° rotation from anterior to posterior.

Movie 11. As in Movie 10 with obturator internus muscles added.

Movie 12. As in Movie 11 with levator ani muscles added.

Movie 13. As in Movie 12 with ischiococcygeus muscles added.

Movie 14. As in Movie 13 with piriformis muscles added.

Movie 15. Urogenital structures. A: As a 360° rotation in the X-axis. B: As a 180° rotation inferiorly from anterior to posterior. C: As a 180° rotation superiorly from posterior to anterior.

Movie 16. Urogenital structures combined with the bony pelvis. A: As a 360° rotation in the X-axis. B: As a 180° rotation inferiorly from anterior to posterior. C: As a 180° rotation superiorly from posterior to anterior.