Biomedical Paper

Use of Three-Dimensional Computer Graphic Animation to Illustrate Cleft Lip and Palate Surgery

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ABSTRACT

Objective: Three-dimensional (3D) computer animation is not commonly used to illustrate surgical techniques. This article describes the surgery-specific processes that were required to produce animations to teach cleft lip and palate surgery.

Materials and Methods: Three-dimensional models were created using CT scans of two Chinese children with unrepaired clefts (one unilateral and one bilateral). We programmed several custom software tools, including an incision tool, a forceps tool, and a fat tool.

Results: Three-dimensional animation was found to be particularly useful for illustrating surgical concepts. Positioning the virtual "camera" made it possible to view the anatomy from angles that are impossible to obtain with a real camera. Transparency allows the underlying anatomy to be seen during surgical repair while maintaining a view of the overlaying tissue relationships. Finally, the representation of motion allows modeling of anatomical mechanics that cannot be done with static illustrations. The animations presented in this article can be viewed on-line at http://www.smiletrain.org/programs/virtual_surgery2.htm.

Conclusions: Sophisticated surgical procedures are clarified with the use of 3D animation software and customized software tools. The next step in the development of this technology is the creation of interactive simulators that recreate the experience of surgery in a safe, digital environment. Comp Aid Surg 7:326–331 (2002). ©2003 Wiley-Liss, Inc.

Key words: **cleft lip; cleft palate; 3D animation; modeling**
Key link: **http://www.smiletrain.org/programs/virtual_surgery2.htm**

OBJECTIVE

Three-dimensional (3D) computer animation is not commonly used to illustrate traditional surgical techniques. Although the advantages of this approach are obvious, textbook illustrations continue to be used. Three-dimensional visualization would be particularly useful as a teaching tool for cleft lip and palate surgery, which involves multiple flaps in a complex 3D environment. We assumed that the use of the current generation of animation software would be straightforward for this application. It quickly became evident, however, that standard animation programs do not contain the tools necessary to illustrate surgery. Recently, we have successfully adapted animation software for this purpose.[1] This article describes the surgery-specific processes that were required to produce animations

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to teach cleft lip and palate surgery. The representation of motion allows modeling of anatomical mechanics that cannot be done with static illustrations.

MATERIALS AND METHODS

Reference models were created using dense CT scans of two Chinese children with unrepaired clefts (one unilateral and one bilateral). Three-dimensional anatomic surface models of relevant structures were created using software previously developed in this laboratory.[2] These "rough" reference models were imported into an animation package (Maya® by Alias/Wavefront, Toronto, Ontario, Canada). Polygonal models of skin, bone, cartilage, and muscle were smoothed and simplified using the tools provided in Maya®.

To perform surgical maneuvers on the models, it was necessary to create several custom software tools (i.e., plugins). An incision tool plugin was programmed to simulate the action of a scalpel on the single-layer model. This enabled us to easily create incisions that were otherwise cumbersome using the standard tools in Maya.

The other difficulty with an "incision" is that it creates a topological change (i.e., change in polygon connections) in the model. Commercial animation programs do not currently allow topological changes to be made during the course of an animation sequence. Every time an incision was required, a new animation scene had to be created. To create a single surgical animation, many separate scenes had to be linked together in the final editing process.

A forceps tool software plugin was created to mimic tissue retraction. Maya has a very rich set of object deformers, but none of these created realistic-looking retraction of skin. As a result of this problem, we were forced to program the "forceps tool" deformer. This plugin allows the user to give a selected flap the appearance of surgically transposed skin.

Finally, it was necessary to program a fat tool to create an underlying layer of fat on the single-layer skin models. The fat tool allows the user to apply "fat" to any aspect of the model to create the illusion of full-thickness skin. Animation also became much easier with the advent of this tool, because all of the difficult aspects of the procedure could be applied on the single-layer skin model. The "fat" simply follows the motion of the single-layer model.

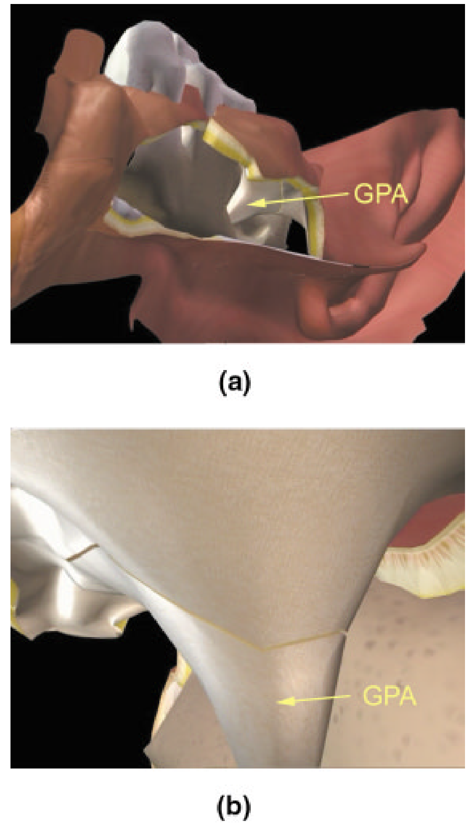

Fig. 1. (a) An inferior–anterior view of the greater palatine neurovascular bundle (GPA). (b) The camera is now placed just posterior to the greater palatine neurovascular bundle. This is an area only a few millimeters in size; it would be impossible to place a "real" camera in this location. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

RESULTS

Examples of the surgical animation frames generated for this project are given in Figures 1–3. A completed animation sequence can be viewed on the SmileTrain web site at: http://www.smiletrain.org/programs/virtual_surgery2.htm.

A number of standard animation tools were particularly useful for the illustration of surgical concepts. Positioning the virtual "camera" made it possible to view anatomy from angles that are impossible to obtain with a real camera (Fig. 1). We used this technique to give the viewer the best vantage point for each maneuver.

Transparency is very useful in surgical animation. Tissues obscuring the view of deeper anatomy can be made progressively transparent. This allows us to see underlying dynamic motion of the anatomy during the repair while maintaining a view of the overlaying tissue relationships (Fig. 2).

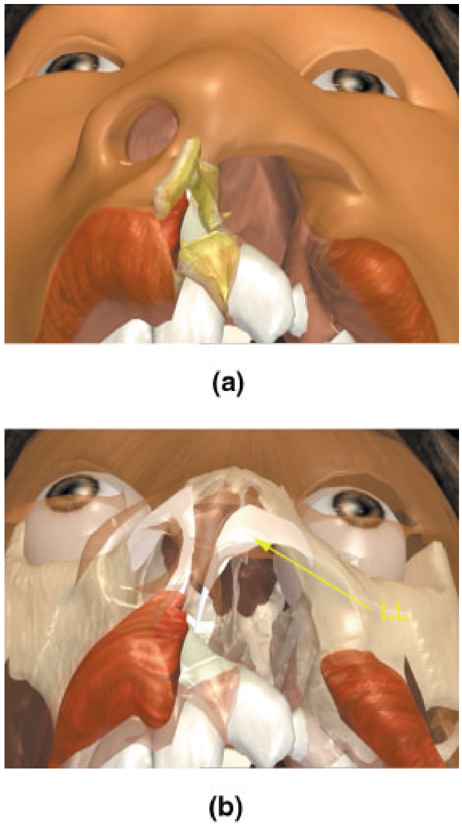

Fig. 2. The skin is made translucent, allowing the viewer to visualize the nasal cartilage complex that lies beneath (LL = lower lateral nasal cartilage). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

The representation of motion allows the modeling of anatomical mechanics that cannot be done with static illustrations. An excellent example of this is the simulation of the pump mechanism of the Eustachian tube (Fig. 3).

Computer graphic representations of anatomy allow the selective removal of objects usually present in a surgical environment. For example, in surgical video, blood, drapes, instruments, etc., often obscure the surgical maneuvers. Digital surgery distills the operating field to its essential elements.

Digital editing allows for the splicing of surgical video with 3D animation. Juxtaposing intraoperative footage with animation allows one to clarify and emphasize key maneuvers that may not be obvious in the surgical video.

Compositing is a technique that allows pointers, words, and images to be overlaid onto animations and surgical footage. For example, labeling both the animations and the surgical video can highlight surgical landmarks.

Another advantage of using digital surgery is the ability to illustrate inferior techniques. For example, the triangle repair for the unilateral cleft lip is still a widely used procedure in developing countries. Using our animations, we are able to show the consequences of this outdated repair, whereas it

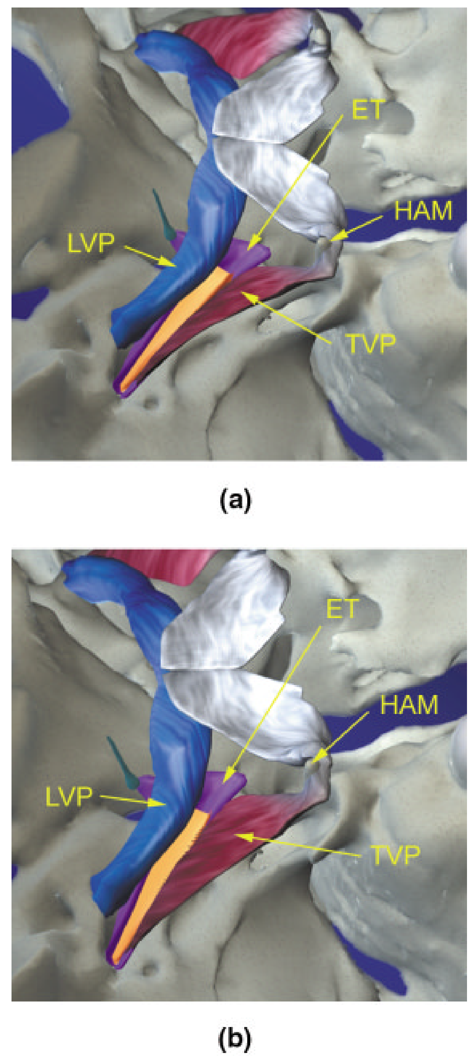

Fig. 3. The mechanics of Eustachian tube opening are demonstrated using 3D animation. (a) The palatal muscles are in the relaxed state (TVP = tensor veli palatini m.; LVP = levator veli palatini m.; ET = Eustachian tube; HAM = hamulus). (b) The palatal muscles contract and dilate the Eustachian tube. This subtle dynamic can only be fully appreciated in the animated clip available online at http://www.smiletrain.org/programs/virtual_surgery2.htm. This clearly illustrates the point of the article that 3D animation is superior to 2D still images for conveying dynamic relationships. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

would be unethical to demonstrate this procedure on a live patient.

DISCUSSION

Computer-based simulation of craniofacial surgical procedures has a rich history. Commercial CAD/CAM software was applied to the problem by Marsh and colleagues,[3,4] and custom software designed specifically to simulate these procedures soon followed.[5–23] The program developed in our laboratory[17,22] automatically optimized bone-fragment position to best fit an average normal form[24] using morphometric techniques initially proposed by Bookstein.[25–28] This was followed by an intraoperative vision system that tracked fragment position with respect to the skull base to allow these procedures to be performed precisely.[22,29–38]

It should be noted that craniofacial surgical simulation is a much simpler computer problem than soft-tissue surgical simulation. Craniofacial simulations perform rigid motions of a finite set of solid bone fragments that do not bend. Soft-tissue simulations require complex deformations of tissues based on anatomical constraints.

Cleft lip and palate surgery involves an intricate interaction of multiple flaps in a complex anatomic environment. These 3D relationships are easily explained with the use of animation software.[39] Three-dimensional animation software provides a solution by clarifying these sophisticated procedures. This approach was used to create animation sequences to facilitate teaching cleft repairs to surgeons in developing countries.[1]

Animation software is not well suited to simulating surgical procedures. In commercial animation, it is common to deform a model within an animation sequence. Unfortunately, making an incision in the model is very rare, whereas creating an incision is at the core of surgical animation.[40] In the end, separate animation scenes were required each time a new incision was added to the model. It is hoped that this situation will change with the next generation of animation software.

Modeling cleft lip and palate anatomy seemed straightforward at the beginning of the project. CT scans provided all of the surface information for the external skin (the top layer). In our original workflow, skin was represented by a block of tissue composed of a top and a bottom layer connected by a cut edge. Much time was wasted on this conception. Manipulation of the outer surface of the skin caused the outer layer to push "through" the inner layer, so any movement of the model had to be applied uniformly to all of the components of a flap to prevent this occurrence. Finally, we realized that the bottom and skin edges of a flap always followed the movement of the top layer. Generating the bottom and edge layer after the top layer was moved resolved these problems. We now model the skin as a single layer and generate the underlying surface and edge just before rendering the animation.

Retraction of tissue is an essential surgical activity. Animation software provides a rich set of deformers that at first seemed promising for simulation of tissue retraction, but this was not, in fact, the case. The available deformers in Maya are unable to duplicate the biophysics of folding back a skin flap. It was necessary to create two custom software plugins to approach realistic-looking tissue retraction.[41]

There are many advantages to using 3D images rather than 2D illustrations or intraoperative video. Intraoperative video is only slightly more than two-dimensional because it is usually filmed via a stationary camera, whereas animation can use different camera rotations and positions to show the three-dimensionality of a procedure. Virtual cameras can also provide the ability to zoom into very small areas that are impossible to view intraoperatively. An example of this can be seen in the animation of the release of the neurovascular pedicle during a cleft palate repair. In this animation, a camera flies through an area only several millimeters wide (see Fig. 1).

The use of transparency in surgical animation provides the opportunity to see the underlying structure of the anatomy in cases where it is ordinarily obscured. Transparency can also provide insight into the placement of sutures. This technique can help provide a clear understanding of suture placement and its underlying reasoning. Another advantage of transparency is the ability to see the effect of the cartilage and muscle directly during a dissection. All of these scenarios are impossible to observe in vivo or with intraoperative footage (see Fig. 2).

Perhaps the most valuable use of animation is the ability to visualize dynamic systems. For example, the pump mechanism of the Eustachian tube can be easily appreciated in Figure 3 (see on-line animation at http://www.smiletrain.org/programs/virtual_surgery2.htm). This animation clearly illustrates the synergy between the tensor and the levator veli palatini muscles.[43]

The next step in the development of this technology is the creation of interactive simulators that recreate the experience of surgery in a safe, digital environment. The novice surgeon can then practice the procedure and make mistakes without putting patients at risk. Recovery from disaster scenarios may also be practiced, as is commonly done with airline pilots learning to fly a new plane on a simulator. The techniques used to create the animations presented in this article may be adapted to the development of a virtual surgery simulator. The most natural computational approach to simulate soft-tissue dynamics would be finite element modeling or some real-time approximation of it using spring networks. This is the approach currently being taken in our laboratory and by Shendel and colleagues working in collaboration with NASA.

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REFERENCES

1. Cutting C, Oliker A, Haring J, Khorramabadi D, LaRossa D, McComb H, Millard DR, Noordhoff MS, Mulliken J, Sommerlad B. SmileTrain video Education Series. CD-ROM, vols 1–3. New York: SmileTrain, 2001.
2. Gueziec A, Dean D. The wrapper algorithm: a surface optimization algorithm that preserves highly curved areas. In: Proceedings of Second Conference on Visualization in Biomedical Computing. Rochester, MN: SPIE, 1994.
3. Marsh J, Vannier M. The "third" dimension in craniofacial surgery. Plast Reconstr Surg 1983;71:759–767.
4. Marsh J, Vannier MW, Stevens WG, Warren JO, Gayou D, Dye DM. Computerized imaging for soft tissue and osseous reconstruction in the head and neck. Clin Plast Surg 1985;12:279–291.
5. Cutting C, Bookstein F, Grayson B, McCarthy JG. Computer aided planning of orthognathic surgery. In: Proceedings of Plastic Surgery Research Council, Detroit, MI, April 1984.
6. Cutting C, Bookstein FL, Grayson B, Fellingham L, McCarthy JG. Three-dimensional computer assisted design of craniofacial surgical procedures: Optimization and interaction with cephalometric and CT-based models. Plast Reconstr Surg 1986;77:877–885.
7. Cutting C, Grayson B, Bookstein F, Fellingham L, McCarthy JG. Computer-aided planning and evaluation of facial and orthognathic surgery. Clin Plast Surg 1986;13:449.
8. Fellingham L, Vogel J, Lau C, Dev P. Interactive graphics and 3-D modelling for surgical planning and prosthesis and implant design. In: Proceedings of NCGA Computer Graphics, 1986.
9. Udupa J. Computerized surgical planning: Current capabilities and medical needs. Proc Soc Photo-Optical Instr Eng 1986;626:474–482.
10. Walters H, et al. Computerized planning of maxillofacial osteotomies: the program and its clinical applications. Br J Oral Maxillofac Surg 1986;24:178.
11. Yokoi S, Ysuda T, Hashimoto Y, Toriwaki J, Fujioka M, Nakajima H. A craniofacial surgical planning system. Proceedings of NGCA Computer Graphics, 1986. p 93.
12. Cutting C, Bookstein F, Grayson B, Fellingham L, McCarthy JG. Three-dimensional computer-aided design of craniofacial surgical procedures. In: Marchac D, editor: Craniofacial Surgery. Berlin: Springer-Verlag, 1987. p 17.
13. Moss JP, Linney AD, Grindrod SR, Arridge SR, James D. A computer system for the interactive planning and prediction of maxillofacial surgery. Am J Orthod Dentofac Orthop 1988;94:469–475.
14. Cutting C, Grayson B, Kim H. Precision multi-segment bone positioning using computer aided methods in craniofacial surgical applications. IEEE Eng Med Biol 1990;12:1926.
15. Udupa J, Odhner D. Interactive surgical planning: High speed object rendition and manipulation without specialized hardware. Proceedings of First IEEE Conference on Visualization in Biomedical Computing, 1990. p 330.
16. Cutting C. Applications of computer graphics to the evaluation and treatment of major craniofacial malformations. In: Udupa J, Herman G, editors: 3D Imaging in Medicine. Boca Raton, FL: CRC Press, 1991. p 163–189.
17. Cutting C, Taylor R, Bookstein F, Kalvin A, Haddad, B, Kim Y, Noz M, McCarthy J. Comprehensive three dimensional cephalometric system for the planning and execution of craniofacial surgical procedures. In: Montoya A, editor: Craniofacial Surgery 4. Proceedings of 4th Biannual Meeting of International Society of Craniomaxillofacial Surgery, 1991. Santiago de Compostela, Spain: Monduzzi Editore, 1991. p 11–13.
18. Cutting C, Taylor R, Bookstein R, Khorramabadi D, Haddad B, Kalvin A, Kim H, Noz M. Computer aided planning and execution of craniofacial surgical procedures. In: Proceedings of IEEE Engineering in Medicine and Biology Conference, Paris, France, 1992. IEEE Eng Med Biol 1992;14:1069.
19. Cutting C, Taylor R, Bookstein F, Khorramabadi D, Haddad B, Kalvin A, Kim H, Noz M. Computer aided planning and execution of craniofacial surgical procedures. In: DARPA Workshop on Computer Assisted Surgery. Washington, DC: Defense Advanced Research Projects Administration, 1993.
20. Altobelli DE, Kikinis R, Mulliken JB, Cline H, Lorensen W, Jolesz FA. Computer-assisted three-dimensional planning in craniofacial surgery. Plast Reconstr Surg 1993;92:576–585.
21. Marsh J, Vannier M. Discussion of Altobelli DE, Kikinis R, Mulliken J, Cline H, Lorensen W, Jolesz F. Computer-assisted three-dimensional planning in

craniofacial surgery. Plast Reconstr Surg 1993;92: 586–587.

22. Cutting CB, Bookstein FL, Taylor RH. Applications of simulation, morphometrics, and robotics in craniofacial surgery. In: Taylor RH, Lavallée S, Burdea GC, Mösges R, editors: Computer Integrated Surgery: Technology and Clinical Applications. Cambridge, MA: MIT Press, 1996. p 641–662.
23. Vannier MW, Marsh JL, Tsiaras A. Craniofacial surgical planning and evaluation with computers. In: Taylor RH, Lavallée S, Burdea GC, Mösges R, editors: Computer Integrated Surgery: Technology and Clinical Applications. Cambridge, MA: MIT Press, 1996. p 673–677.
24. Cutting C, Bookstein F, Haddad B, Dean D, Kim D. A spline-based approach for averaging three-dimensional curves and surfaces. Proc Soc Photo-Optical Instr Eng 1993;2035:29–44.
25. Bookstein FL. Morphometric Tools for Landmark Data—Geometry and Biology. New York: Cambridge University Press, 1991.
26. Bookstein FL. A brief history of the morphometric synthesis. In: Marcus L, Bello E, Garcia-Valdecasas A, editors: Contributions to Morphometrics. Madrid: Monografias, Museo Nacional de Ciencias Naturales, Consejo Superior de Investigaciones Cientificas, 1993. p 15–40.
27. Bookstein F. Biometrics, biomathematics and the morphometric synthesis. Bull Math Biol 1996;58: 313–365.
28. Bookstein F. Landmark methods for forms without landmarks: morphometrics of group differences in outline shape. Med Image Anal 1997;1:225–243.
29. Taylor R, Paul H, Cutting C. Augmentation of human precision in computer-integrated surgery. In: IEEE Transactions on Robotics and Automation. Philadelphia: IEEE, 1991.
30. Taylor R, Cutting C, Kim Y, Kalvin A, Larose D, Haddad B, Khorramabadi D, Noz M, Olyha R, Bruun N, Grimm D. Model-based optimal planning and execution system with active sensing and passive manipulation for augmentation of human precision in computer-integrated surgery. In: Proceedings of 2nd International Symposium on Experimental Robotics, Toulouse, France, 1991.
31. Taylor RH, Paul HA, Cutting CB, Mittelstadt B, Hanson W, Kazanzides P, Musits B, Kim YY, Kalvin A, Haddad B, Khorramabadi D, LaRose D. Augmentation of human precision in computer-integrated surgery. Innovat Technol Biol Med 1992;13(4):450–459.
32. Taylor R, Funda J, LaRose D, Kim Y, Bruun N, Swarup N, Cutting C, Treat M. A passive/active manipulation system for surgical augmentation. In: Proceedings of First International Workshop on Mechatronics in Medicine and Surgery, Malaga, Spain, 1992.
33. Cutting C, Taylor R, Khorramabadi D, Larose D. Use of a robotic system for precision execution of craniofacial surgical procedures. In: Virtual Reality and Medicine: The Cutting Edge. New York: SIG Advanced Applications, 1994.
34. Taylor RH, Kim YY. Signalling device and method for monitoring position in a surgical operation. U.S. Pat. 5,279,309 (1994).
35. Cutting C, Taylor R, Khorramabadi D, Haddad B. Optical tracking of bone fragments during craniofacial surgery. In: Proceedings of Second Annual International Symposium on Medical Robotics and Computer Assisted Surgery, Baltimore, MD, November 1995. New York: John Wiley & Sons, 1995.
36. Cutting C, McCarthy J, Thorne C, Khorramabadi D, Haddad B, Taylor R. Clinical experience with multisegment midface advancement using a virtual reality approach. In: Proceedings of International Society of Craniofacial Surgery, 1997. Santa Fe, NM: Plastic Surgery Education Foundation, 1997.
37. Cutting C, Grayson B, McCarthy J, Thorne C, Khorramabadi D, Haddad B, Taylor R. A virtual reality system for bone fragment positioning in multisegment craniofacial surgical procedures. Plast Reconstr Surg 1998;102:2436–2443.
38. Cutting C, McCarthy J, Thorne C, Khorramabadi D, Haddad B, Taylor R. Virtual Reality Approach to Multisegment Craniofacial Surgical Procedures. PSEF Video # 9910, 1999.
39. Tanaka D, Kobayashi M, Fujino T, Nakajima T, Chiyokura H. A computer-aided cleft lip simulation surgery system. Keio J Med 2001;50(Suppl 2):121–127.
40. Voss G, Hahn JK, Müller W, Lindeman R. Virtual cutting of anatomical structures. In: Proceedings of Medicine Meets Virtual Reality (MMVR'99). Amsterdam: IOS Press, 1999. p 381–383.
41. Cover SA, Ezquerra NF, O'Brien JF, et al. Interactively deformable models for surgery simulation. IEEE Comp Graphics Appl 1993;13(6):68–75.
42. Ackerman M. The Visible Human Project. Proc IEEE 1998;86(3):504–511.