FOLIA MEDICA CRACOVIENSIA
Vol. LIX, 2, 2019: 15–22
PL ISSN 0015-5616
DOI: 10.24425/fmc.2019.128450

A concise survey on 3D modeling in the science of anatomy

Janusz Skrzat[1], Matthew J. Zdilla[2,3,4]

[1]Department of Anatomy, Jagiellonian University Medical College, Kraków, Poland
[2]Department of Natural Sciences and Mathematics, West Liberty University, West Liberty, West Virginia, USA
[3]Department of Graduate Health Sciences, West Liberty University, West Liberty, West Virginia, USA
[4]Department of Pathology, Anatomy, and Laboratory Medicine (PALM), West Virginia University School of Medicine, Morgantown, West Virginia, USA

Corresponding author: Janusz Skrzat, PhD, DSc
Department of Anatomy, Jagiellonian University, Medical College
ul. Kopernika 12, 31-034 Kraków, Poland
Phone/Fax: +48 12 422 95 11; E-mail: j.skrzat@uj.edu.pl

Abstract: This report provides a concise overview of the rendering and utilization of three-dimensional models in the field of anatomy. Anatomical three-dimensional virtual models are widely used for educational purposes, preoperative planning, and surgical simulations because they simply allow for interactive three-dimensional navigation across the human organs or entire body. Virtual three-dimensional models have been recently fabricated as accurate replicas of the anatomical structures thanks to advances in rapid prototyping technology.

Key words: 3D anatomical models, anatomical education, anatomy, mesh models, volume rendering, surface rendering.

Introduction

The anatomy of the human body has captivated the attention of scientists, even in ancient times. For example, Alcmaeon of Croton, Herophilus of Chalcedon, Erasistratus of Chios, Hippocrates, Aristotle, and Galen, among others, have laid the foundation upon which the current knowledge of human anatomy has been built. They were not only philosophers but, principally, experimentalists and investigators who practiced human dissections and animal vivisections in order to gain knowledge of the structure and function of anatomy [1–4].

Historically, knowledge of the anatomy of the human body has been mainly obtained by gross anatomical exploration. Contemporary imaging technologies now have the capacity to show the structure of the human body and its many parts in a variety of different modes (e.g., visible light scanning, laser light scanning, radiographic scanning, computed tomography, magnetic resonance imaging, ultrasonography, scintigraphy, etc.).

Proper interpretation of images is particularly essential for analyzing and understanding scans of small and intricate anatomical structures. For this reason, considerable attention is paid to the effectiveness of image interpretation and its application in the creation of virtual models [5]. Therefore, image analysis is often supported by computer algorithms designed for the extraction of information from series of images, allows for both visualization and objective evaluation of the morphological properties [6].

Prosected anatomical specimens have always been indispensable in teaching and learning human anatomy. Nevertheless, technological progress has led to the advancement in the accuracy of fabricated anatomical models, owing to possibilities of rapid prototyping of high-quality virtual models. Therefore, there is increasing interest in the supplementation of traditional learning with virtual anatomical renderings and physical renderings derived from modern scanning methods. At present, anatomical models, both virtual and physical, can accurately reveal a broad spectrum of morphological details and demonstrate individual patient anatomy. The potential for rendering models of the unique anatomy of one particular individual is particularly important for presurgical planning and the manufacturing of customized prostheses.

The intention of this paper was to give concise information how the virtual models are created and briefly demonstrate their contemporary role in the clinically-oriented study of human anatomy.

Modalities Used in the Creation of 3D Anatomical Models and Rendering Techniques

Radiological techniques play an important role in imaging the internal anatomy of the human body. Computed tomography is one of the most popular techniques use in modern diagnostic imaging. According to data cited by Brenner and Hall more than 62 million CT scans per year are obtained in the United States, including at least 4 million from children [7].

Another popular source of medical data which can be used for creating anatomical virtual models is magnetic resonance imaging (MRI). This imaging technology, like CT, has broad application in medical diagnosis. It is estimated that there were approximately 36,000 MR scanners being used around the world in 2017 [8].

Both CT and MRI provide high-resolution volumetric data sets of the human body. Applicability of these imaging modalities in medical diagnosis depends on nature of structures that are intended to be visualized. Usually, CT is dedicated for viewing bony structures or diagnosing chest pathology, whereas MRI is well-suited for examining soft tissues, pathology of the spinal cord and brain, and pathological changes in the abdomen. Visual data delivered either by CT or MRI can be processed in both two and three dimensions. Therefore, both CT and MRI are often used in the creation of virtual models of human anatomy [9].

Outside of the clinical setting, a quite different source of data suitable for creating virtual models has come in the way of digital photography and optic scanning systems using so called structured light or laser light. In the case of digital photography and optical scanning, a 3D model or the volumetric scene is rendered from a series of 2D images depicting the object from many directions (so-called 360-degree photography). Accordingly, the number of pictures from unique vantage points relates to improved quality of the 3D model [10–11]. For example, by using 360-degree photography, Jacquesson *et al.* produced an accurate 3D model of the sphenoid bone [12].

Photogrametric techniques deliver information about external features of the object; therefore, they are more often used in anthropological and forensic sciences. The 3D models created with the aid of this technique can be used, for example, in the visual evaluation of morphological variants of the craniofacial skeleton or the shape of the human face. Hence, metric traits captured from the virtual models allow for quantitative evaluation of shape and size of surface features [13–17].

In medical applications, virtual 3D models are preferably created from the radiological data delivered by the CT and MRI scanners. Although each modality uses different physical effects (X-ray and magnetic field, respectively) they both generate cross-sectional images which converted to 3D images are essential step in creation virtual models demonstrating anatomy of the organs in three-dimensional manner [18–20]. Virtual 3D models are displayed by the volume rendering — a technique of creating a 3D volumetric representation from 2D projection slices, or surface rendering — a technique which visualizes a 3D object as a set of the iso-surfaces (surfaces of equal values, containing points of the same intensity on all slices). These two techniques were compared by independent researchers who indicated advantages of surface rendering over volume rendering technique concerning speed in image performance, graphical appearance, and computer requirements (type of CPU, size of memory, disk space) necessary for processing and storing rendered data [21–22]. However, volume rendering convey more information than surface rendering images, but requires more effective algorithms for processing image data and longer time for performing 3D visualization [23]. Extracted iso-surfaces from the volume can be rendered as polygonal meshes (usually mesh of triangles which approximate object's surface). The polygonal meshes created from the image data obtained from CT, MRI, laser scanners and digital photography are indispensable for materializing virtual models into the physical models manufactured by rapid prototyping technologies.

Materializing Physical Models from Virtual Models

Computer mesh modeling and surface reconstruction may serve as a preliminary for the manufacturing of 3D models. For example, a triangular mesh model may be materialized as a solid, tangible object by rapid prototyping techniques. Thus, an anatomical structure intended for manufacturing as a physical 3D model has to be represented by the set of triangles which approximate their surface configuration. The amount of the triangles in the mesh depends on the source data (e.g., resolution, number of CT scans, density of points captured by the light scanner on the object surface). A larger number of the triangles ensure a more realistic appearance of the anatomical structures.

From digital meshes, anatomical models are usually manufactured by two different processes: additive and subtractive. Additive manufacturing (termed also as 3D printing) is a process by which 3D objects are constructed by successively depositing material (e.g., acrylonitrile butadiene styrene, a thermoplastic polymer) in layers until the designed shape is attained. Additive modeling can be executed by technological processes including selective laser sintering, fused deposition modeling, multi-jet modeling, or stereolithography. Conversely, in a subtractive manufacturing process, 3D objects are constructed by successive removal of material from a large block of material (e.g., polyurethane foam) through machining processes such as milling or drilling until the desired shape of the model is attained [24]. Several reviews regarding the applications of the aforementioned techniques have been published [25–29].

Since the 1990s, stereolithography has been used for quick manufacturing of accurate 3D anatomical models, including models presenting details of both external and internal anatomy registered by medical imaging systems [30–32]. Hence, combined with computer software, 3D models can be helpful in surgical training. They became a valuable tool in surgical planning and minimizing failure in reconstructing damaged parts of the body when biomaterials or autografts are utilized. Three-dimensional models are frequently used to help construct cranioplasty plates as well as fabricate customized prosthetics and implants [33].

Quality of 3D Digital Renderings versus Prosected Specimens

Gross dissection has been espoused all over the world. Likewise, gross dissection is time-honored, having been held in high regard in anatomical education for centuries.

The regular use of the human cadavers for teaching anatomy began in Europe in the Late Middle Ages and was propagated during the 18th and 19th centuries [34–35]. Today, cadaveric dissection continues to remain an important and reliable source of anatomical information. However, restricted accessibility to prosected cadavers and natural anatomical specimens has prompted the production of digital renderings and subsequent physical models. Such models are widely used for educational purposes because they enhance spatial perception, making easier understanding of spatial relationships among components of the human body [36–37].

The limitations regarding human anatomical specimens have also led scholars to create web-based gross anatomy atlases and publicly-available datasets (e.g., the visible human dataset being the anatomical platform for human simulation) which facilitate learning of human anatomy [38–39]. Similarly, virtual 3D models have become a novel teaching tool which improve understanding particularly complex anatomy and the topography of structures. For example, the "Visible Ear" is a library of digital images of a human temporal bone and surrounding structures. The Visible Ear is a high-fidelity computer-based modeling, simulation, and visualization system used to teach temporal bone anatomy and, likewise, the application of anatomy to middle ear surgery [40–42].

In academic medicine, only high-fidelity anatomical models can meet the expectations of the instructors and students who utilize virtual reality for educational purpose. Therefore, medical models must include all anatomical details of interest, be free from any artifacts and be dimensionally accurate [43]. Analysis of errors concerning discrepancies between virtual models and natural anatomical structures has been the subject of numerous studies. For example, Choi *et al.* [44] found that the absolute mean deviation between linear measurements taken on the original dry skull and its rapid prototyping model was 0.62 ± 0.35 mm (0.56 ± 0.39%). Barker *et al.* [45] reported a comparison between measurements skulls and measurements of stereolithographic skull models gave absolute differences ranging from +0.1 mm to +4.62 mm (Mean = +0.85 mm). Also, Colman *et al.* [46] tested the precision of virtual models of the human pelvis derived from clinical computed tomography and found that geometrical variability of the virtual pelvis rarely exceeds linear error of 2 mm. Such accuracy of virtual models appeared sufficient for medical studies and surgical pre-operative planning. Further, Quimby *et al.* [47] maintained that the accuracy and reliability of measurements from on computer-based digital models is clinically acceptable and that the virtual models can be an alternative to the conventional plaster models utilized by orthodontists. It should be also mentioned that quality of the replicated anatomical model is related to the manufacturing technology (e.g., selective laser sintering, PolyJet, etc.) used in the production of the model [48].

Conclusions

Volume and surface renderings are commonly used for imaging anatomical structures in three-dimensional manner, thereby facilitate understanding the orientation of the structure in 3D space. Indeed, virtual modeling helps to simulate surgical operations and enhance intra-organ navigation in presurgical planning and training medical procedures.

Conflict of interest

None of the authors have any conflict of interest nor any financial interest.

References

1. *Bay N.S., Bay B.H.*: Greek anatomist herophilus: the father of anatomy. Anat Cell Biol. 2010; 43 (4): 280–283. doi: 10.5115/acb.2010.43.4.280.
2. *Habbal O.*: The Science of Anatomy: A historical timeline. Sultan Qaboos Univ Med J. 2017; 17 (1): e18–e22. doi: 10.18295/squmj.2016.17.01.004.
3. *Malomo A.O., Idowu O.E., Osuagwu F.C.*: Lessons from history: human anatomy, from the origin to the renaissance. Int J Morphol. 2006; 24 (1): 99–104. doi: 10.4067/S0717-95022006000100018.
4. *Reverón R.R.*: Herophilus and Erasistratus, pioneers of human anatomical dissection. Vesalius. 2014; 20 (1): 55–58. PMID:25181783.
5. *Erkonen W.E., Albanese M.A., Smith W.L., Pantazis N.J.*: Effectiveness of teaching radiologic image interpretation in gross anatomy. A long-term follow-up. Invest Radiol. 1992; 27 (3): 264–266. doi: 10.1097/00004424-199203000-00016.
6. *Taguchi K., Aradate H.*: Algorithm for image reconstruction in multi-slice helical CT. Med Phys. 1998; 25 (4): 550–561. doi: 10.1118/1.598230.
7. *Brenner D.J., Hall E.J.*: Computed tomography — an increasing source of radiation exposure. N Engl J Med. 2007; 357 (22): 2277–2284. doi: 10.1056/NEJMra072149.
8. *Rinck P.*: Magnetic resonance: a critical peer-reviewed introduction. In Magnetic resonance in medicine. The basic textbook of the European magnetic resonance forum. 11th Edition, 2017. http://www.magnetic-resonance.org.
9. *Chen J., Pavlov A., Smith A., Sinning A., Conway M., Cui D.*: Creating 3D virtual models from CT and MRI for anatomy education. FASEB J. 2014; 28 (1 Suppl.): 923.2.
10. *Lavoie P., Ionescu D., Petriu E.M.*: 3D object model recovery from 2D images using structured light. IEEE Trans Instrum Meas. 2004; 53 (2): 437–443. doi: 10.1109/TIM.2004.823320.
11. *Slabaugh G., Schafer R., Malzbender T., Culbertson B.*: A survey of methods for volumetric scene reconstruction from photographs. In Volume Graphics pp.: 81–100. Springer, Vienna 2001. https://doi.org/10.1007/978-3-7091-6756-4_6.
12. *Jacquesson T., Mertens P., Berhouma M., Jouanneau E., Simon E.*: The 360 photography: a new anatomical insight of the sphenoid bone. Interest for anatomy teaching and skull base surgery. Surg Radiol Anat. 2017; 39 (1): 17–22. doi: 10.1007/s00276-016-1702-1.
13. *Da Silveira A.C., Daw J.L. Jr., Kusnoto B., Evans C., Cohen M.*: Craniofacial applications of three-dimensional laser surface scanning. J Craniofac Surg. 2003; 14 (4): 449–456. doi: 10.1097/00001665-200307000-00009.

14. *Hennessy R.J., McLearie S., Kinsella A., Waddington J.L.*: Facial shape and asymmetry by three-dimensional laser surface scanning covary with cognition in a sexually dimorphic manner. J Neuropsychiatry Clin Neurosci. 2006; 18 (1): 73–80. doi: 10.1176/jnp.18.1.73.
15. *Jacobs R.A.*: Plastic Surgery Educational Foundation DATA Committee. Three-dimensional photography. Plast Reconstr Surg. 2001; 107 (1): 276–277. doi: 10.1097/00006534-200101000-00049.
16. *Lee S.*: Three-dimensional photography and its application to facial plastic surgery. Arch Facial Plast Surg. 2004; 6 (6): 410–414. doi: 10.1001/archfaci.6.6.410.
17. *Weinberg S.M., Kolar J.C.*: Three-dimensional surface imaging: limitations and considerations from the anthropometric perspective. J Craniofac Surg. 2005; 16 (5): 847–851. doi: 10.1097/01.SCS.0000164330.96675.0C.
18. *Ameil M., Delattre J.F., Cordobes B., Flament J.B.*: Computerized reconstruction of an anatomical structure based on digitized sections. Preliminary study. Anat Clin. 1984; 5 (4): 261–264. https://doi.org/10.1007/BF01798749.
19. *Cline H.E., Dumoulin C.L., Hart H.R. Jr, Lorensen W.E., Ludke S.*: 3D reconstruction of the brain from magnetic resonance images using a connectivity algorithm. Magn Reson Imaging. 1987; 5 (5): 345–352. doi: 10.1016/0730-725X(87)90124-X.
20. *Thali M.J., Braun M., Wirth J., Vock P., Dirnhofer R.*: 3D surface and body documentation in forensic medicine: 3-D/CAD Photogrammetry merged with 3D radiological scanning. J Forensic Sci. 2003; 48 (6): 1356–1365. doi: 10.1520/JFS2003118.
21. *Calhoun P.S., Kuszyk B.S., Heath D.G., Carley J.C., Fishman E.K.*: Three-dimensional volume rendering of spiral CT data: theory and method. Radiographics. 1999; 19 (3): 745–764.
22. *Udupa J.K., Hung H.M., Chuang K.S.*: Surface and volume rendering in three-dimensional imaging: a comparison. J Digital Imaging. 1991; 4 (3): 159–168. PMID: 1911974.
23. *Kaufman A., Mueller K.*: Volume visualization and volume graphics. Stony Brook, pp.: 10–15. Stony Brook University, 2003.
24. *Bikas H., Stavropoulos P., Chryssolouris G.*: Additive manufacturing methods and modelling approaches: a critical review. Int J Adv Manuf Technol. 2016; 83 (1–4): 389–405. https://doi.org/10.1007/s00170-015-7576-2.
25. *Esses S.J., Berman P., Bloom A.I., Sosna J.*: Clinical applications of physical 3D models derived from MDCT data and created by rapid prototyping. AJR Am J Roentgenol. 2011; 196 (6): W683–668. doi:10.2214/AJR.10.5681.
26. *Hieu L.C., Zlatov N., Vander Sloten J., Bohez E., Khanh L., Binh P.H., Oris P., Toshev Y.*: Medical rapid prototyping applications and methods. Assembly Autom. 2005: 25 (4): 284–292. https://doi.org/10.1108/01445150510626415.
27. *McGurk M., Amis A.A., Potamianos P., Goodger N.M.*: Rapid prototyping techniques for anatomical modelling in medicine. Ann R Coll Surg Engl. 1997; 79 (3): 169–174. PMID: 9196336.
28. *Petzold R., Zeilhofer H.F., Kalender W.A.*: Rapid protyping technology in medicine--basics and applications. Comput Med Imaging Graph. 1999; 23 (5): 277–284. doi: 10.1016/S0895-6111(99)00025-7.
29. *Webb P.A.*: A review of rapid prototyping (RP) techniques in the medical and biomedical sector. J Med Eng Technol. 2000; 24 (4): 149–153. doi: 10.1080/03091900050163427.
30. *Bouyssié J.F., Bouyssié S., Sharrock P., Duran D.*: Stereolithographic models derived from x-ray computed tomography. Reproduction accuracy. Surg Radiol Anat. 1997; 19 (3): 193–199. https://doi.org/10.1007/BF01627975.
31. *Klimek L., Klein H.M., Schneider W., Mösges R., Schmelzer B., Voy E.D.*: Stereolithographic modelling for reconstructive head surgery. Acta Otorhinolaryngol Belg. 1993; 47 (3): 329–334. PMID: 8213143.
32. *Mankovich N.J., Cheeseman A.M., Stoker N.G.*: The display of three-dimensional anatomy with stereolithographic models. J Digit Imaging. 1990; 3 (3): 200–203. doi: 10.1007/BF03167610.

33. *Gür Y.*: Additive Manufacturing of Anatomical Models from Computed Tomography Scan Data. Mol Cell Biomech. 2014; 11 (4): 249–258. doi: 10.3970/mcb.2014.011.249.
34. *Ghosh S.K.*: Human cadaveric dissection: a historical account from ancient Greece to the modern era. Anat Cell Biol. 2015; 48 (3): 153–169. doi: 10.5115/acb.2015.48.3.153.
35. *Habicht J.L., Kiessling C., Winkelmann A.*: Bodies for Anatomy Education in Medical Schools: An Overview of the Sources of Cadavers Worldwide. Acad Med. 2018; 93 (9): 1293–1300. doi: 10.1097/ACM.0000000000002227.
36. *Aziz M.A., McKenzie J.C., Wilson J.S., Cowie R.J., Ayeni S.A., Dunn B.K.*: The human cadaver in the age of biomedical informatics. Anat Rec. 2002; 269 (1): 20–32. doi: 10.1002/ar.10046.
37. *Fredieu J.R., Kerbo J., Herron M., Klatte R., Cooke M.*: Anatomical models: a digital revolution. Med Sci Educ. 2015; 25 (2): 183–194. doi: 10.1007/s40670-015-0115-9.
38. *Brinkley J.F., Bradley S.W., Sundsten J.W., Rosse C.*: The digital anatomist information system and its use in the generation and delivery of Web-based anatomy atlases. Comput Biomed Res. 1997; 30 (6): 472–503. https://doi.org/10.1006/cbmr.1997.1461.
39. *Spitzer V.M., Whitlock D.G.*: The Visible Human Dataset: the anatomical platform for human simulation. Anat Rec. 1998; 253 (2): 49–57. doi: 10.1002/(SICI)1097-0185(199804)253:2<49::AID-AR8>3.0.CO;2-9.
40. *Bennett W.O., Wilmot V.V., Reddy V.M., Alderson D.J.*: The realism and usefulness of the Voxel-Man TempoSurg and the Visible Ear simulator. Bull Roy Coll Surg Engl. 2015; 97 (2): 66–69. doi: 10.1308/rcsbull.2015.97.2.66.
41. *Sørensen M.S., Dobrzeniecki A.B., Larsen P., Frisch T., Sporring J., Darvann T.A.*: The visible ear: a digital image library of the temporal bone. ORL J Otorhinolaryngol Relat Spec. 2002; 64 (6): 378–381. doi: 10.1159/000066089.
42. *Wang H., Northrop C., Burgess B., Liberman M.C., Merchant S.N.*: Three-dimensional virtual model of the human temporal bone: a stand-alone, downloadable teaching tool. Otol Neurotol. 2006; 27 (4): 452–457. doi: 10.1097/01.mao.0000188353.97795.c5.
43. *Bibb R., Winder J.*: A review of the issues surrounding three-dimensional computed tomography for medical modelling using rapid prototyping techniques. Radiography. 2010; 16 (1): 78–83. https://doi.org/10.1016/j.radi.2009.10.005.
44. *Choi J.Y., Choi J.H., Kim N.K., Kim Y., Lee J.K., Kim M.K., Lee J.H., Kim M.J.*: Analysis of errors in medical rapid prototyping models. Int J Oral Maxillofac Surg. 2002; 31 (1): 23–32. https://doi.org/10.1054/ijom.2000.0135.
45. *Barker T.M., Earwaker W.J., Lisle D.A.*: Accuracy of stereolithographic models of human anatomy. Australas Radiol. 1994; 38 (2): 106–111. https://doi.org/10.1111/j.1440-1673.1994.tb00146.x.
46. *Colman K.L., Dobbe J.G.G., Stull K.E., Ruijter J.M., Oostra R.J., van Rijn R.R., van der Merwe A.E., de Boer H.H., Streekstra G.J.*: The geometrical precision of virtual bone models derived from clinical computed tomography data for forensic anthropology. Int J Legal Med. 2017; 131 (4): 1155–1163. doi: 10.1007/s00414-017-1548-z.
47. *Quimby M.L., Vig K.W., Rashid R.G., Firestone A.R.*: The accuracy and reliability of measurements made on computer-based digital models. Angle Orthod. 2004; 74 (3): 298–303. doi: 10.1043/0003-3219(2004)074<0298:TAAROM>2.0.CO;2.
48. *Salmi M., Paloheimo K.S., Tuomi J., Wolff J., Mäkitie A.*: Accuracy of medical models made by additive manufacturing (rapid manufacturing). J Craniomaxillofac Surg. 2013; 41 (7): 603–609. doi: 10.1016/j.jcms.2012.11.041.