Computers & Graphics xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Computers & Graphics

journal homepage: www.elsevier.com/locate/cag

Survey Paper

A survey of virtual human anatomy education systems☆

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ARTICLE INFO

Article history:
Received 20 October 2017
Revised 5 January 2018
Accepted 11 January 2018
Available online xxx

Keywords:
Medical visualization
Virtual anatomy

ABSTRACT

This survey provides an overview of visualization and interaction techniques developed for anatomy education. Besides individual techniques, the integration into *virtual anatomy* systems is considered. Web-based systems play a crucial role to enable learning independently at any time and space. We consider the educational background, the underlying data, the model generation as well as the incorporation of textual components, such as labels and explanations. Finally, stereoscopic devices and first immersive VR solutions are discussed. The survey comprises also evaluation studies that analyze the learning effectiveness.

1. Introduction

Anatomy education aims at providing medical students with an in-depth understanding of the morphology of anatomical structures, their position and spatial relations, e.g. connectivity and innervation. Students should be able to locate anatomical structures, which is an essential prerequisite for surgical interventions. They should also be aware of the variability of the morphology and location, e.g. of branching patterns of vascular structures. The traditional methods for anatomy education involve lectures, the use of text books and atlases as well as cadaver dissections. Cadaver dissection plays an essential role for many reasons, e.g. the training of manual dexterity and communication skills [1]. The realism of this experience, however, is limited, since the color and texture of anatomical structures in cadavers differ strongly from living patients. Other disadvantages associated with the use of cadavers, include their high cost, the difficulty of supply and short time they can be used only.

While cadaver dissection is often part of anatomy education in medicine, anatomy education in related disciplines, e.g. sport and dentistry do not benefit from dissections.

Interactive 3D visualizations, in particular when combined with specific learning tasks, have a great potential to add to these traditional methods and even partially to replace them. The latter is desirable due to a shortage of cadavers and available teaching time in anatomy [1]. Many studies indicate that students perceive interactive systems as valuable learning resources and, moreover, they made substantial progress in understanding spatial relations [2,3].

Anatomy education was one of the driving applications of medical visualization techniques with the VOXEL-MAN as the outstanding example [4]. Early medical visualization papers discussed high-quality volume renderings of segmented volume data [5] or efficient realization of clipping and cutting techniques, such as using the virtual scalpel [6], all aiming at anatomy education. Another development motivated by anatomy education is *labeling*, where sophisticated algorithms were developed to ensure an efficient and pleasant label placement. Although the focus of most medical visualization research shifted towards diagnosis, treatment planning and intraoperative support, anatomy education made progress as well. The advent of web-based standards, in particular the introduction of WebGL, and the recent progress of affordable VR glasses triggered the development of new systems in research and in commercial settings.

Besides technically motivated developments, progress was also made w.r.t. motivational design partially inspired by serious games and w.r.t. a proper balance between self-directed learning and guidance. The essential questions from an application point of view are, of course, how the learning is affected and which students will benefit from virtual anatomy systems. This survey article also pays attention to studies where the learning effects are analyzed.

So far, there is no survey article on this issue. However, in the chapter "Computer-Assisted Medical Education" (with a focus on surgery training) of the book "Visual Computing for Medicine" [7], anatomy education is discussed in some detail. Also in the previous book by Preim and Bartz [8] anatomy education is part of one chapter. The latter is outdated, since many systems were introduced later. We pay attention to avoid large overlaps to these

☆ This article was recommended for publication by Stefan Bruckner.

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https://doi.org/10.1016/j.cag.2018.01.005

chapters, focusing on more recent developments and on evaluations that were barely discussed at all there.

Scope of the survey. Anatomy education may be discussed from a teacher perspective and from a learner perspective. The teacher perspective involves the tools necessary to *author* interactive 3D visualizations and relate them to the symbolic information (anatomic names, categories, relations) as well as self-assessment tools and other methods to directly support learning. These tools comprise segmentation and model reconstruction as well as hypertext facilities to organize textual information. In this survey, however, we restrict to the *learners' perspective*, i.e. we focus on the character and quality of the available information and the techniques to explore this information space and acquire knowledge. We do not discuss *how* the information space was created. We also restrict to anatomy education for medical students and exclude related disciplines, such as dentistry or studies of veterinarians.

There is wide variety of computer systems that support anatomy education, including those that use only static 2D images and associated text or additional media, such as audio. Multimedia versions of anatomic atlases are popular examples. We restrict our discussion to systems that support the exploration of anatomical structures in 3D and refer to these systems as *virtual anatomy* (VA) systems. Such VA systems enable to display anatomical structures from any viewpoint and are not restricted to a few familiar viewing directions such as a text book. This includes desktop solutions, semi-immersive and virtual reality systems. We do, however, consider systems that integrate 2D slice-based visualizations and 3D visualizations, since this integration is important for many clinical disciplines.

Recently, considerable effort was spent on using *augmented reality* for anatomy education [9,10] including a survey on augmented reality in medicine [11]. To restrict this survey to a manageable size, we do not consider these systems since a number of specific topics would be involved. Another recent development in anatomy education is the creation of *physical models* with 3D printing [12,13]. These models offer tactile cues when explored and can be generated in a cost-effective manner and thus can potentially be used widely. In this survey, we do not discuss these developments. A related medical education topic is surgery simulation where virtual reality solutions are advanced but since target users, goals and systems are strongly different, we do not discuss them.

Selection strategy. This survey is based on a comprehensive search in various digital libraries (Sept. 2017). A search for the keyword “anatomy” in the Eurographics digital library resulted in 292 publications and a search for “anatomy education” in the IEEE digital library to a further 202 publications with “anatomy” being part of the title or abstract. Moreover, Google Scholar and PubMed were used for searching. The selection of the papers to actually consider was based on relevance, originality and visibility. Papers, where anatomy education is not central, were discarded. This relates to papers where anatomy is considered with the goal of character animation and also papers with focus on education in surgery. Journal publications were favored instead of, e.g. local EG chapter publications. Short papers were excluded, except they present a highly innovative concept. As a minor criterion, citation numbers were also considered to ensure that highly visible papers are included.

2. Educational background

E-learning in general is an essential trend in many disciplines. Students may use e-learning resources at any time and adapt the system to their learning goals. Self-assessment facilities, such as multiple choice questions, careful guidance, and motivational strategies, are essential components. Communication functions to share thoughts and questions with other students and teachers further enhance the learning experience. E-learning systems may even be tailored to the individual user by managing their learning progress and adapting the presentation of tasks and material. The potential of e-learning is only realized with highly motivated self-disciplined users — a prerequisite that is fulfilled in case of medical students. Many studies indicate that medical students enjoy online anatomy resources. The survey of Jastrow and Hollinderbäumer [14] shows that students consider them as motivating and appreciate high-quality visualizations, keyword searches and up-to-date information in particular.

All general principles of e-learning, for example w.r.t. instruction design and use of media, apply to anatomy education as well. The special situation in anatomy is the extremely complex structure of the human body, characterized by various systems that are closely related to each other. The level of required *spatial understanding* in anatomy is extraordinary. Anatomic structures have to be recognized from different perspectives, understood in relation to adjacent structures and finally integrated in an understanding of regions and systems [15]. The potential of interactive 3D visualization is that students actively explore anatomical structures and their spatial relations in a direct way [16].

2.1. Learning theories

In the following, we discuss major learning theories that are mentioned in VA system descriptions to justify design decisions. These theories have in common that they go beyond learning of mere facts, as supported by drill-and-practice programs—the earliest type of e-learning software. Pedagogical background information is provided by Dev et al. [17], including a history of e-learning in medicine since the 1960s.

Constructivism and embodied cognition. According to constructivists' theories, active learning favors spontaneous knowledge construction and thus reduces cognitive load compared to traditional learning experiences. Moreover, the handling of anatomical structures—the interactive rotation—resembles the way students would explore such structures in reality when they, e.g. rotate real bones in their hands. The advantage of this similarity is due to the phenomenon of *embodied cognition*, i.e. learning benefits from the involvement of body movements. Based on increasing evidence, embodied cognition considers the perceptual and motor systems as essential ingredients of cognitive processes [16]. As an example, Kosslyn et al. found that physical rotation leads to a stronger activation of the motor cortex in a subsequent mental rotation task [18]. Of course, the similarity between movements in the real world and in the virtual world is higher with a 3D input device or with head tracking in VR compared to a 2D mouse. But even a 2D input device provides the experience how the view changes depending on the speed and direction of movement. A 3D input device has the added advantage of a good *stimulus-response compatibility*; a close correspondence between movements to steer an object and the resulting changes in the visualization. Jang et al. [19] highlight the additional learning effect due to interactive manipulation of 3D content compared to passive viewing of prepared video sequences showing the same content. Thus, anatomy learning requires more than passive viewing even if the presented material is of high didactic quality. The relation between constructivism and virtual reality learning environments is discussed by Huang et al. [20].

There are different links between constructivism and anatomy education. Murray and Stewart [21], for example, use a physical 3D model of the skeletal system and learners should place wires as models for nerves to learn about the origin and path of nerves. This active engagement may generate knowledge in the constructivists' sense. A similar experience may be provided in a virtual anatomy system. Ma et al. [22] argue that students learn anatomy

Please cite this article as: B. Preim, P. Saalfeld, A survey of virtual human anatomy education systems, Computers & Graphics (2018), https://doi.org/10.1016/j.cag.2018.01.005