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A Head in Virtual Reality: Development of A Dynamic Head and Neck Model

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Advances in computer and interface technologies have made it possible to create three-dimensional (3D) computerized models of anatomical structures for visualization, manipulation, and interaction in a virtual 3D environment. In the past few decades, a multitude of digital models have been developed to facilitate complex spatial learning of the human body. However, there is limited empirical evidence to guide the development and integration of effective computer models for teaching and learning. The purpose of this article is to describe the development of a dynamic head and neck model with flexible displays (2D, 3D, and stereoscopic 3D) and interactive control features that can be later used to design and test the efficacy of computer models as a means of improving student learning. The model was created using computer tomography scans of a human cadaver. Anatomical structures captured on the scans were segmented into discreet areas, and then reconstructed in three-dimensions using specialized software. The final model consists of 70 distinct anatomical structures that can be displayed in 2D, 3D, or stereoscopic 3D. In 3D mode, a mouse can be used to actively and continuously interact with the model by manipulating viewer orientation, altering surface transparency, superimposing 2D scans with 3D reconstructions, removing or adding structures sequentially, and customizing animated scenes to show complex anatomical pathways or relationships. Anat Sci Educ 2:294–301, 2009. © 2009 American Association of Anatomists.

Key words: Gross anatomy; three-dimensional; stereoscopic views; interactivity; medical education; computer-assited learning; undergraduate medical teaching

INTRODUCTION

In the past, models of biological or anatomical structures have been created using available materials such as bronze, ivory, wax, and plastic (Vernon and Peckham, 2008). Today, new advances in computer and interface technologies have made it possible to generate detailed anatomical models for visualization, manipulation, and interaction inside a computer-simulated environment (Trelease, 1996). Computer models permit users to change perspectives, toggle between normal and diseased, and appreciate the variability of the human body without the risks or ethical concerns associated with traditional teaching materials. In addition, models are reusable, portable, durable, and consistent, allowing access outside the traditional constraints of the classroom or laboratory. As a result, anatomical educators are beginning to recognize the pedagogical potential of virtual anatomy. They see computer models as emerging and viable adjuncts, and in some cases replacements, to traditional teaching materials and recommend that these digital representations be integrated into future medical curricula to facilitate the comprehension of complex spatial and 3D information. (Cottam, 1999; Florance and Moller, 2002).

Computer models vary widely in the way they are visually displayed and the degree to which they permit interactive control by the user. A model displayed on a computer screen provides a virtual 3D impression of the anatomical structure, by incorporating depth cues such as motion parallax, accretion, and deletion. A snapshot of the screen model provides a 2D representation of the 3D object, which is analogous to the static illustrations presented in anatomy textbooks and atlases. Pictorial depth cues such as shading, occlusion, texture gradient, and shadow are applied to the 2D image creating a sense of depth where none previously exist. A model projected stereoscopically onto a nondepolarizing screen pro-

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Received 5 May 2009; Revised 26 September 2009; Accepted 28 September 2009.

Published online 4 November 2009 in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/ase.115

duces the illusion of depth by presenting the observer's left and right eyes with two slightly different projections of the model. This leads to the 'popping out' effect one would experience at an IMAX^{TM} 3D theatre. When displayed in a virtual environment, users may have low-level control over the pace and direction of the model (play, pause, or rewind an animated sequence); no control (passive visualization of an image or animated sequence); or high-level control (active exploration of the model) (Keehner, 2008).

Both static and dynamic computer models have been developed and introduced into anatomy courses to help students learn anatomical concepts and understand spatial relationships of the human body. Although the application of computer models in teaching anatomy has received considerable attention, research on the impact of computer models on student learning has been minimal. Educators who have attempted to examine the relationship between these digital aids have found that computer models are not equally effective for all users, and that the different depth cues and interactive control features provided by different computer models can either faciliate learning or impose cognitive demands that interferes with the learning process. (Garg et al.,1999, 2001, 2002; Luursema et al., 2006; Nicholson et al., 2006; Kheener et al., 2008). With trends towards increasing use of computer models in the classrooms, further research concerning the educational effectiveness of computer models need to be done to guide the development and implementation of effective and efficient models for teaching and learning anatomy. In an effort to address this problem, the authors have created a dynamic head and neck computer model with flexible display (2D, 3D, and stereoscopic 3D) and interactive control features (none, low, high). These different features can later be assessed to discern optimial condition(s) for learning anatomy in a virtual environment.

The aim of this article is to describe the development of the head and neck computer model. The head and neck region has been chosen for reconstruction because of it's 3D complexity, anatomic importance, and the limited supply of physical models for student usage.

METHODS

A freshly embalmed edentulous male cadaver was obtained for use from the Body Bequeathal Program in accordance with the Ethical Review Board of the University of Western Ontario, London, Ontario. Data acquisition was performed using a multislice computer tomography (CT) scanner (Lightspeed VCT, GE Medical System, Waukesha, WI) at the London Health Science Centre. At 0.6 seconds/rotation (140 kV, 715 Ma, pitch 1.375:1), slice thickness were 0.625 mm with isotropic voxel dimensions. Raw data were saved as DICOM (Digital Imaging and Communications in Medicine) format files.

A subset of the DICOM file set containing the head and cervical region (consisting of 576 slices) were uploaded onto a computer workstation (Intel® Core^{TM} 2 Quad CPU @ 2.40 GH2 Processor, 3.25 GB RAM, Windows XP pro professional), supported by a specialized graphics card (GeForce 8800 Ultra, NVIDIA, Santa Clara, CA). Digital reconstruction was achieved by importing the DICOM dataset into a 3D visualization and modeling software (Amira 4.1, Mercury Computer System Inc., Chelmsford, MA). The software displays the 2D images in the x-y- (coronal), y-z- (sagittal), and x-z- (transverse) orientations. For each plane, users can scroll through the image dataset, slice by slice, to examine 2D internal aspects of the head and neck region. Anatomical structures captured on the scans were then segmented into discreet areas and three-dimensionally reconstructed. Both 2D manual and 3D semi-automatic segmentation tools were used to delineate structures, one-by-one, on separate scans. Each structure was assigned to a user defined label (such as bones, skin, muscles) so that when an individual label is selected for viewing then all areas allocated to that specific label appear simultaneously on the computer screen, creating a volumetric 3D polygon reconstruction. Next, a corresponding surface reconstruction was rendered from each volumetric reconstruction for processing. The final surface reconstruction produced has smooth boundary interfaces and topologically correct spatial orientation.

The surface model of the head and neck region can be presented three-dimensionally on a computer screen, two-dimensionally by taking a snapshot of the 3D computer image, or stereoscopically via stereo-projection. The 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, images emitted from the projectors are filtered by the polarized lenses. The lenses are placed so 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 who wear polarized glasses will 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 disparity between the two retinal images and reconstucts the depth dimension in the observers' visual world (Poggio and Poggio, 1984).

RESULTS

Using the previously-described methods, more than 70 major structures of the head and neck region (including muscles, nervous tissue, glands, vessels, and bones) have been segmented and reconstructed from CT data (Table 1). The model provides many unique and practical features:

1. Each reconstruction is saved as a separate surface file, therefore each of the 70 digital structures can be displayed and manipulated individually;
2. the reconstructions can be projected in 2D, 3D, or stereoscopic 3D;
3. in 3D or stereoscopic 3D mode, the reconstructions can be rotated and viewed from any arbitrary viewpoints;
4. the reconstructions can be enlarged (using the zoom feature) to enhance visualization and exploration of specific structures or details;
5. the reconstructions can be disassembled and reassembled in any sequence;
6. the opacity of individual reconstructions can be modified to allow "see through" visualization;
7. animated scenes can be created to show complex anatomical pathways or relationships;

Table 1.

Summary of the 3D Reconstructions Created from Raw CT Data of the Head and Neck Region

Bones and cartilages	Muscles of the neck	**Central Nervous System and related structures**
Skull	Mylohyoid	Left cerebral hemisphere
Mandible	Geniohyoid	Right cerebral hemisphere
Hyoid	Stylohyoid	Cerebellum
Paranasal sinuses	Digastric	Thalamus
Thyroid	Sternohyoid	Ventricles
Cricoid	Sternothyroid	Midbrain
Arytenoid	Thyrohyoid	Pons
Corniculate	Sternocleidomastoid	Medulla
Epiglottis	Trapezius	Falx cerebri
Tracheal rings	Levator scapulae	Tentorium cerebelli
Muscles of the head	Splenius capitis	Spinal cord
Temporalis	Semispinalis capitis	**Arteries**
Masseter	Rectus capitis posterior minor	Aorta (arch)
Medial pterygoid	Rectus capitis posterior major	Brachiocephalic trunk
Lateral pterygoid	Obliquus capitis inferior	Subclavian
Superior rectus	Obliquus capitis superior	Common carotid
Inferior rectus	Hyoglossus	External carotid
Lateral rectus	Tongue	Internal carotid
Medial rectus	Trachealis	**Veins**
Superior oblique	**Structures of the respiratory and digestive system**	Brachiocephalic
Inferior oblique	Pharynx	Subclavian
Salivary glands	Nasal cavity	External jugular
Submandibular	Oral cavity	Internal jugular
Parotid		Superior sagittal sinus
Skin		Inferior sagittal sinus
		Transverse sinus
		Sigmoid sinus

8. the original raw scan data may be displayed concurrently with the model in any orthogonal or arbitrary plane;
9. using a mouse, users may have high-level control over the pace and direction of the model (rotating and manipulating the model throughout a 360° sphere, magnifying details, altering surface transparency, extracting 2D orthogonal or oblique CT scans, and superimposing 2D images with 3D reconstructions), low-level control by playing, pausing, and rewinding an animated sequence, or no control by passively visualizing an image or animation.

To illustrate the results here, selected 3D reconstructions are presented in Figures 1–4 as static 2D images because of the limitations inherent in the use of printed media. Nevertheless,

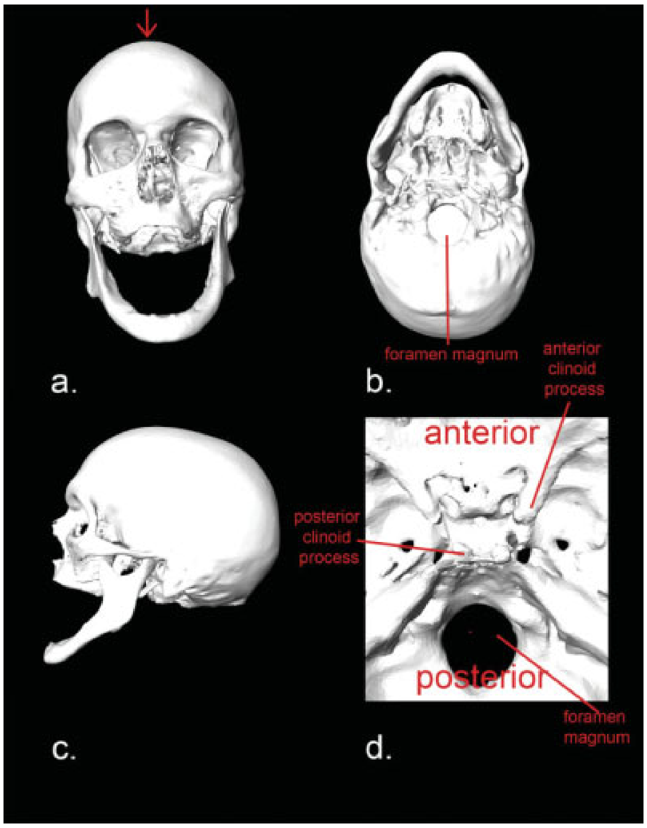

Figure 1.

Static 2D images of the skull reconstruction in several orientations: (**a**) anterior; (**b**) inferior; (**c**) lateral orientation; (**d**) internal view of skull obtained by flying through the superior aspect of the calvaria (as shown by the red arrow in Fig. 1a).

essential features such as depth and solidity are best conveyed on the computer monitor or with the stereo projection system.

Figure 1a–1c depicts static snapshots of the reconstructed skull from the anterior, inferior, and lateral perspectives, similar to the illustrations usually depicted in conventional textbooks or atlases. Figure 1d highlights specific details of the internal aspect of the skull, including essential features of the anterior, middle, and posterior cranial fossae. This view was obtained by 'flying' through the superior aspect of the bony calvaria (marked by an arrow on Fig. 1a) and taking a snapshot of the skull inside the cranial cavity.

Figure 2a–2f illustrates a layer-by-layer dissection of the muscles of mastication. The skin (shown intact in Fig. 2a) has been removed to display the skull and four muscles of mastication (temporalis, masseter, medial pterygoid and lateral pterygoid) (Fig. 2b). Digital excision of the masseter exposes the mandible and gives a clearer view of the temporalis, medial pterygoid and lateral pterygoid muscles (Fig. 2c). By removing the temporalis muscle, its origin, the broad temporal fossa, is revealed (Fig. 2d). Next, by detaching the mandible the deeply hidden medial and lateral pterygoid muscles are uncovered (Fig. 2e). Finally, the lateral pterygoid muscle is removed leaving the medial pterygoid muscle attached to the cranium (Fig. 2f). The opposite operation is also possible by adding structures one-by-one until an intact head and neck model is achieved (Figs. 2a–2f).

To amplify the visualization of complex anatomical relationships, users can alter the opacity of individual structures. For example, in Figure 3, the opacity of the cranium is reduced to expose the four pairs of muscles of mastication as well as their insertion points on the mandible.

Since reconstructions are rendered directly from CT scans of the head and neck region of the cadaver, users can extract any individual scan from the original raw data set and display it concurrently with the 3D reconstructions, or separately as its own entity. Furthermore, users can adjust the position and orientation of the scans to display arbitrary slices in the oblique orientation, creating unique 2D views of the human body that are not generally shown in conventional textbooks. Figures 4a and 4b illustrates the integration of a coronal and sagittal CT scan with the model shown in Figure 3.

All of the features described here can be incorporated into animated scenes to illustrate certain anatomical relationships or concepts that are difficult to demonstrate with conventional methods. For example, the model can be animated to give the sense of flying through the vertebral canal, as if traveling in a bony tunnel in virtual space, and then up though the foramen magnum into the cranial cavity. Within the intact cranial cavity, users can explore the inner features of the neurocranium from within to gain a better understanding of the bones that protect and support the human central nervous system. The animation may be saved as .mpeg (or .mpg) file formats, which is the standard cross-platform format for computer video (and audio) data compression (CRIPT, 2009).

DISCUSSION

The reconstructions presented here offer new and exciting perspectives of individual head and neck structures. The model enables users to investigate head and neck anatomy in ways that are difficult or even impossible in laboratory settings. For example:

- the size or scale of structures can be altered to enhance visualization of small or hidden structures (such as the ossicles of the ear and foramina passage);
- endoscopic views can be afforded to allow visualization inside hollow structures (such as those of the skull presented in Fig. 1d);
- structures can be removed or added to improve conceptualization of the topography and spatial relationships of the particular anatomy in question (Figs. 2a–2f);
- the opacity of tissues could be modified to reveal its internal architecture or enhance visualization of anatomical relationships (such as those shown in Fig. 3);
- 2D scans, can be projected onto 3D reconstructions to improve interpretation of 2D and 3D anatomy (Figs. 4a and 4b).

The different display (2D, 3D, or stereoscopic 3D) and interactive control features (low-level control, high-level control, or no control) provided by the current model will be used to test the usefulness of different computer model configurations for optimal learning conditions in a virtual environment. Spatial ability, the capacity to perceive the visual world, reconstruct the perception in one's own mind and perform transformations and modifications upon one's mental reconstruction, is an important predictor of success in learning anatomy (McGee, 1979; Gardner, 1983; Luursema,

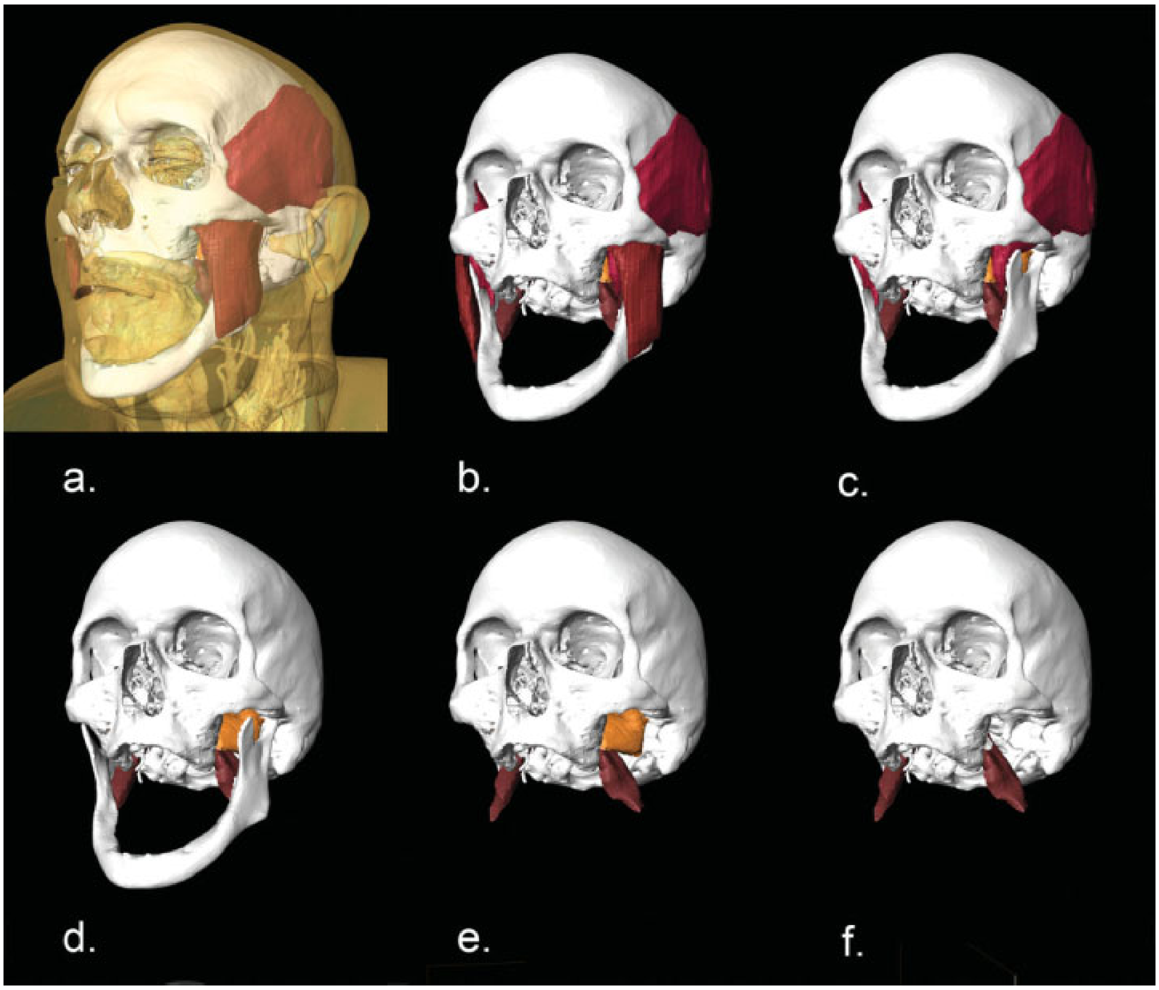

Figure 2.

Images displaying a layer-by-layer dissection of the muscles of mastication: (**a**) skull and muscles of mastication displayed with transparent skin; (**b**) skin is removed to reveal the skull and muscles of mastication; (**c**) masseter muscle removed, displaying the mandible, temporalis, medial and lateral pterygoid muscles; (**d**) temporalis removed to expose its origin, the broad temporal fossa; (**e**) the mandible is detached, revealing partially hidden medial pterigoid and lateral pterygoid muscles; (**f**) the lateral pterigoid removed exposing medial pterygoid muscle and skull.

2006). Early evidence was provided by Rochford (1985) who found a correlation between spatial learning disabilities and underacheivement among unversity anatomy students, and later corrobrated by Garg et al. (1999) suggesting spatial ability to be an important predictor of success in learning anatomy using 3D computer models. Further experiments need to assess the relative importance of display type. In particular, the effect of different depth cues inherent to each type of display and to what anatomical regions these depth cues make the most contribution or hindrence to anatomical pedagogy. Furthermore, levels of user interactivity with computer models may modify the development of mental representations, and thus, learning of these materials. If objects are remembered as key-view images, then the additional depth cues provided by 3D and stereoscopic models may impose extraneous and unnecessary information that are inconsistent with cortical organization of spatial information. It is thought that unneccesarry cognitive loads may impose demands on working memory capacity and interfere with the accurate perception and imagery of spatial information. However, if mental representations include spatial information, then the additional depth cues provided by 3D and stereoscopic models may better communicate the 3D structures of anatomy, which facilitate imagined spatial rotation of the object (Luursema et al., 2006; Nicholson et al., 2006).

Active exploration of the model may further mediate imagined spatial rotation. The additional benefits may result from efferent commands used to move about the model or proprioceptive information or both, which help integrate the different views by allowing users to anticipate the upcoming view and relate it to the previous view (Harman et al., 1999; James et al., 2001). However, making interactivity available does not ensure effective use of the model. Additional working memory resources may also be required for actively rotating the model, which may divert attention from the main task (Keehner et al., 2008).

Previous studies investigating the effect of computer models on learning have failed to show consistent benefits to users. For instance, Garg et al. (1999, 2001, 2002) conducted a series of experiments that investigated the usefulness of interactive 3D

Figure 3.

Image displaying a transparent skull with the muscles of mastication.

models for learning wrist anatomy and found no advantages for 3D reconstructions or interactivity over static images. In the first experiment, they compared wrist-bone anatomy presented in a multiple view condition (anatomy self rotating at 10° intervals throughout a 360° horizontal plane) with a key view condition (anterior and posterior views at 180° intervals). They concluded that when presented in a fixed sequence, 3D models offer minimal advantages to some learners while disadvantaging learners with poor spatial ability (Garg et al., 1999). In the second experiment, where participants in one group were given active control of the 3D model, they found a significant advantage for the multiple view condition (Garg et al., 2001). In the third experiment, both groups were allowed active control over the presentation. The rotation was unconstrained for the multiple view group but restricted to a wiggle (±10° around the anterior and posterior orientations) for the key view group. They found that the learner-controlled multiple view condition offered no advantages over learner-controlled key view plus wiggle condition, which minimized the proposed benefits of the multiple view condition found in the earlier study (Garg et al., 2002).

In contrast, other studies have determined a significant advantage for learners using both interactivity and 3D reconstructions. In a randomised contolled study, where participants had to complete an online tutorial with or without access to an interactive 3D model of the middle and inner ear, Nicholson et al. (2006) demonstrated that students using their digital ear model as a learning aid, scored significantly higher on a subsequent test that assessed students learning than students without access to the model. Similarly, Luursema et al. (2006) demonstrated that both stereopsis (depth perception enabled by the use of shutter-glasses) and interactivity improved learning of abdominal anatomy, especially for those with poor spatial ability.

The conflicting results from the aforementioned studies suggest that more research concerning the usefulness of computer models needs to be done to guide the development and integration of effective models for teaching and learning anatomy. Moreover, these data suggest certain anatomical systems may be better suited to active control with multiple perspectives while other areas do not require such control as the majority of spatial and perceptual information can be expressed in key views.

In the next phase of this research, we will be evaluating the impact of this computer model with different combinations of display and interactive control features on learning, and examining how individual differences among users affect the efficacy of computer model as a learning aid. We hope to provide empirical evidence to guide the design and implementation of effective computer models. Our goal is to create computer models and accompanying criteria that will optimize conditions for acquiring anatomical knowledge in the evolving virtual learning environments, while accounting for individual differences in spatial ability and controlling for anatomical areas where extra spatial information or active control is unneccesary.

LIMITATIONS

Despite the ability to enhance the visualization potential of the anatomical relationships of head and neck anatomy, there are some inherent limitations to our model, arising from the use of cadaveric material, the development software, native CT scan limitations, and/or the technology employed to display the virtual model. First, as mentioned above, the head and neck model is created from CT scans of a cadaver. Post mortem changes due to tissue decomposition, settling, and/or chemical fixation could cause the anatomy of the cadaver to differ from those of the living patient. Hence, data from living persons need to be employed to increase the realism and quality of our reconstructions. Second, the number of reconstructions produced and the accuracy of the reconstructions are limited by how well users can physically identify structures on separate 2D images, as well as by the base resolution of these images. Due to this limitation, minute structures, such as cranial nerves, sutures, small vessels, lymph nodes, and overlapping structures with similar tissue density, such as the muscles of facial expression, are not easily separated for reconstruction. These structures are either too difficult to distinguish and delineate on the CT images, or they do not appear on scans at all due to lack of adequate spatial resolution or partial volume averaging. To compensate for this limitation, increases in the base resolution of the CT images may improve constrast between existing structures. In addition, other volumetric data sources with greater soft tissue constrast, such as magnetic resonance images (MRI) or photorealistic images of serially sectioned and unfixed frozen cadavers, could be employed to facilitate further reconstructions. The adoption of these techniques, combined with ever-evolving imaging modality technology, will afford better identification and differentiation of smaller structures, materials that have similar radiological linear attenuation properties, or those that are in close apposition. By

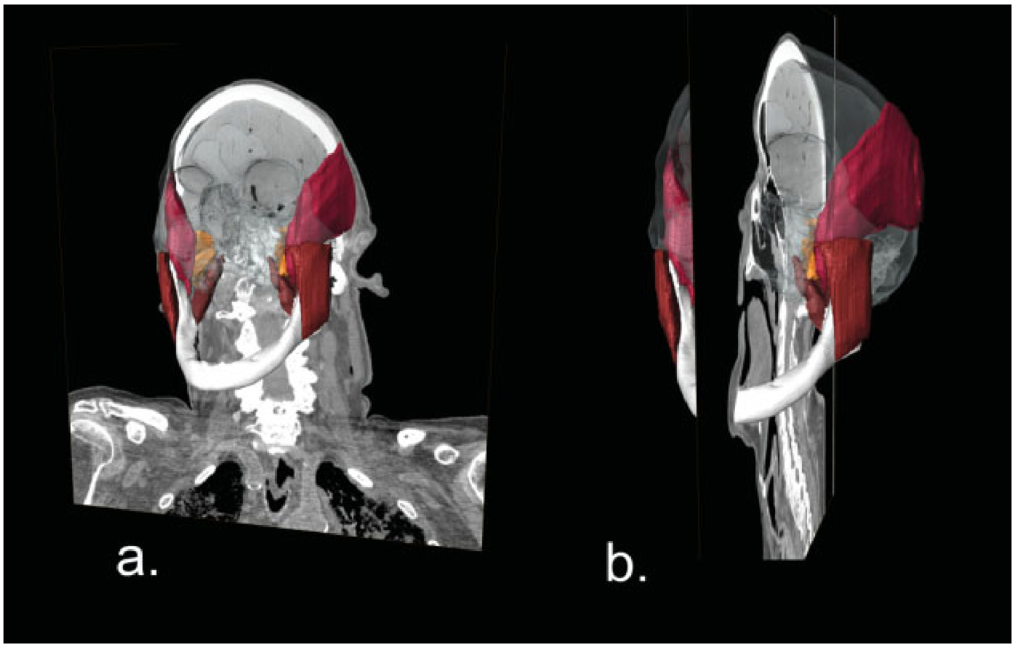

Figure 4.

Image displaying the integration of 2D scans with the 3D reconstruction. (**a**) 2D coronal; (**b**) sagittal scan superimposed with the 3D reconstructions of the muscles of mastication.

achieving better resolution, delineation, and thus, accurate segmention, the number and detail of anatomical structures that can be rendered for visualization will expand. The second limitation arises from the fact that the structures that are successfully reconstructed are then simplified (by downsampling or smoothing) to produce surface representations that are easily displayed on the computer monitor or projected stereoscopically onto a nondepolarizing screen. Simplification however, is akin a low pass digital filtre, resulting in a reduction of fine anatomical detail in the final model. For example, simplification of the skull causes fine details of the neurocranium (sharp edge of crista galli) and viscerocranium (length and pointedness of styloid process) to be lost. As appropriate image-processing software and hardware develops to match image acquisition modalities, finer anatomical details such as muscle fibres, fat globules and bony landmarks may be added to enhance the realism of the current head and neck model. Finally, displaying the digital model on a computer monitor or nondepolarizing screen with full interactive capabilities requires ultra-high speed graphics processors that enable real-time manipulation. As the visualizations become more complex (i.e. as we increase the number of reconstructions concurrently displayed on the screen), more time is needed to render the display image, which will reduce user ability to interact and manipulate the object in real-time. As computer graphics and interface technologies continue to advance, we hope to find new ways to develop and display our virtual models in a more efficient and effective manner.

ACKNOWLEDGMENTS

The authors thank their institution's Instructional Technology Resource Centre (ITRC) for their support and exploration with them. They thank Yang Ding and his committment, hard work, and digital expoloration with this project. They also thank Dr. Andrew Nelson, Dr. Marjorie Johnson, and Dr. Peter Haase for their valuable input and encouragement throughout this project.

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