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Survey Paper

A survey of virtual human anatomy education systems☆

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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

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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

Fig. 1. The correlation between real structures of a cadaver and radiological image data is explained in a VA system (From: [24]).

by developing a serious game. Provided that the authoring systems are very powerful and easy to use, this may be possible.

Problem-based learning. A major trend in medical education is *problem-based learning* (PBL). Instead of isolated learning of facts, with PBL, small groups of students should cooperate and solve problems, e.g. to locate a deep anatomic structure and describe the regional surroundings or to treat a particular injury. A tutor facilitates problem solving by making necessary resources available [1]. Virtual anatomy systems may employ carefully chosen tasks to fit in a problem-based curriculum. This educational background is carefully discussed in a number of publications, e.g. by Chittaro and Ranon [16].

Blended learning. VA systems will be particularly efficient if they are linked to other forms of learning, supported by anatomy teachers explaining in which stages and how to use them as a kind of *blended learning*. VA systems cannot replace other types of anatomy education. Brenton et al. [1], for example, discuss the advantages of dissection that are also valid in the presence of VA systems. Also lectures that are used to introduce important concepts, remain indispensable. Some VA systems are not primarily intended for (isolated) self-study, but for use in the classroom or dissection room. As an example, Philips et al. [23] show how a VA system with radiological image data of a cadaver is operated in the dissection room to explain students the structures of the corresponding real cadaver (see Fig. 1).

2.2. Aspects of anatomy education

Anatomy education is an essential basis for many clinical disciplines. Prevention of surgical complications and successful interventions requires an in-depth anatomical knowledge of the target region. A general distinction can be made in non-spatial and spatial anatomy knowledge. Non-spatial knowledge includes terminology, taxonomy, and functions of structures, whereas spatial anatomy knowledge includes the position, orientation, extent and shape of structures [25]. Our focus is on the acquisition of spatial knowledge that may be enhanced by 3D visualizations. Anatomy is studied under the following aspects:

- *clinical anatomy*: the study of anatomy that is most relevant to the practice of medicine.
- *comparative anatomy*: the study of anatomies of different organisms, related to the shape and size of anatomic structures, or the variants of the topology in case of branching structures, such as arteries, veins and nerves.
- *cross-sectional anatomy*: anatomy viewed in the transverse plane of the body.
- *radiographic anatomy*: the study of anatomy as observed with imaging techniques such as conventional X-ray, MRI, and CT.
- *regional anatomy*: the study of anatomy by parts of the body, e.g. thorax, heart, and abdomen. In regional anatomy, all biological systems, e.g., skeletal, circulatory, are studied with an emphasis on the interrelation of the systems and their regional function. Dissection supports learning of regional anatomy.
- *systemic anatomy*: the study of anatomy by biological systems, e.g., skeletal, muscular, digestive, and circulatory system. In systemic anatomy, a single biological system is studied across all body regions. Dissection is less relevant for systematic anatomy learning.
- *macroscopic anatomy*: the study of anatomy with the unaided eye, essentially visual observation. Typically, macroscopic anatomy is explored using dissected cadavers.
- *microscopic anatomy*: the study of anatomy with the aid of the light microscope and with electron microscopes that provide subcellular observations. Microscopic anatomy is based on very high resolution images and provides insight at a level that is neither possible with tomographic image data nor dissecting cadavers.
- *surgical anatomy*: the application and study of anatomy as it relates to surgery, e.g. the relevance of anatomical structures for avoiding complications or guiding the surgeon during an intervention.

These different aspects represent different “views” on the anatomy. For example, the kidney is part of the abdominal viscera in the *regional anatomy* and part of the urogenital system in the *systemic anatomy* [26].

Ideally, anatomy education systems integrate all aspects, for example by smoothly blending in data in different resolutions. Currently, such an ideal system is not fully realized due to many technical problems such as acquiring and analyzing a large variety of image data and adapting visualization techniques. Very few VA systems integrate microscopic anatomy. An example is the digital pelvic atlas focusing on anatomical relations that are essential for surgery [27]. Clinical anatomy and radiographic anatomy can be explored with medical volume data and derived information. As an early example for combining different aspects of anatomy, the DigitalAnatomist [28] provides 3D overviews, where the position of certain slabs is marked. For each slab, the related information is shown as CT slice and as photographic data.

The study of comparative anatomy requires a variety of different datasets that represent at least the typical anatomic variants. Most systems do not support this important aspect of anatomy. Many VA systems focus on regional anatomy and represent the relation between labels and segmentation results.

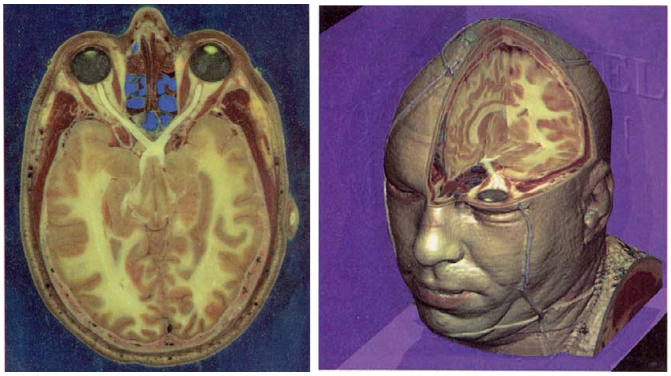

Fig. 2. Photographic data from the Visible Human Male dataset. Left: a slice view, right: a volume rendering with clipping enabled (From: [38]).

3. Datasets

Radiological imaging plays an important role in anatomy education, since the relation between radiological image data and live patients is important not only for radiologists, but also for many physicians. VA systems are often based on image data and segmentation results representing anatomic structures. Based on these data, high-quality renderings can be generated and interactively explored. Direct volume rendering as well as surface rendering techniques may be employed. While clinical applications require fast segmentation and visualization for the current patient, educational systems require primarily high quality results that are typically achieved after careful image analysis and modeling. Accuracy of visualizations is less important in educational settings since the visualization does not serve to plan surgery on *this* patient. The visualization should convey a plausible instance of the spatial relations. Therefore, smooth surfaces without distracting features are preferred.

As a source for anatomy education, commercial 3D model catalogs can be employed. Leading vendors are Digimation (formerly Viewpoint Datalabs), providing almost 600 excellent anatomic models (http://www.digimation.com/the-archive/), and TurboSquid where even 9.000 anatomy models in very good quality are available https://www.turbosquid.com/3d-model/anatomy. Some systems, such as ZygoteBody [29] and the BioDigital Human [30] rely on artistically created 3D models.

3.1. Cadaver data

For diagnostic purposes, the image quality is only as good as necessary, thus reducing the time of image acquisition or radiation in case of CT data. Imaging data of cadavers, however, aims at a high resolution and low level of noise. Therefore, VA systems are often based on anatomic models extracted from imaging data of cadavers.

The most widely used cadaver datasets are the Visible Human (VH) datasets from the National Library of Medicine (see Fig. 2). These 3D datasets originate from two bodies that were given to science, frozen, and digitized into horizontally spaced slices. A total number of 1871 cryosection slices was generated for the Visible Man (1 mm slice distance) and even more for the Visible Woman (0.33 mm slice distance) [31]. Besides photographic cryosectional images, fresh and frozen CT data have been acquired.

The quality of the VH datasets was unprecedented at that time. CT data were acquired with high radiation—resulting in an excellent signal-to-noise ratio—and without breathing and other motion artifacts. However, the frozen body was cut in four blocks prior to image acquisition leaving some noticeable gaps in the data. The VH datasets are employed for a variety of virtual anatomy systems, e.g. the VOXEL-MAN [32,33] (see Fig. 2), the “Internet Atlas of Human Gross Anatomy” [34] and the “Anatomic VisualizeR” [35]. The VH datasets were also used for functional anatomy, e.g. for biomechanical animations of the musco-skeletal system [36]. Juanes et al. [37] provide a comprehensive survey of early applications of the VH data for anatomy teaching. The website https://www.nlm.nih.gov/research/visible/products.html currently (September 2017) lists 25 products based on the VH dataset including three regional and radiological anatomy resources of the VOXEL-MAN family (Brain and Skull, Inner Organs and Upper Limbs) and the “Complete 3D model of the human body (male and female)” from Primal Pictures.

Visible Korean and Chinese Visible Human. Datasets from people of other regions in the world were also needed for medical education. In the Visible Korean Human project, a dataset of a 65-year-old patient was provided [39]. The Visible Korean dataset was employed, e.g. for the Online Anatomical Human [40]. The Chinese Visible Human avoided some problems of the VH project [41]. In particular, the image acquisition was performed with a very large milling machine that did not require to cut the body avoiding any section loss.

The Chinese Visible Human dataset contains healthy female and male adults and exhibits a superior spatial resolution (in-plane resolution: 170 μm). The raw data (photographs, CT and MRI data) were carefully segmented (869 structures of the male dataset and 860 of the female dataset) [42].

Further anatomical data. The University of Colorado, Center for Human Simulation continued its efforts to acquire anatomical data at a very high-quality. Spitzer and Ackerman [43] describe datasets acquired between 2003 and 2008. The dataset with the highest quality represents the foot and ankle region with 5000 visible light photographs. This increased resolution resembles high magnification images from arthroscopy. Other datasets represent the prostate and pelvis region, the wrist and hand as well as the thorax and heart region. Spitzer and Ackerman [43] report on ongoing work to simulate the movement of ligaments and spinal nerves depending on the movement of the vertebrae.

3.2. Clinical image data

Although the image quality of clinical data is lower than that of cadaver data, they provide an alternative image source. As an example, the first versions of the VOXEL-MAN were based on a cerebral MRI dataset [44]. Datasets used for anatomy education are from carefully selected healthy persons with normal anatomic relations.

3.3. Segmentation

The segmentation of anatomic structures can be accomplished with general segmentation techniques, such as thresholding, region-growing, live wire or watershed segmentation depending on the shape and contrast of the target structure. A special case is the segmentation of the photographic datasets of the VH project. These datasets represent colored voxels (24 bits representing a red, green, and blue component). Thus, regions in RGB-space have to be separated [45].

For anatomy education, all anatomic structures, which can be derived from the image data, are relevant. Therefore, considerably more objects are segmented compared to clinical applications where the time pressure is high. The VOXEL-MAN, for example, is based on the segmentation of 650 objects. A challenge is the identification and delineation of functional areas, for example in the brain, since these areas are not represented as recognizable objects

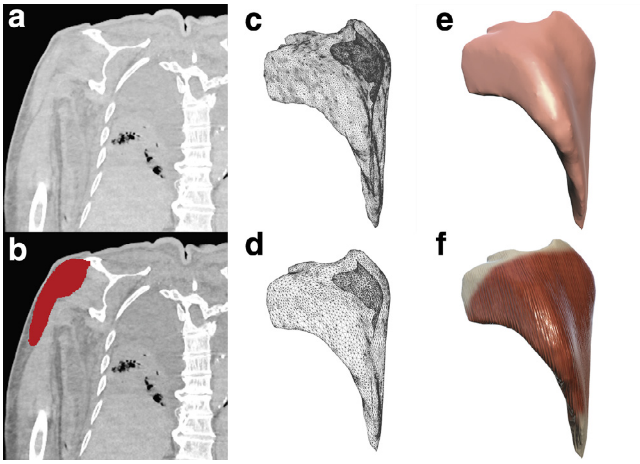

Fig. 3. Reconstruction of anatomical structures from clinical image data. Objects are segmented (a–b), transformed into a mesh (c), remeshed to reduce model size and improve smoothness (d), shaded (e) and optionally textured (f) (Inspired by: [1]).

in the image data. Considerable expert knowledge is necessary to delineate these features.

4. Visualization techniques

In the following, visualization techniques used in VA systems are described. In addition, we briefly discuss illustrative visualization techniques since they are inspired by anatomic illustrations and have potential for enhancing VA systems.

4.1. Surface visualization

Most VA systems rely on surface rendering. Azkue [46] argues that surface representations with their solid appearance resemble real anatomic structures, such as bones. Either segmented objects are transformed into polygonal meshes or the meshes are constructed with a modeling tool. A hybrid approach is also possible: structures that are only partially segmented in the image data, such as small blood vessels and nerves, are used as input for modeling where they are "completed", e.g. by fitting a spline to the extracted cross-sections. A corresponding "tube editor" is described by Pommert et al. [26]. The direct transformation of binary segmentation results to surfaces via the Marching Cubes algorithm is not recommended since artifacts occur. Mesh smoothing is typically applied afterwards. Constrained elastic surface nets [47] is a particularly method useful for meshes resulting from binary segmentation results on a regular grid. With this method, considerable smoothing is achieved while limiting the displacement of vertices to half of the diagonal size of a voxel. Also mesh simplification may be essential to reduce the number of polygons and to enable fast transfer and rendering (see the pipeline in Fig. 3). Mesh simplification is particularly important for web-based applications to reduce the download speed. For elongated branching structures, such as vessels, dedicated reconstruction methods are available based on splines, convolution surfaces or MPU implicits (see [48] for a survey). The polygonal models are typically shaded and may also be textured to enhance realism.

Texturing surface models. Applying textures to 3D surface models can enhance the representation of medical structures by making them more realistic or illustrative, which eventually supports learning. Texturing is mostly done manually using 3D modeling applications. This approach works for single surface models, but is too time-consuming if the process from image acquisition to a textured model should be automated. To automatically apply textures to models, procedural terrain modeling techniques can be used. Saalfeld et al. [49] use tri-planar texture mapping to texture arbitrary vascular structures. Here, the normal of each vertex is mapped to a texture on the x, y, and z plane to get three colors. The final color is calculated by a weighted combination of these colors. This weight depends on the direction of the normal. For example, if the normal is facing exactly to the z-direction, only the texture color of the x-y-plane would be taken into account. This approach is sufficient for structures, where the orientation of the texture does not matter. This is not the case for muscles and tendons, where the orientation give hints about the origin and insertion. For these models, an approach from Gasteiger et al. [50] can be used. They calculate the direction for a hatching texture by using the principle curvature direction for each vertex and the skeleton of the model. By deriving the skeleton's direction of the nearest skeleton point and combining this with the principle curvature direction, an orientation for the whole model is calculated.

4.2. Volume visualization

Volume data provides more detail and enables relevant exploration facilities beyond surface visualizations. In particular clipping and cutting surfaces (virtual dissection) makes only sense if information on the inner portions of the objects is available, which is not the case when only the outer wall is represented by triangles. The use of volume rendering is also challenging. Whole volume data have a larger memory consumption than polygonal meshes of selected objects. This may cause bandwidth-related problems in web-based systems. For VA systems, where typically all essential structures are segmented, the high-quality rendering of these *tagged volumes* is essential. Tiede et al. [5] introduced an appropriate algorithm where the object borders are displayed at subvoxel accuracy to avoid terracing artifacts. A useful variant of volume rendering for VA is the simulation of X-ray images to teach learners how an anatomic region would look like as X-ray. With GPU support, the X-ray attenuation through complex objects can be efficiently simulated [51].

In the last two decades, the performance of GPUs improved drastically. This enables to add a number of visual effects that enhance the realism of volume-rendered images. *Boundary emphasis* may be achieved with curvature-based transfer functions [52]. Deferred shading enables to incorporate advanced lighting effects [53]. Screen-space ambient occlusion further improves depth perception [54]. A realistic display of colors to enhance recognition of structures in surgery was developed and evaluated for displaying the brain [55]. Recent developments lead to photorealistic rendering systems, such as Exposure Render [56] and the CinematicRenderer (see Fig. 4) developed at SIEMENS [57,58]. These systems are based on the Monte-Carlo path tracing of volumetric data [59] instead of simple raycasting. With this method, thousands of photon paths per pixel are traced by a stochastic procedure and the complex interactions of photons with the human anatomy are faithfully simulated [58]. Effects, such as soft shadows and volumetric scattering, are represented well. Besides advanced lighting, also the camera model is extended: it has variable aperture and focal length and thus enables to simulate depth-of-field and motion blur. The additional power and flexibility comes with additional parameters for the renderer, e.g. illumination parameters. Templates, e.g. for bones and muscles, are used to summarize viewing parameters and reuse them [57].

The advantage of the increased realism for anatomy education seems obvious. Shape perception indeed benefits from increased realism [60]. However, no study was carried out to actually demonstrate differences in knowledge gains due to improved visualizations.

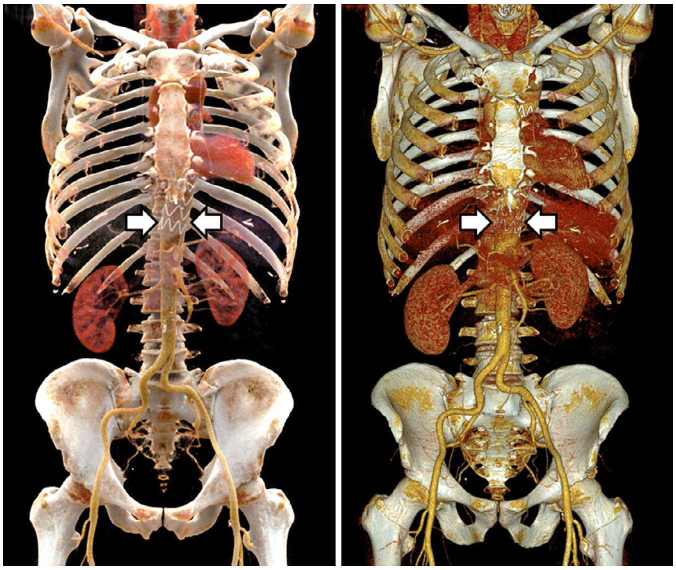

Fig. 4. Comparison of traditional volume rendering (left) and cinematic rendering (right). The arrows point to portions where the differences become obvious. Cinematic rendering provides more shape cues (From: [57]).

4.3. Illustrative visualization

Illustrations play a crucial role in knowledge dissemination since centuries. Before the advent of photography there was no alternative means to visually convey the morphology and structural relations, but even after photography was widely available, anatomy text books and atlases primarily employ manual illustrations where colors are chosen to optimally convey relations and provide sufficient contrast and where the level of detail is carefully adapted to the educational goal. Thus, some structures might be shown without details serving as anatomic context, whereas others employ prominent colors and more detail. The development of anatomical illustrations is summarized in a recent article [61].

Anatomical illustration is an interdisciplinary field where both the expert knowledge in anatomy and in art is required. Whereas in earlier centuries, anatomy illustrations were often shown along with plants and animals leading to a dramatized display, later illustrators, such as Henry Gray and Frank Netter, focussed consequently on the human anatomy.

Since the 1960s, also radiological image data was used as a source for anatomy education [23]. More recently, computer support was employed to create 3D models to be displayed with illustrative styles. Pioneering work in this field was carried out by Corl et al. [62].[1] While they focussed on specific medical scenarios, e.g. the position of the kidney in the pelvic region, recent research in computer graphics and visualization focused on general methods that generate feature lines and hatchings from polygonal surfaces. These 3D illustrations combine the advantages of illustrations and those of interactive visualizations. Notable developments include the combination of surface, volume and line renderings with a consistent visibility computation introduced by Tietjen et al. [63], the automatic generation of stippling images [64], and the automatic computation of hatching to reflect lightings [65]. Lawonn et al. introduced the ConFis method that combines feature lines and hatchings. Thus, depending on the local curvature either features are emphasized, or, if no features are available, principal curvature directions [66]. In particular the use of stippling for a 3D visualization may be disadvantageous compared with shaded surfaces and semi-transparent rendering. Probably, in the era of computer graphics, stippling may be replaced by other and more efficient techniques.

[1] Meanwhile a gallery of illustrations in twelve regions is available at http://www.ctisus.com/redesign/learning/illustrations

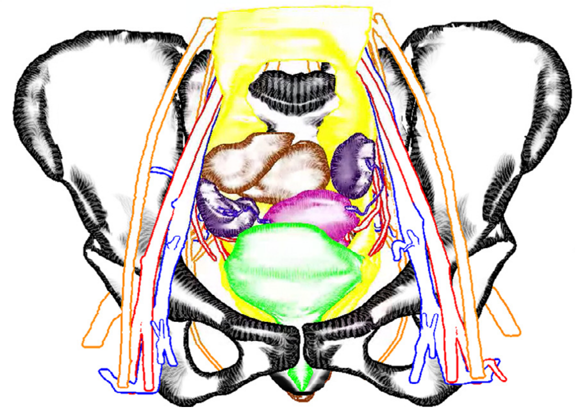

Fig. 5. The complex anatomy of the pelvic region displayed with an illustrative rendering style. The large skeletal structures serve primarily as orientation and are thus rendered in black and white, while finer anatomical structures are emphasized with colors (From: [67]).

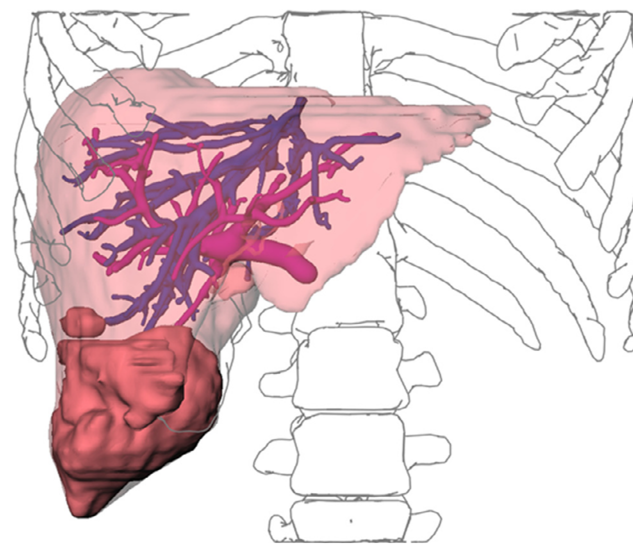

Fig. 6. Surface rendering of the hepatic anatomy embedded in a silhouette rendering of the skeletal structures to provide anatomic context (From: [63]).

The ConFis method was recently refined and combined with an illustrative color scheme, thus emphasizing different categories of anatomic structures (see Fig. 5).

Also volume rendering-based VA systems may benefit from illustrative visualization styles. Two-level volume rendering [68] and the VOLUME SHOP [69] as well as focus-context renderings [70] are essential examples.

Whether anatomy education systems indeed benefit from illustrative visualization techniques is not clear, since none of these techniques were actually used for anatomy education and subject to rigorous testing for learning effects. In VA systems, pure line-based renderings certainly are not successful, since lines cannot convey shape information as efficiently as shading [71]. However, the level of detail in the display of an anatomical structure can be adapted well with these rendering styles. Thus, illustrative line renderings may have a role to display structures that serve as anatomic context (see Fig. 6).

4.4. Viewpoint selection

When a 3D model of a certain part of the body is loaded, e.g. the inner ear, the question arises which viewpoint should be initially chosen. Stull et al. [15] argue that a *canonical* orientation, such as a frontal or lateral view, should be selected. Even if the virtual camera can be controlled to adjust any possible viewpoint, a carefully chosen initial viewpoint is helpful to reduce the mental load of the learner. The same situation occurs when the name of an anatomic structure is selected and this structure should be emphasized in a 3D view. Emphasis, obviously, requires visibility. Vazquez et al. developed methods to automatically select good viewpoints for an object in a polygonal model using *viewpoint entropy* as measure [72]. Later, they incorporated this technique in an anatomy education framework [73].

4.5. Animations

Video sequences are an established resource for anatomy education [74]. In the last decade, such video sequences are primarily available in digital form, e.g. at YouTube. Several attempts were made to test the effectiveness of videos to assist anatomy students in dissection tasks [75,76]. Such videos are perceived as useful learning resources, although they do not always improve the examination score [75]. The successful use of video sequences gave rise to research attempts to provide computer-generated animations using geometric models and a related knowledge base. Such animations involve rotations of anatomic models and provide motion parallax as an essential depth cue. However, they are not superior to a series of static images under all circumstances. The information provided is of transient nature, it may be very complex and can lead to information overload. Animations may also lead to the *illusion of understanding* [77,78]. A number of studies indicate that high spatial ability learners benefit significantly more than low spatial ability learners from animations, which supports the hypothesis that a certain level of spatial ability is a prerequisite for understanding movements of anatomic models (see [25] for a discussion of such studies). To enable low spatial ability learners to benefit from animations, they should be able to slow down, stop and repeat segments of the animation.

Animations that *introduce* an anatomic region, e.g. by slowly approaching it from outside, removing outer layers of information and rotating it around a canonical axis may be very effective to give a first impression of an anatomic region. *Animated emphasis*, where a target object is focused, e.g. by gradually reducing transparency or saturation of nearby objects may be a useful component of such animations. Passive viewing of predefined animations is less effective than active exploration (recall Section 2 and [19]), but may prepare learners for this active stage. Such animations can be manually created with 3D modeling software as it is used for the film industry. Since this is very expensive and strongly tailored to a very specific learning scenario, some researchers developed systems to *generate* animations based on high-level textual descriptions. Graphics libraries, such as Open Inventor and Unity, with their support for interpolations may be used to realize the actual movements.

Computer-generated animations. Inspired by computer-generated animations for technical illustrations [79] and by available anatomy teaching videos, Preim et al. [80] introduced an extendable scripting language, where authors can specify which objects should be emphasized and optionally which techniques should be employed (otherwise, automatically generated suggestions apply). The high level statements, such as *show spine with focus on lumbar spine*, are translated via decomposition rules in a low-level script that may be executed. Moreover, the display of labels and further textual explanations, like subtitles in a video, can be specified. The animations can be interrupted by the learner, i.e. they may rotate the geometric model themselves or zoom in and then return to the animation mode where the system returns gradually to the original position and continues the animation. Muehler et al. [81] extended this work and incorporated also clipping planes and optimized viewpoints. Thus, to emphasize an object, a camera position is chosen that is optimal w.r.t. the visibility of that object. Their scripting language also allowed to specify measures, e.g. distances or angles, that should be displayed. It is essential that computer-generated animations consider motion perception. In particular, the path of the virtual camera should change smoothly. The same holds for the speed; sudden accelerations, for example, should be avoided. Humans can follow a few movements simultaneously, but not too many. Otherwise, change blindness occurs.

Manually created 3D animations. Hoyek et al. [77] created 3D animations of the upper limb (a part of the muscoskeletal system) and provided these animations to students by means of a QuickTime VR player enabling learners to slow-down and repeat segments of the animation. Compared to a control group, where students employed Powerpoint slides with static images, the “animation group” could significantly better answer spatial questions. Animations may also be effective when applied to cross-sectional data. Jastrow and Vollrath [34] provide animations that show adjacent slices of the VH dataset comprising a region, such as the thorax. Discussions with radiologists reveal that they infer additional information in such movements compared to the analysis of static images. Therefore, any radiology workstation provides a *cine mode* where the slices are animated. Mueller-Stich and colleagues employed such animations in a VA system for studying liver anatomy [82].

4.6. Modeling and visualization for functional anatomy

Functional anatomy comprises, e.g. the range of motion of joints, the tension of muscles, and tendons. In addition to such biomechanics-based models, functional anatomy serves to better understand the physiology of certain anatomical systems, such as the respiratory tract. VA systems for functional anatomy require a modeling of the underlying movements. This modeling is typically carried out by motion capture, i.e. healthy persons walk, climb or perform other movements. These movements are tracked either based on markers associated with the persons or marker-less using depth cameras, such as the Kinect. Albrecht et al. [83] described the creation of a dynamic model representing limb movements based on motions captured from six man and four women, all selected to be *normal* w.r.t. body weight and height. The underlying models do also consider constraints, such as non-compressibility and collision constraints [84]. The movement of skin and other soft tissue typically follows from modifying a parameter, such as muscle contraction. Thus, other structures move according to the muscle movement. In biomechanics and computer graphics, there are a number of detailed and anatomically plausible models that can be used for functional anatomy support [84,85]. Such models can be employed to generate animations (recall Section 4.5). So far, we discussed animations to present the anatomy from different viewpoints. Functional anatomy benefits from animations that display the dynamic character of processes, such as breathing and heart beats.

5. Knowledge representation and labeling

Although interactive visualizations are the primary components of anatomy education systems, they are not sufficient to effectively support learning processes. The *mental integration* of visual elements and related symbolic knowledge is an essential learning goal.

5.1. Knowledge representation

Symbolic knowledge relates to concepts, names, and functions of anatomic objects and to various relations between them. Knowledge representation schemes employ segmentation information and allow to add various relations between individual objects, for example, an object is *part of* a system. In the spirit of PBL, it is also useful to add comments on the clinical relevance of an anatomical structure, e.g. complications that would arise if this structure is damaged.

A sophisticated representation of symbolic anatomic knowledge effectively builds an *ontology* composed of different views, e.g. different kinds of relations between anatomic objects. The first advanced (digital) knowledge representation for anatomy has been developed by Schubert et al. [86] as a *semantic net*. It serves as a basis for interactive interrogation. Among others, they represent:

- *part of relations* (one object belongs to a larger object, for example a functional brain area),
- *is a relations* which group anatomic objects to categories, and
- *supplied by relations*, which characterize the blood supply.

The relation between labeled volumes and the symbolic knowledge is referred to as *intelligent voxel*. Similar concepts for knowledge representation have been used for the Digital Anatomist [28] and the AnatomyBrowser [87]. The last notable development in this area was presented by Rosse and Mejino [88]. They suggested a standardized *ontology* of anatomical knowledge that can be used by any system that requires an anatomy knowledge base. The connection of a VA system to a standardized ontology is meanwhile typical [89].

5.2. Labeling anatomical models

Labels are used to establish a bidirectional link between visual representations of anatomic structures and their textual names. Students should learn how anatomical structures are named and where they are, as well as their shape features.

Almost all of the presented labeling techniques were inspired by anatomic illustrations and most of them were integrated in anatomy education frameworks used as research prototypes [73,90]. However, none of these techniques were integrated in wide-spread virtual anatomy systems.

Interactive labeling. The simplest and most general solution is to let the labeling task to the user: she might select a position, initiate a “label” command and then interactively place that label. The label name corresponds to the object visible at the position selected by the user. A line is generated to connect the label with the selected position. If more labels should be included, the user tries to avoid overlapping labels (see Fig. 7). This simple strategy is not appropriate in interactive scenarios where the objects are rotated and zoomed in, since the labels might simply disappear.

In addition to placing predefined labels, users may add labels and textual descriptions as personal notes, flexibly move and save such labels. The BioDigital Human provides such advanced interactive labeling [30].

Automatic labeling. Automatic labeling strategies can be classified into *internal* and *external* [91]. Internal labels overlap with the objects to which they refer, whereas external labels are arranged at the background and connected to the visual representation of their *reference object*. The relation between a visual object and its label is easy to perceive with internal labels.

The use of external labels requires *anchor points* and *connection lines*. The selection of anchor points is crucial to establish a clear correlation between a label and its reference object. Despite the problems of providing a correlation between a label and related visual objects, *external labels* are more promising. They have better legibility, since they are placed on top of a background in uniform color. Moreover, they do not disturb the perception of complex shapes.

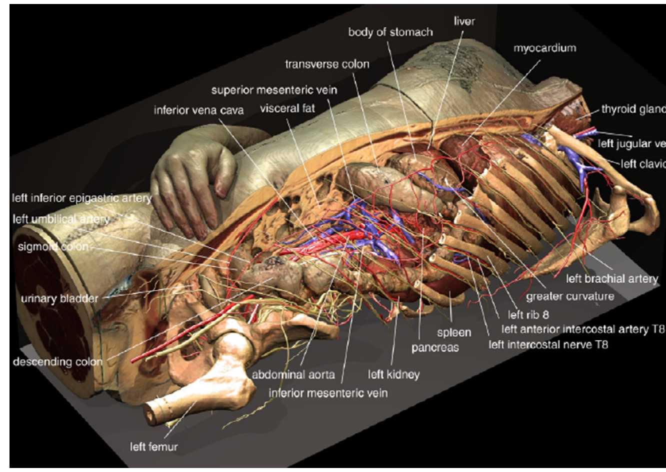

Fig. 7. Interactive labeling with the VOXEL-MAN (From: [26]).

5.3. Placement of external labels

We discuss several labeling strategies based on the following labeling requirements (LR) (cf. [69,92,93]):

LR1. Anchor points should be visible.
LR2. Labels must not hide any graphical representation.
LR3. A label should be placed as close as possible to its reference object.
LR4. Labels must not overlap.
LR5. Connection lines should not cross.
LR6. Label placement should be coherent in dynamic and interactive illustrations. “Coherent” basically means that strong and sudden changes of anchor point and label positions should be avoided.

The list above represents a minimal subset of requirements discussed by various authors. For the moment, we assume one anchor point only. This point might be the center of gravity (typically approximated as the average coordinate of all vertices) or the bounding box center. Since these points are often hidden, a nearby vertex should be chosen that is actually visible (LR1). For this purpose, the projection of an object in screen space should be analyzed to select a point of a visible segment of that object. In case an object has several visible segments, it is often appropriate to select a point from the largest segment [94].

In order to fulfill LR2-LR5, some general layout strategy is necessary. Observations in medical illustrations reveal two typical strategies: either labels are arranged in vertical columns to the left and right of the drawing or they are placed closely to the silhouette of the model. With both strategies, LR2 is fulfilled. Since it is difficult to place labels in concave notches, Hartmann et al. [93] as well as Bruckner and Gröller [69] suggest to use the projection of the convex hull of the drawing to guide label placement (see Fig. 8). Closeness of labels and graphical objects (LR3) is known to be essential for cognition [95]. Convex hull-guided placement (see Fig. 8) is the better choice according to LR3.

LR4 and LR5 relate to the distribution of labels in the area that is “reserved” for labels. Once the areas are defined that are used for labeling, a layout algorithm is necessary that manages occupied space and ensures that each label has a separate space (and

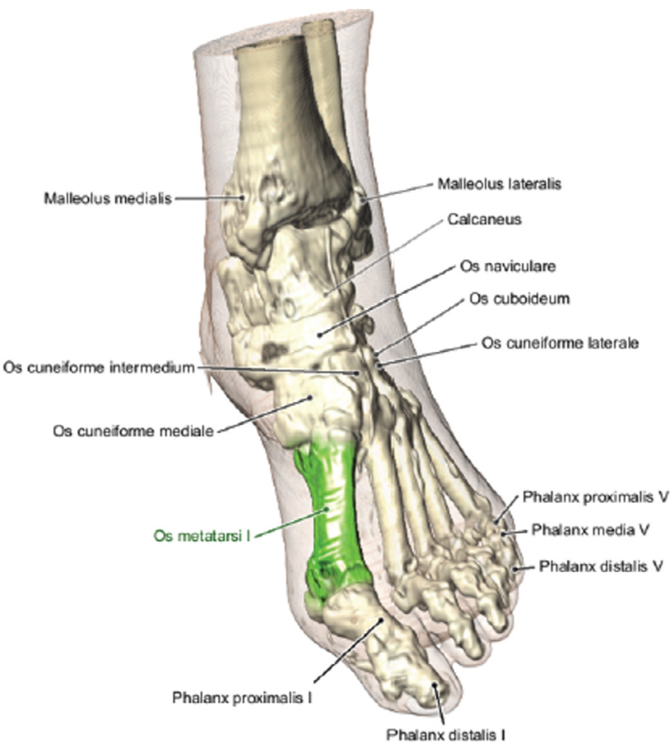

Fig. 8. External labeling of an anatomic illustration of a foot. Labels are arranged close to the convex hull of the whole model. Labels do not overlap each other and connection lines do not cross (From: [69]).

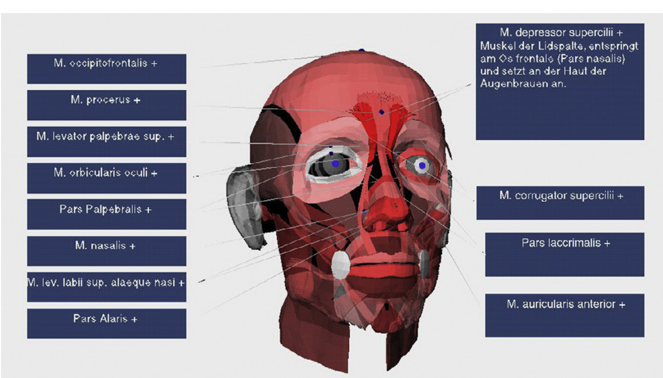

Fig. 9. Initial layout of labels arranged in columns left and right of an illustration (From: [90])..

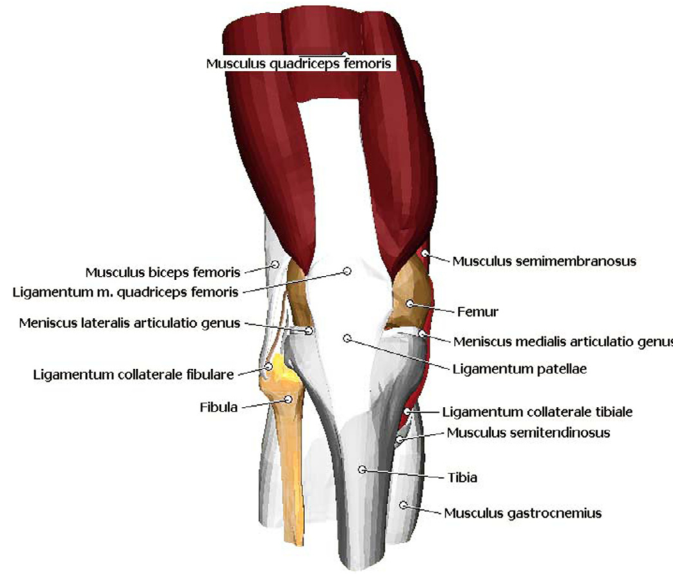

Fig. 10. Labeling anatomic objects of the knee region with potential fields. Overlapping labels are effectively avoided (From: [93])..

a small margin). As an example, the algorithm described by Hartmann et al. [93] proceeds as follows. Starting from initial labels close to the silhouette of the whole model, labels are exchanged or slightly translated to prevent overlaps and crossing connection lines. A maximum number of iterations ensures that the algorithm terminates. Bruckner and Gröller [69] also employed this algorithm (Fig. 8).

During interaction the area occluded by the illustration changes considerably and therefore the label positions have to be adapted. The layout in Fig. 9 considers the 3D bounding box of the underlying model and places labels outside which can be done with fewer changes (LR6). However, even more important is that the label positions are not automatically updated after every small rotation. Updating may be performed after a user initiated it or after the user stopped rotating the model. The placement of external labels w.r.t. a balanced layout is described by Preim et al. [96].

Anchor point determination. While simple strategies are sufficient for labeling compact and visible objects, they may fail for other objects. In case of branching objects, or objects that are only partially visible, more anchor points are needed to convey the relation between a label and a graphical object. This requires to analyze the shape of graphical objects, e.g. by means of skeletonization. Since the skeleton represents the medial axis, points on the skeleton are good candidates for being anchor points. Since branching objects may be partially hidden, the visibility of anchor point candidates has to be considered as well [92].

Using potential fields for label placement. An advanced labeling algorithm is based on *potential fields* and their applications in robot motion planning [94]. The requirements for a good configuration of labels are translated to the definition of attractive forces (between a label and a related anchor point) and repulsive forces (between different labels and between a label and anchor points that do not belong to the graphical object). This algorithm starts from an initial configuration of labels and moves them according to the forces. Fig. 10 shows an automatically generated result.

Generation of intermediate connection points. Once the anchor points for an object have been defined, the label may be connected with each of them via straight lines. If the angle between two connection lines is very small and the lines are hard to distinguish, the resulting layout is confusing. The edge bundling principle introduced in the visualization of graphs and networks [97] is useful to improve the label layout.

5.4. Placement of internal labels

Internal labels are placed on top of the visual representation of an object. The use of internal labels is only feasible for objects large enough to accommodate a label and that are not partially obscured [98]. With respect to legibility, it is preferred to present labels horizontally. If this is not possible, Götzelmann et al. [91] suggest to place a label along the centerline. The skeleton path is smoothed to gently accommodate a label. Fig. 11 illustrates the principle approach. The readability of internal labels has been improved by incorporating thresholds on the allowable curvature of the path. In interactive scenarios, internal labels have a role when graphical representations are strongly zoomed in. An alternative strategy by Azkue [46] uses numbers instead of textual labels and

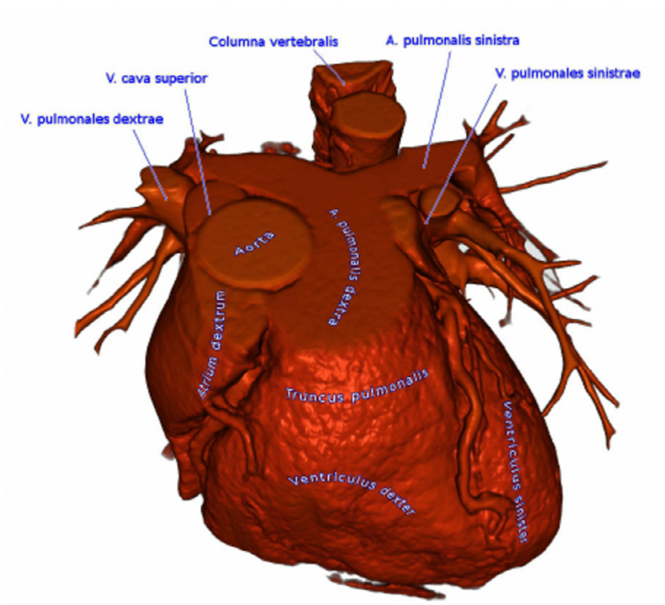

Fig. 11. Hybrid labeling of heart anatomy with internal and external labels. Internal labels smoothly fit to the 3D shapes, but legibility is reduced compared to external labels (From: [98])..

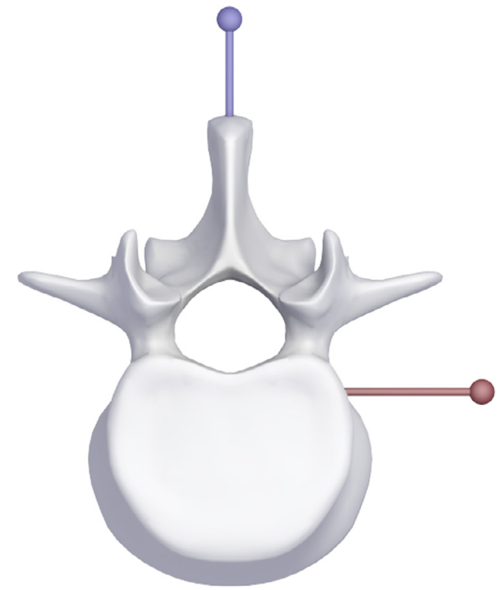

Fig. 12. Rotation of anatomical structures is strongly improved with handles derived by an anatomy-oriented coordinate system (Inspired by: [15]).

accompanies a legend with the associated names. The placement of numbers is easier due to their smaller space requirements, but the use of the legend increases the cognitive load.

5.5. Labeling of interactive illustrations

Labeling interactive 3D illustrations poses some challenges. When a 3D model is zoomed in, the visibility of objects and their relative positions do not change. With an external labeling strategy, only the connection lines need to be updated. Labels may, however, occlude part of the geometry. Therefore, it is reasonable to switch to internal labeling for such objects.

When the 3D model is rotated, the visibility of objects as well as their relative position in screen space will change. Different strategies are viable to account for this situation: Labels relating to objects that are no longer visible are hidden or rendered more transparent to indicate that they are “invalid”. The labels may be rearranged in vertical and horizontal position to reflect the new screen space position of their anchor points. As a consequence, connection lines may get long and cross each other. “Rearranging” labels yields consistency between labels and related objects. However, it is highly distracting when labels “fly” around a 3D model while the user’s focus is on perceiving the movement of anatomical structures. Better strategies are to rearrange labels after a rotation is finished or to provide a command that triggers a new computation of the label layout [96]. Mühler and Preim [99] discussed more options, e.g. to change the style of the connection line when the anchor point becomes hidden.

More details on labeling, in particular on internal labeling, presentation variables, such as line width and fonts as well as implementation of labeling algorithms, are discussed in a survey article [100]. In this article also labeling of 2D images for radiographic and cross-sectional anatomy is discussed.

Other annotations. In addition to textual labels, graphical annotations may be useful for educational purposes. Fairen et al. [101], for example, add red and blue arrows to represent arterial and venous blood flow. Anatomical structures may also be encircled or pointed at with arrows to emphasize some relations between them. This needs to be prepared in the design of a knowledge base (recall Section 5.1) and requires an appropriate layout strategy where the annotation is clearly visible and does not hamper the recognition of other structures.

6. Interaction techniques

Before discussing interaction techniques, we briefly mention requirements that we derived from a number of publications, e.g. the cognitive task analysis by Berney et al. [102] and our own experience.

6.1. Basic interaction techniques

There are some basic functions that are available in almost all VA systems. A hierarchical list widget often allows to show/hide individual anatomical structures or whole categories, such as muscles or tendons. Some systems support a layer-based exploration, i.e. outer structures may be removed and subsequently more and more inner structures are removed as well. This layer-based exploration better fits to volume-rendering based systems, where structures may be clipped instead of being always completely removed.

It is possible to select objects with a pick on a rendered image resulting in some emphasis and often a label displayed, e.g. as a tooltip. Some systems provide advanced selection support, such as snapping, that is useful for small structures, e.g. vascular structures. Probing tools that can be freely placed in a 3D model and that list all anatomical structures along the ray defined by the tool are helpful for learning. Probing and selection within large geometric models may lead to a delay if not efficiently implemented. Hierarchic data structures, such as octrees, accelerate the computation of polygons hit by a selection ray. As an alternative with reduced preprocessing, Smit et al. [40] suggested to use an offscreen renderer where for every object a unique color is assigned so that the color in the render buffer reveals the object visible at that pixel.

Rotation is the core function of any VA system. It is typically unrestricted, i.e. an anatomic surface model can be rotated on any axis, e.g. with a trackball widget. Panning and zooming are other essential features. Mouse-based rotation of 3D models is not very intuitive. An improved solution is possible with *handles* displayed (see Fig. 12). These handles should convey an object-specific reference frame. This enhancement is motivated by vision research that indicates that mental rotation benefits from a clear reference frame. The integration of an orientation widget, e.g. a mannequin, to convey the current viewing direction and the facility to return to a "home" position improve the experience during rotations.

6.2. Advanced interaction techniques

In the following, we briefly discuss additional interaction techniques that are provided by a few systems only but seem justified by the education goals of virtual anatomy. Some systems provide also measurement facilities, e.g. a virtual ruler to assist students in understanding absolute and relative sizes of anatomical structures [35].

An advanced feature of VA systems is to let learners duplicate a selected object to rotate it in a separate view. This *ghost copy* [103] enables a detailed inspection of that object. Clipping and cutting are typically restricted to VA systems based on volume rendering.

In addition to planar clipping, more advanced cutting, such as with a virtual scalpel (recall [6]), a deformable cutting plane [104] or illustrative membrane clipping [105] may provide a substantial learning experience. The virtual scalpel and the deformable cutting plane are inspired by surgical approaches and thus provide a link to clinical medicine. The illustrative membrane clipping is a modified type of clipping where the clipping plane is locally deformed to avoid that structures are cut if there border is close to the plane. The resulting visualizations often better follow the user's intents. We also want to mention *peel-away visualizations* [106]. Here the user is provided with peel-away templates for separating anatomical regions to be rendered with a different transfer function. This technique is realized in a view-dependent manner and enables a focus-context-type of visualization. *Magic Lenses* [107] is another potential useful interaction technique for exploring 3D anatomical models. As an example, a volumetric lens, e.g. a spherical lens, may be moved over a model and show a different layer, such as the nerves. It must be noted that only the virtual scalpel was indeed used for anatomy education.

Facilities to enable drawing on surfaces to mark regions, comment on them, and eventually share with others are also useful. Self-assessment exercises and real-time feedback are essential components of VA systems [1].

Haptic interaction. Haptics would greatly enhance the experience of learners exploring and interacting with anatomical models. In particular, interactions, such as cutting would benefit from tactile feedback that conveys the different stiffness and elasticity of tissue structures. Basic strategies of incorporating haptics in the exploration of anatomical models were developed by Petersik et al. [108]. Tactile feedback needs a higher frame rate than the visualization that is challenging if complex geometric structures are involved. This is feasible meanwhile, however, we are not aware of virtual anatomy systems that really incorporate haptics. Haptic is however used in a variety of surgical simulation systems.

Gesture and touch input. Multi-touch interaction, pioneered with the iPhone, is very familiar among medical students. The Medical Visualization Table provides a great user experience when exploring medical volume data with gestures for pan, zoom and rotation [109]. This system, provided by SECTRA, was recently enhanced to support collaborative medical education.[2]

Gesture-based input, as a natural interaction style, may improve the user experience and contribute to the motivation of learners. Hochmann et al. [110] employed gestures with the Microsoft Kinect and [40] employed the Leap Motion Controller for 3D interaction with anatomic models. However, both systems were not evaluated w.r.t. longterm experience of learners. Thus, it is currently not clear whether a VA system would benefit from incorporating gesture-based interaction.

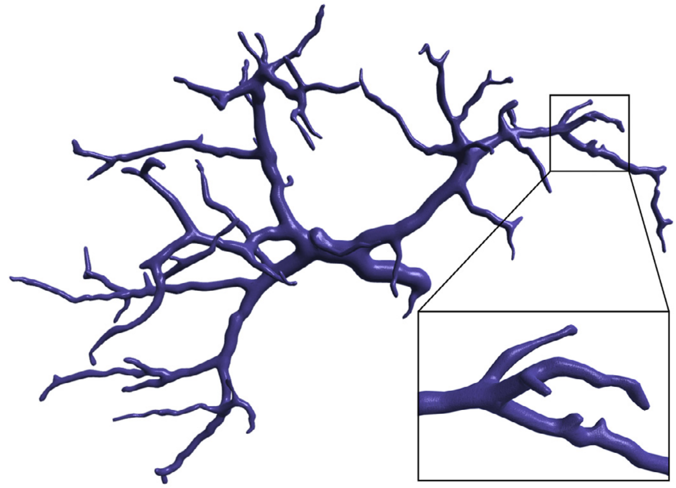

Fig. 13. A teacher may intuitively load and sketch branching structures, such as vessels of the liver, to explain vascular structures (created with an approach from [112]).

Fig. 14. A simple model of the Aortic arch is sketched (left) and converted into a 3D model (right) (From: [111]).

Sketching. An innovative and not yet carefully evaluated interaction for education is to employ free-hand sketching. Pihuit et al. [111] developed a first system strongly inspired by chalkboard illustrations performed by anatomy teachers. Anatomy teachers are used to draw, explain, and refine the illustration with further objects and explain how they relate to the overall system or organ. Students reproduce such sketches and thus favor memorization of the spatial relations. Chalkboard illustrations, however, are restricted to 2D.

Pihuit et al. [111] present a system where teachers provide sketches of anatomic structures, containing hatching lines and silhouettes. This sketch is then transformed in a smooth implicit surface representation. The process of reconstructing a 3D geometry from 2D sketches involves a number of constraints. Vascular surface models arise by applying convolution (see Fig. 13). The models are displayed with an illustrative rendering technique, recreating the appearance of chalkboard drawings (recall Section. 4.3 and Fig. 14).

Saalfeld et al. [112] came up with a similar technique using the semi-immersive zSpace and pen-based input to make the drawing process more convenient. In addition to completely sketched 3D models, an existing model may be enhanced by drawing further structures, such as nerves, that may not be part of the original model due to their small size.

Guidance. Instead of a powerful highly flexible system that lets users do everything but without any support for efficient learning, users may be supported by various forms of *guidance*. Predefined learning paths may be available as an optional orientation. Halle et al. [89] suggest an *anatomic tour* consisting of bookmarks

[2] https://www.sectra.com/medical/sectra_table/

created by a group of learners. Like a guided tour for tourists, an anatomic tour could be a good starting point for the navigation and exploration of a learner.

7. Virtual anatomy systems

In the following three sections, we describe selected examples of virtual anatomy systems. We put emphasis on the new concepts introduced in these systems and classify them w.r.t. the aspects of anatomy that are supported (recall Section 2.2). Also, we mention the underlying data for all systems. Most system descriptions do not mention an educational concept or are clearly related to a learning theory (recall Section 2.1). Instead, they explore the space of possible solutions to provide access to 3D anatomy models and related textual descriptions. In case, an educational concept is mentioned or obvious from the paper, it is explicitly mentioned.

Most of the VA systems were described as *digital atlas*, thus using the anatomy atlas as a metaphor. This is a good choice, since students of medicine are familiar with the term “atlas” and have rich associations with it. Unfortunately, the term “atlas” does not encourage 3D interaction, such as rotation and cutting. We will see that other metaphors are discussed as well.

After a short discussion of requirements, we start with early systems, while in Section 8 we discuss systems that employ 3D web standards. Basically, this is a distinction in early and recent systems, since most recent VA systems employ Web 3D technology.

System requirements.

SR1. Provide a dataset where the target anatomy is represented in sufficient level of detail to recognize structures, such as smaller vessels, nerves and the lymphatic system.
SR2. Provide facilities to flexibly explore a 3D dataset from arbitrary perspectives and in a user-selected scaling factor.
SR3. Provide techniques to explore the related semantic information, e.g. membership of a structure to a certain category, a group of adjacent objects, and connectivity.
SR4. Provide direct support for rehearsal, e.g. a quiz function, puzzle options.
SR5. Provide clipping and cutting tools to enable users to expose inner structures and study their location in relation to outer structures.

SR1 is not always fulfilled. In particular, nerves and the lymphatic system are often considered by learners as missing. Heinrich et al. and Kraima et al. discuss the creation of *anatomically complete* models in the sense of SR1 [27,113]. SR2-SR4 are typically fulfilled to some extent. VA systems differ in their specific realization. Clipping and cutting (SR5) is only fulfilled in systems that are based on volumetric data.

VOXEL-MAN. The VOXEL-MAN is a pioneering work that inspired many later developments [114,115]. The first version was based on clinical data; later versions employed the VH datasets. Two aspects of the development are crucial: substantial visualization research was carried out, e.g. to achieve high-quality and efficient rendering of tagged volume data and cut surfaces [5,6], and the image data was connected to a sophisticated knowledge base prepared by an anatomist [86] (recall Section 5.1). The knowledge base was designed to be extendable, e.g. to add biomechanical properties. A virtual endoscopy mode was essential to better understand air-filled or fluid-filled structures, such as the colon or the bronchial tree.

The VOXEL-MAN supports cross-sectional, regional, and systematic anatomy (see Fig. 15). Later developments added the correlation of X-ray images with 3D anatomy, gastrointestinal endoscopy, and the correlation of ultrasound images with 3D anatomy [116].

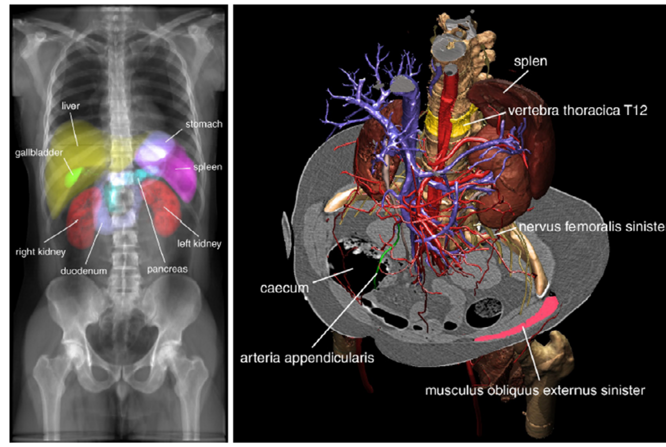

Fig. 15. Different viewing modes used in the VOXEL-MAN. **Left:** simulated X-ray. **Right:** CT slices combined with surface rendering of selected objects. (From: [26]).

Primal pictures. Primal Pictures is a series of individual packages that support regional, functional, cross-sectional, and system anatomy. Later versions are web-based. With the PrimalPictures packages, users can add or remove layers. Some packages provide biomechanics, such as muscle flexion and hip range of motion, and other functional anatomy animations including respiration. The packages follow a *guided* approach to learning and provide many functions to support the authoring process of anatomy teachers. Primal Pictures is a company where anatomists and graphic artists have been working together since 1991 to create high-quality 3D surface models based on clinical data.[3] Since it is a commercial product, its design is not discussed in scientific publications.

Digital Anatomist. The Digital Anatomist was another early and influential system [28,117]. Its focus was the knowledge representation that was both deep and comprehensive. Already in 1999 the system incorporated 26.000 anatomical concepts connected by 28.000 links. The system incorporates 3D renderings and predefined movies. Some of these movies show exploded views that may help to understand spatial relations. A group of these movies presents neuroanatomical structures in relation to essential anatomic landmarks.

The Digital Anatomist supports regional and cross-sectional anatomy in the brain, including major fiber tracts and functional areas. The system is based on cadaver scans and clinical MRI data. The educational aspects are considered as well: a tutorial and a question-and-answer mode are available. The DigitalAnatomist is still available, but restricted to rendered images of 3D models. Interactive exploration is not supported. Following the neuroanatomical examples, a knee and a thorax atlas with many detailed 2D and 3D views were added.

Anatomy Browser. The AnatomyBrowser is also focussed on neuroanatomy. It is based on a multitude of brain MRI data and thus supports comparative anatomy (as well as regional and cross-sectional anatomy) [87,118]. The cases also include patient data providing a link to clinical medicine. Again, a comprehensive knowledge base is used. Interactive labeling is available and quite flexible: users may adjust colors, line styles, fonts and font sizes. Although this seems a minor aspect, it may be very helpful for learners, in particular if they exhibit vision deficiencies.

Anatomic VisualizeR. In contrast to previous VA systems, the Anatomic VisualizeR is inspired by the *virtual dissection* metaphor and thus puts emphasis on clipping tools. The Anatomic Visual-

[3] This information is based on the website https://primalpictures.com/

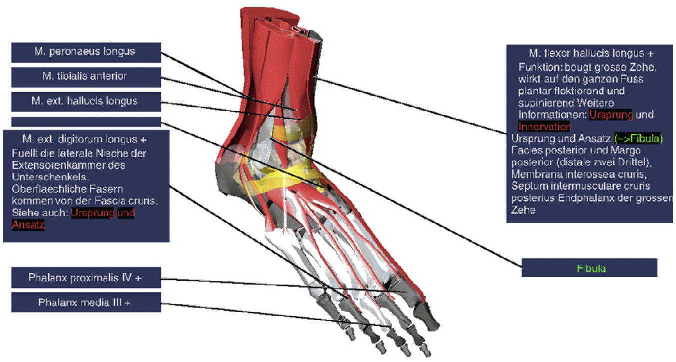

Fig. 16. Muscles, ligaments and bones of the foot. The user selected a label on the left and one on the right. The ZoomIllustrator lets the labels grow so that it can accommodate explanations. Other objects mentioned in the explanations are highlighted (From: [90]).

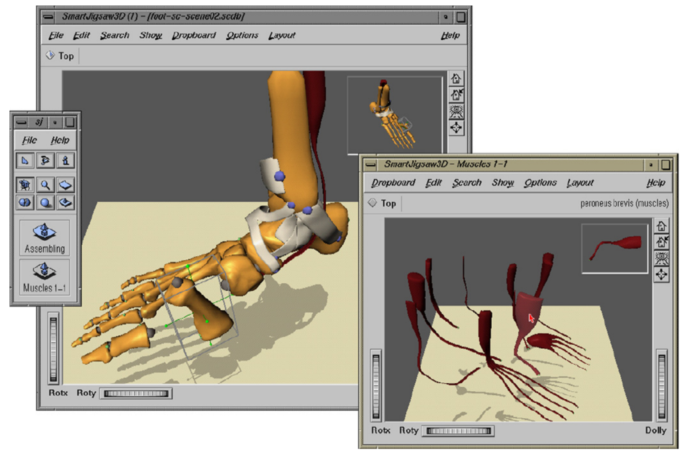

Fig. 17. A 3D model of the bones and tendons is correctly assembled in the left view. In the right view, the user has models of all muscles in the foot region. Her task is to move them in the left viewer and dock them at the right position (Courtesy of Felix Ritter, University of Magdeburg).

izeR was developed to provide a flexible and extensible tool. It may be linked to images, textual information, video and animations [35]. In addition to detailed renderings based on the VH dataset, schematic 3D renderings are available for an introduction. The schematic renderings may also be compared with the detailed renderings in the same view.

Educational concept. In contrast to other systems that emphasize flexibility, the Anatomic VisualizeR provides *guidance*. A study guide provides an organized presentation of key concepts, exercises and recommended actions for each learning module.

ZoomIllustrator. The ZoomIllustrator [90] focuses on the interactive exploration of the information space consisting of geometric models, labels, brief explanations, more detailed explanations and figure captions [119]. It is a zoomable user interface that flexibly allocates space for the currently needed textual explanations (see Fig. 16). Geometric models were acquired from a commercial provider (Viewpoint Datalabs) where these models were created manually. Figure captions are automatically generated and reflect, e.g. the visible objects, the viewing directions and the colors employed. To enable comparisons of different views, two renditions can be displayed side by side and structures visible in both views are labeled in-between.

Automatic labeling with external labels is incorporated (recall Section 5.1). Also animations can be generated based on a scripting language [80] (recall Section 4.5). The evaluation of the ZoomIllustrator was focussed on acceptance and usability [120]. A major result was that students used the available 3D interaction facilities quite rarely.

3D Puzzle. The 3D Puzzle [121] was developed at the same institution (using the same geometric data) and was partly a consequence of the ZoomIllustrator evaluation. The hypothesis underlying the 3D Puzzle was that another metaphor is needed that encourages 3D interaction. To compose a 3D model of many individual objects using predefined docking positions requires to grab objects, rotate them and zoom into the regions around the docking positions. A snapping mechanism supports the docking task. Learners have to think about the sequence of docking actions, since inner structures can only be placed correctly if not too many outer structures are already connected. This thinking about anatomical layers corresponds well to relevant anatomic knowledge.

To enable users to compose an anatomic model is challenging. Thus, the 3D puzzle incorporates depth cues, such as shadow projection, shadow volumes, stereo rendering and collision detection (see Wanger et al. [122] for a discussion of depth cues). 3D input with a SpaceBall and the facility to bimanually use the system further support the 3D exploration. The selection of an object name triggers an animation that shows and emphasizes the related anatomical structure. Fig. 17 gives an example of the system's use.

Educational concept. The 3D puzzle is designed to provide *implicit guidance* by the design of the tasks [123]. Enabling learners to compose or decompose anatomical structures is mentioned as an anatomy learning strategy by Dev et al. [17] and associated with *constructivism*. In a similar vein, Ma et al. discuss constructivism and anatomy learning [22]. Today, the 3D Puzzle could be considered a *serious game*. However, it does not fully use the motivational potential of serious games, e.g. it misses a reward strategy.

Virtual ear anatomy. A variety of systems were developed for ear anatomy education. These developments are motivated by the filigrane structure of the inner and middle ear that need to be fully understood in case of surgery. Cadaver dissection is not effective in the ear region due to the extremely small size of the involved structures and their complex relation [3].

As an example for such systems, we discuss the system of Nicholson et al. [3]. They employ a high-resolution MRI scan of a cadaver. The extracted geometric model is comprehensive, carefully smoothed and stored as a VRML file. Instead of building a complete VA system, they used the CosmoPlayer that supports the exploration of VRML models incorporating pan and zoom as well as rotation. No type of clipping or virtual dissection is supported.

This VA system did not pioneer any visualization or interaction technique. The contribution of Nicholson et al. [3] is to provide a high-quality model of such a complex anatomic region and the evaluation. In the anatomy community, this is often considered the first convincing example that VA systems may indeed improve anatomy education. We come back to this system in Section 10, since the evaluation of this VA system followed high standards.

Several VA systems for ear anatomy have been developed later, e.g. Venail et al. [124] employed an ear model derived from the VH datasets as well as a model they created based on serial-histological slices, i.e. with a very high spatial resolution. The VA system built around these models was also assessed very positively.

Integrated pelvis model. The integrated 3D pelvic model presented by Kraima et al. [27] is focused on *surgical anatomy*, i.e. it is driven by possible major complications, such as damage of nerves. Thus, increased knowledge of these nerves and adjacent lymphatic structures is essential. Kraima et al. argue that surgically vulnerable tracts need to be identified. For creating a complete pelvic model, Kraima et al. argue that immunochemistry and fluoroscopy need to be integrated in one unified model. The data structures

Table 1
Major early VA systems.

System	Data	Key Features	Key Publications
VOXEL-MAN	VH	High-quality rendering, cutting, rich knowledge base	[5,26]
Primal Pictures	Artistic	Functional anatomy (range of motion)	–
Digital Anatomist	Clinical	Rich knowledge base, neuroanatomy	[28,117]
Open Anatomy Browser	Clinical datasets	Neuroanatomy, comparative anatomy	[87,118]
Anatomic VisualizeR	VH	Provides guidance, exercises	[35]
ZoomIllustrator	Artistic	Zoomable UI, automatic labeling	[80,90]
3D Puzzle	Artistic	3D interaction, support for depth perception	[121,123]
Virtual Ear	Cadaver	Realistic display of filigrane ear anatomy	[3]

for a unified model are discussed by Smit et al. [125] with a focus on a joint coordinate system for structures derived from data with different resolution.

VarVis. As last VA system in this section, we briefly discuss a system aiming at *comparative anatomy* teaching [126]. The VarVis system is focused on branching structures, where the differences between variants relate to topological differences, e.g. missing branches or additional branches. As an example, there are eight major variants of arterial supply of the liver. The variant that occurs in a patient is relevant for avoiding complications in surgery. Major learning goals are:

- the knowledge of occurring variants,
- the frequency of variance, and
- similarities and differences.

Smit et al. employ a text book illustration of the relevant branching structures and enhance it with further information. A *global view* indicates the similarity between variants, whereas a *local view* enables an in-depth analysis of differences between a pair of variants. Branching structures are modeled as graphs with nodes representing branching points. Based on the graph representation, similarity is assessed based on graph matching (the better two graphs can be matched with each other, the more similar they are).

While variations in anatomy are frequently studied, e.g. in basic research, few attempts were made to support educational scenarios in comparative anatomy. Besides the VarVis system, only a framework by Handels and Hacker is notable [127]. It conveys the variability of organ shapes, such as the kidney.

Summary. We have discussed a variety of VA systems that differ in the underlying data and in the viewing tools used to enable learners to explore them. As Halle et al. [89] point out, a large drawback of most developments is that atlas data and viewing tools are not standardized and cannot be exchanged. None of the discussed major VA systems support any type of cooperation; they are all focused on the (isolated) learner. The presented systems are summarized in Table 1.

8. 3D web-based anatomy education

The promise of e-learning is that resources for learning are available at any time and any place. This promise can only be fully realized with web-based systems. Web-based VA systems may reach a large number of learners and may support collaborative learning. The design of web-based VA systems needs to consider general experiences and recommendations related to web-based learning environments, as discussed by Cook and Dupras [128]. A special challenge in anatomy education is to handle large geometric models.

Open web-based standards. Since 3D visualizations are the essential components of anatomy learning systems, 3D standards for the web are essential. The first web-based anatomy education systems, e.g. [129,130], were built on top of the VRML standards developed by the Web3D consortium. The virtual reality markup language enables to represent a complex 3D model as a hierarchy of objects, e.g. using vessels, nerves and other categories as group nodes. For individual objects and groups, transformations, material properties, animations, e.g. by interpolation, and predefined viewpoints can be specified. The integration of a volume rendering node in VRML, essential for VA systems, was carried out by Behr and Alexa [131]. VRML (1995) and its extension VRML2 (1997) require plugins to be installed. In hospitals this is often not possible and the students at that time were often not technical savvy. This problem persisted with the X3D standard [132], an eXtensible 3D standard that adds capabilities relevant for VA systems, such as nodes that support programmable shaders and multi-texturing. X3D provides an XML-like structure [16]. Clipping planes were added in X3D version 3.2.

WebGL, a JavaScript graphics API based on OpenGL ES 2.0, finally enables 3D graphics displayed in modern web browsers without any plugin. It is widely available on mobile and desktop platforms. The current version, WebGL 2.0, extended WebGL with support for flexible and powerful rendering, including 3D texture mapping. Because WebGL exploits the graphics card at the client, it is not necessary to perform rendering at a server. Thus, WebGL-based applications may be simultaneously used by many learners with sufficient performance. For VA systems, there is only one major drawback of WebGL: volume rendering is still not part of the standard.

The Web3D consortium's Medical Working Group[4] is continuing to develop X3D and related technologies for medical use, particularly to integrate the technology with the DICOM standard, such as the ability to drag and drop DICOM files on a web browser to view medical volumes. MedX3D is an implementation of the volume rendering component of X3D consisting of a *volume data node*, a *segmented volume node*, a *volume style node*, e.g. boundary or silhouette enhancement. The default volume renderer is implemented using a GPU-based raycaster. Polygonal surfaces and volumes may be rendered together with correct depth sorting [133]. So far, there are no essential web-based VA systems based on volumetric data.

In addition to the open standards, QuickTime VR was frequently used to provide animations as part of web-based VA systems [116,134].

Teaching of the nervous system. Brenton et al. [1] discuss general concepts of web-based VA systems and use the specific example of the nervous system of the brachial plexus (a network of nerves extending from the neck to the shoulder, arm and fingers) to refine their concepts. The nerves are modeled in form of a diagrammatic representation with labels, measurements and clearly visible branchings. As anatomical context, the vertebrae are required. Brenton et al. [1] argue that high-quality surface models are needed and show how they may be generated with subdivision modeling (see Fig. 18).

EVA. A prominent example for a web-based anatomy learning tool was EVA (educational virtual anatomy) presented by Peters-

[4] http://www.web3d.org/working-groups/medical/charter

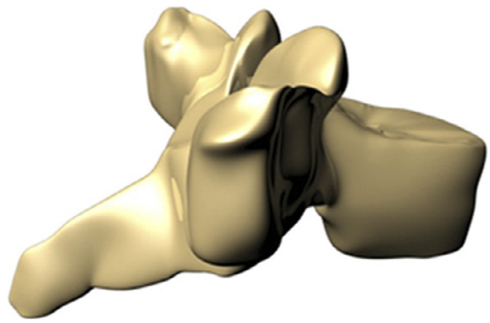

Fig. 18. The surface model of a vertebrae is considerably smoothed with subdivision surfaces to avoid distracting details (From: [1]).

son et al. [135]. Their system was focussed on arteries extracted from clinical CT angiography data comprising nine regions of the body. They used QuickTime VR in combination with the medical image viewer Osirix as technical basis following a recommendation from [136]. The 3D visualizations were provided in three levels of detail resulting in more or less finer branches. Color-coding was employed to separate major vessels, such as Arteria carotis interna, Arteria vertebralis, and Arteria basilaris with clearly different hues. The artery visualization was shown along with visualizations of the skeletal anatomy, e.g. the skull or the pelvis. Besides the 3D visualization a panel with textual information is shown, where the arteries of the selected region are explained with hyperlinks to other arteries that reflect branchings. The texts are taken from Gray's Anatomy [137]. The only link between the 3D visualization and the textual components of EVA is provided by the use of colors. An artery is colored in the textual description in the same way like in the 3D visualization. EVA is comprehensive, comprising nine regions of the body.

Google body and ZygoteBody. The first VA system based on WebGL was Google Body introduced in 2010 using beta versions of current web browsers. The system is based on artificially generated data and provides an easy-to-use zoomable interface inspired by other Google applications, such as Google Maps and Google Earth. Free exploration, search for anatomical structures and different layers that could be shown or hidden were available. When objects are selected (and labeled), all other objects are rendered transparently to emphasize the selected object. Realistic textures, in particular of muscles, are employed. From the beginning, the system also aims at mobile use from smartphones and tablets. After Google finished this project, Zygote continued with their ZygoteBody project [29]. The system design is explicitly linked to constructivist theory.

BioDigital human. The development of the BioDigital Human started at the School of Medicine's Division of Educational Informatics [30] at the New York university and turned into a commercial product of BioDigital in 2013. It is a comprehensive web-based system that incorporates the normal anatomy and more than 1.000 health condition models. It provides dissection facilities and a collapsable browser of the hierarchy of anatomic structures. BioDigital Human can be highly personalized for both teachers and learners and has over 2 million registered users.

The geometric models used in ZygoteBody and the BioDigital Human were created by artists.

Liver Anatomy Explorer. One of the first anatomy education systems that were built on top of WebGL is the LiverAnatomyExplorer [138]. This system was designed to rehearse the vascular anatomy that is crucial for liver surgery. Thus, the system provides a large variety of cases (derived from clinical CT data) to represent the variability of the arterial supply and venous drainage as well as the portal vein along with a visualization of the liver sur-

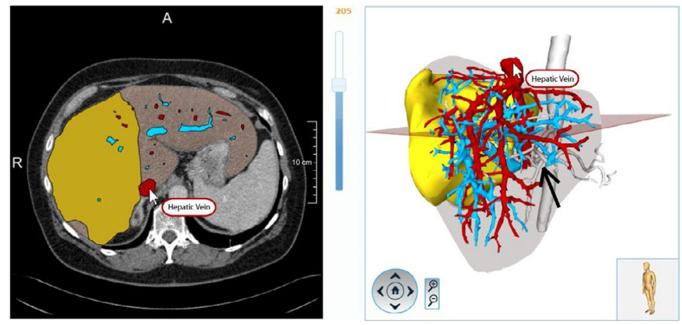

Fig. 19. Hepatic anatomy is shown in enhanced slice-based views and in a 3D visualization as part of the LiverAnatomyExplorer. Labels are shown as tooltip. Incremental rotation and zooming is possible (Courtesy of Steven Birr, University of Magdeburg).

face and pathologies, e.g. liver metastasis. Besides 3D visualization, 2D slice images are available and can be integrated with the 3D visualization (see Fig. 19). The SVG standard is employed to realize the visualization of cross-sectional slices. Interactive labeling is supported as well as emphasis of selected objects with a focus-context visualization. The 3D models were simplified to some 10% of their original size to make interactive exploration possible.

Surgical anatomy of the liver is a worthwhile topic for VA systems. Other examples are presented by Crossingham et al. [139] and Mueller-Stich et al. [82]. The VirtualLiver system [139] employs older web technologies.

Online anatomical human. The Online Anatomical Human provides also access to slice-based and 3D visualizations. It provides advanced functions to annotate 3D models (derived from clinical image data). Anatomical landmarks, lines, e.g. incision lines for surgery, and region annotations may be added [40]. Region annotation requires special functions to draw directly on meshes. These functions may be used by learners and teachers, e.g. for exercises where learners should annotate structures. Gesture-based interaction with the Leap Motion controller is another speciality of this VA system.

Open anatomy browser. The most recent and substantial development was published by Halle et al. [89], again using WebGL. Their Open Anatomy Browser is based on a longterm experience at the Surgical Planning Lab in Boston to create digital atlas data and viewing tools (recall [87,118]). The Open Anatomy Browser employs clinical MRI data. Two contributions are essential:

- The cooperation between users is directly supported by enabling to share bookmarks and dynamic views and
- an architecture that decouples atlas data and viewing tools.

We want to elaborate on the second aspect: When atlas data is represented based on official and widely used standards, a whole community may focus on creating viewing tools. The atlas data comprises image and geometry data, annotation and is managed by a Google Database. Moreover, the atlas data may be updated, enhanced with further information, or corrected if necessary. This reflects a new perspective on anatomy atlas data: they are no longer considered as complete and authoritative but subject to interpretation and revision. While all previous systems employed static atlas data that was not meant to be changed, like a printed encyclopedia, the Open Anatomy Browser is inspired by Wikipedia: a team effort to maintain the knowledge source based on mechanisms that check for consistency and support versioning promises high-quality and up-to-date information. Both the viewing tools and the atlas data are freely available as open source. In the same vein, Azkue [46] argue that surface meshes should be reviewed "for anatomic accuracy and educational relevance" before being widely used. Halle et al. describe interesting implementation

Table 2
Major web-based VA systems.

System	Data	Key Features	Key Publications
EVA	CT angiography	Three levels of detail, Osirix integration	[135]
ZygoteBody	Artistic	Link to constructivism, WebGL support	[29]
BioDigital Human	Artistic	Anatomy + many health conditions, personalization	[30]
LiverAnatomyExplorer	Clinical CT	WebGL, SVG, focus on surgical anatomy	[138]
Online Anatomical Human	Clinical	Advanced interaction, drawing, gestures	[40]
Open Anatomy Browser	Clinical MRI	Cooperation support, standardization	[89]

details, e.g. how to store the application state and use this information to enable other viewers to share the view.

Mobile VA systems. Apps for mobile anatomy education are potentially useful although the small display clearly is a disadvantage for understanding the complex human anatomy. According to Lewis et al. [140] Visible Body, 3D4Medical, and PocketAnatomy are leading examples. Checking their websites and Youtube videos reveals that they exhibit convenient touch-based interaction and the full range of interactions that we discussed earlier. Detailed, textured surface models are the basis for such systems. These are commercial systems where no scientific publications describe and discuss their design and evaluation.

Summary. The availability of VA systems in web browsers, in particular if no plugins are needed, spread the use of virtual anatomy. Performance aspects, such as providing a high frame rate, are more important when web-based systems are designed. Simplification of geometric models may be necessary. Web browsers enable cooperative working. The cooperative features, however, are not adequately used so far. The presented web-based VA systems are summarized in Table 2.

9. Stereoscopic and VR systems

Although many papers in medical journals are entitled "VR-based" and imply some form of stereoscopic or head-worn display, the majority of VA systems is "only" a desktop-based interactive 3D visualization.

9.1. Stereoscopic systems

The recent survey by Hackett et al. [141] lists 38 VA systems using stereoscopic viewing (mostly with shutter glasses) or autostereoscopic viewing where the stereo rendering is perceived without glasses. The learners reported a number of perceived advantages related to the understanding of spatial structures, but also state problems related to perception conflicts and artifacts that are more severe with autostereoscopic displays [142]. In reality, the pupil's accommodation length coincides with the focal plane where everything is seen sharply. This coincidence is violated with stereoscopic displays. The larger the difference between these lengths, the more disturbing is this perceptual conflict. Complex vascular structures are among the anatomical structures where the benefit of stereo perception is particularly large [143].

Luursema et al. [144] found that low spatial ability learners benefit stronger from stereoscopic displays. These results correlate to a reduced perceived cognitive load compared to a display without stereo. Brown et al. [145] visualized CT data and interactive labels as 3D stereoscopic images. A study with 183 medical students showed that the 3D system aided their understanding of anatomy. Weber et al. [146] used real-life photos of dissected brains to create stereoscopic content. These were compared with static images, interactive 3D models, and interactive stereoscopic models. Their study showed significantly higher scores for the interactive groups. However, no difference was shown for the stereoscopic and non-stereoscopic group.

A stereoscopic system that tracks the user's head position is the zSpace. The Visible Body system was ported to the zSpace to employ its benefits. Another example of the usage of the zSpace is the mentioned system from Saalfeld et al. [112] to sketch anatomical structures. Although primarily aiming at neurosurgery training, the system presented by John et al. [147] provides concepts useful for anatomy education as well. Surprisingly, it demonstrates that for the chosen tasks stereoscopy (provided by the zSpace again) did not add any value.

9.2. VR systems

Immersive VR systems "provide an interactive environment that reinforces the sensation of an immersion into computer-specified tasks" [20]. The following aspects are often discussed as essential for VR learning environments as they are related to a high motivation [20]:

- intuitive interaction,
- the sense of physical imagination, and
- the feeling of immersion.

While previous VR systems were expensive and fragile, the recent development of VR glasses has the potential for a wide adoption also for anatomy education. The design of VR-based systems aims at exploiting the potential of VR for an enhanced understanding and at avoiding motion sickness, that, as well as fatigue, may occur when such systems are used for a longer time.

SpectoVive. A yet unpublished system is the SpectoVive VR room[5] that combines a powerful volume rendering framework with the exploration by means of the HTC Vive. In addition to transforming a volume-rendered image, users may select a cutting plane to cut in the volume data and reveal the clipping surface. Although the system is described as a tool for diagnosis and treatment planning, it would be clearly useful in teaching.

3D Puzzle in VR. The idea of a 3D puzzle for anatomy education was also explored by Messier et al. [148] who compared the use of a puzzle on a 2D monitor, on a stereo monitor and with the Oculus Rift. In a recent master thesis, the idea of a 3D puzzle for learning anatomy (recall [121]) was transformed in a VR system with HTC Vive [149]. The student can choose between several anatomical structures, and scale them freely from realistic to large scales. Beside assembling a puzzle (see Fig. 20), the VR puzzle allows the disassembly in a specific order, which mimics the dissection course. The additional depth cues of the fully immersive environment support the spatial understanding and learning.

Cinematic rendering in VR. Cinematic rendering (recall Section 4.2) was recently used in a 3D projection space for an audience of up to 150 people [58]. Users wear 3D shutter glasses to get a stereo impression and may control the display with a game controller. This is an impressive setting for virtual anatomy. However, the hardware requirements to render the high-resolution images efficiently are huge.

[5] https://www.unibas.ch/en/News-Events/News/Uni-Research/Virtual-Reality-in-Medicine.html

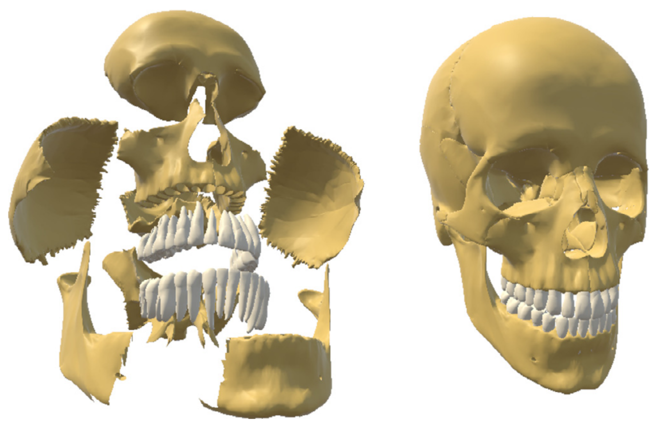

Fig. 20. The anatomy of the skull is learned in a VR environment by assembling the skull from an unsolved (left) to a solved (right) state (Inspired by: [149]).

Cooperative VR systems. Cooperative systems come in two flavors: *co-located cooperative VR systems* enable that different users inspect a virtual environment at the same place, e.g. in a CAVE or dome projection, whereas *remote cooperative VR systems* allow distantly located students and teachers to learn together in a "shared reality" [150]. In co-located collaborative VR, a group of users are in a VR room, seeing and thus being aware of each other. As an example, Fairen et al. [101], introduced a VR system for anatomy education that was run on a Power wall and a in a CAVE (a four-sided CAVE where virtual anatomy is projected on four walls. In both settings, small groups of up to ten students could follow a VR exploration of complex anatomical structures, such as the heart with ventricles, atriums and valves. One student is tracked and guides the inspection whereas the others are more passive. This system is quite promising. However, the hardware is very expensive and typically not available in medical faculties. Thus, the use of such a system beyond a research project is difficult to accomplish. In remote collaboration, cheaper VR glasses may be used. Special care must be taken by representing the students and teachers in the virtual environment. Avatars can be used to mimic movement, interactions and looking directions of the users. A teacher can benefit from knowing the location of all students. However, it can be cluttering and distracting for students to know where the fellow students are.

There exist several possibilities for remote collaborative settings, such as group instructions or one-on-one scenarios. These settings differ in effectiveness of learning, applicability and costs. Moorman [151] showed a one-on-one scenario where an anatomist in her office supports a learner via video conferencing. A recent master thesis uses a one-on-one tutoring system to teach the human skull base [152]. Here, an asymmetric hardware setup is used. The teacher uses a zSpace to be able to see the surroundings and easily input text via a keyboard. The student uses a HTC Vive and explores a scaled up skull from inside. For collaboration, the teacher may set landmarks and sketch 3D annotations in front of the student or reposition the student to direct her attention to something. Additionally, the student's first person view is shared with the teacher.

10. Evaluation of VA systems

In this section, we will discuss some general principles how VA systems are evaluated and continue with selected examples. There are four typical categories of evaluation in the area of educational software [17]:

- *preference*, i.e. whether learners prefer the e-learning system compared to other learning resources,
- *knowledge gain*, i.e. whether learners indeed acquire new knowledge,
- *usability*, i.e. whether a VA system is easy to learn and efficient to use, and
- *behavioral change*, i.e. whether the use of educational software changes the way learners practice medicine.

Although the last category is most important, evaluations of VA systems focus on knowledge gain. Behavioral change is just too difficult to assess in anatomy teaching, since students are far from actually practicing medicine. Often, the gain of knowledge achieved with a VA system is compared to another conventional learning scheme. We use the term *intervention group* for the group of learners who employed the new technique and the term *control group* for the other group. Some studies also report on the time learners take to complete a test. We mention time differences of major studies, but consider time as less important compared to the gain of knowledge. A high usability is largely a prerequisite for acceptability and knowledge acquisition. However, a VA system may be very usable and engage learners but does not lead to a substantial knowledge gain. In most evaluations, usability is not explicitly discussed and therefore also omitted in our survey.

In addition to the measureable knowledge gain, the subjective assessment of the learners is considered. Do they trust a VA system to provide an efficient way to learn anatomy? This and related questions are clearly essential.

Systematic and in-depth evaluations of VA systems have been primarily conducted in the last decade. While Nicholson et al. [3] only found four randomized controlled studies before 2005 in a systematic search, Azer and Azer in 2016 [2] reported of 30 evaluation studies. This strong increase is likely due to availability of comprehensive commercial systems that enable anatomists to carry out such studies without having to build models and systems themselves.

10.1. Evaluation strategies

After introducing virtual anatomy systems in Sections 7–9 we briefly discuss selected evaluation studies in the following. We put emphasis on evaluation criteria and strategies.

Assessment of knowledge gain. All evaluations described in the following employ a pre-test to analyze the knowledge available before using the VA or an alternative system. Multiple choice questions are frequently used, but some authors use more open interviews, video tape them, and let a group of anatomical instructors assess them later. A post-test is performed ideally in the same way and the difference between the two test results is the knowledge gain. The questions in the pre- and post-test should be focused on the spatial aspects of anatomy. Various questionnaires were designed for this purpose. In addition to verbal questions related to the shape and position of objects, drawings may be used. As an example Nguyen et al. [25] show for several 3D models a horizontal line and ask learners to select from a series of cross-sectional images the one that fits to the depicted line. Another type of questions shows again 3D models now with several horizontal lines together with a cross-sectional image. Learners should answer to which line the cross-sectional image fits [25].

The role of spatial ability. Since not all learners are likely to benefit in the same way, their spatial ability is assessed typically based on the mental rotation test (MRT) according to Vandenberg and Kuse [153]. It may be used to correlate knowledge gain to MRT results or to classify learners in low and high spatial ability learners to be analyzed separately. As an example, Nguyen et al. [25] showed that high spatial ability learners using animated rotations solved spatial anatomy tasks significantly faster and more correctly than low spatial ability learners [25]. While most studies consider the interaction between spatial ability and knowledge gain, there are other learner-related features that influence the results [2,154]:

- the experience of students with 3D applications, such as games,
- the experience with graphics modeling,
- familiarity with computers, and
- active experience with painting and sculpting.

Thus, evaluations of VA systems should analyze individual differences and relate them to the performance of learners.

Integration in the curriculum. An essential aspect of any evaluation of a VA system is whether and how it is integrated in the curriculum (recall the discussion of blended learning in Section 2.1) . What do the students know already? Is the use of the VA system guided by anatomy teachers? Do anatomy teachers provide feedback or may answer questions related to the use of a VA systems? Azer and Azer [2] require that evaluations should be explicit about these questions.

10.2. Overview

A structured overview of evaluation studies for VA systems is given by Yammine et al. [154]. They identified 36 high-quality evaluations (peer-reviewed full papers with convincing study design and a high number of participants). Most studies were randomized, that is neither teachers nor the learners influenced the decision whether a VA system was used or alternative non-interactive resources. This randomization avoids a selection bias; otherwise it is likely that students voluntarily using VA systems differ in their capabilities from other students.

Almost all systems that were evaluated focus on a limited (regional) aspect of anatomy. Frequently, they were focussed on neuroanatomy, vascular anatomy, the anatomy of the middle ear, the pelvis, or the abdominal area.

10.3. Selected evaluations

The selected examples are described in a chronological order. All evaluations are designed as comparisons between a VA system and more classic form of teaching, either conventional learning or a VA system with reduced functions. The major motivation to include an evaluation is, whether new and relevant evaluation methods were employed. We focus also on these new aspects which may lead to the wrong impression that evaluation methods strongly differ.

Carpal bone anatomy. In a series of publications Garg et al. [155,156] analyzed VA systems focussed on the carpal bone anatomy. In the first study, Garg et al. found no advantage of presenting the carpal bone in multiple views (15 degree steps) compared to presenting three key viewpoints only.

In a second experiment [156], the intervention group could control multiple views of the carpal bone, whereas the control saw only key views. The questions were divided in two groups: one half relates to questions where key viewpoints are sufficient to answer them, whereas the other half requires to understand unfamiliar views that strongly differ from these key viewpoints. High spatial ability learners (determined with the mental rotation test [153]) in the intervention group improved their spatial understanding according to both types of questions. Low spatial ability learners could not benefit. This result was later theoretically explained with the connection between mental rotation tasks and manual rotation. Low spatial ability learners are less effective using manual rotation of a virtual object. Garg et al. argued that key viewpoints are indeed important but the active control of the viewing direction in particular close to the key viewpoints adds a sense of the third dimension. This is also based on an analysis of the viewpoints actually taken by the learners: They spent much more time close to the key viewpoints. An interesting conjecture of Garg et al. [156] is that anatomy education benefits from 3D models, probably more from physical models than virtual ones.

3D Puzzle. The 3D Puzzle (recall [121]) was evaluated with 16 participants (students of physiotherapy with already existing basic anatomic skills) [123]. To understand the effect of the puzzle on the knowledge gain, two systems were used for learning. Both employ exactly the same geometric models of the foot anatomy comprising 28 bones, 11 muscles and 14 ligaments. Both systems also contain the same textual information. They differ only in the support for the 3D puzzle.

In a between-subject study the knowledge gain was evaluated for the two groups of 8 students. The pre-test anatomic knowledge was on average 52% of all questions and increased by 11 % in the intervention group and only by 8% in the control group. This difference was observed for all questions that relate to spatial knowledge. The participants took part in a subset of an intelligence test focused on mental rotation, figurative classification and recognition. The differences in the post-test knowledge cannot be explained by different spatial abilities. Students in the puzzle group were also more confident in their abilities. They liked to use the 3D mouse for model rotation although it took them some time to become familiar with it. To improve the system, it was suggested that the correct solution of the puzzle should be shown first before the students solve the task.

Use of supportive handles. In Section 6 we briefly mentioned the idea of providing orientation handles to support rotation of anatomical structures (recall [15] and Fig. 12). The handles represent a coordinate system for the selected object and can be based either on anatomical knowledge or on an analysis of the object shape with a principal component analysis. For testing the effectiveness of these models, Stull et al. [15] assembled a number of difficult tasks that require the users to rotate the object in all directions until the view matches a given target view. The tasks are designed to test whether students can recognize anatomical structures from different directions. 75 participants were assigned to an intervention group (38 participants, among them 17 with high and 21 with low spatial ability) and a control group without orientation handles (in total 37 students among them 19 with high and 18 with low spatial ability). Learners could use a 3D input device which eases 3D rotation tasks compared to mouse input or touch gestures on the screen.

The results indicate that both low and high spatial ability learners benefit from the supportive handles, whereas low spatial ability learners benefit stronger. In other words, the difference between low and high spatial ability learners gets reduced, probably because the cognitive load for low spatial ability learners was strongly reduced. At the same time, students in the intervention group completed the tasks even faster. The handles obviously enabled them to rotate an object more goal-directed.

Virtual ear anatomy. We briefly discussed the evaluation of a virtual ear anatomy system (recall [3]). Here, we add some essential facts. 57 students took part in the evaluation divided in an intervention and a control group that used a web tutorial for learning without any interactive 3D model. The authors aimed at 60 participants, since this would enable them to identify significant differences (at least two points in a quiz with 15 questions) with a 95% level. The resulting difference between the intervention group (mean score 12.5/15) and the control group (9.8/15) was indeed significant. Learners in the intervention group were not only better, but also faster taking only 16 min. to complete the quiz compared to 21 min. in the control group.

EVA evaluation. In Section 8, we described the EVA system (recall [135]) which was carefully evaluated. The questions were chosen such that unusual views, not present in an anatomy atlas, are essential to answer them. In the knowledge assessment part, 90 second semester students (41 using EVA, 49 using alternatives resources) and 77 fifth semester students (51 using EVA, 26 using alternatives) were compared. The mean score for the second semester students was significantly higher in the EVA group (mean score 13.5 vs. 11.1), where as in the fifth semester group the scores were almost the same and no significant difference was observed.

In addition to this quantitative assessment, students' preferences were analyzed w.r.t. a comparison of EVA to anatomy text books, anatomy lectures, and dissections as the major conventional forms of education. On average, EVA was considered as similar. EVA was assessed as slightly better compared to text books (16/37 considered it as equal and 12/37 as better). Also in comparison to lectures, the largest group (14/37) considers EVA as equal. Only compared to dissections, 19 students assessed EVA as worse and only 7 as better. The individual differences are interesting: some students do not prefer the interactive visualization and may also perform worse with them, whereas another group considers the VA system as the best teaching resource. The authors stated the limitations of their work: EVA was not integrated in the curriculum, the QuickTime plugin was not easily available for some students and there was no reward for using the software. In particular, it was not clear whether the case of the software is directly relevant for the examinations. The integration of EVA in a PBL scenario, was considered the most important extension.

Evaluation of a VR system for anatomy teaching. In Section 9 we briefly discussed a system for co-located collaborative VR. This system was used for a comprehensive evaluation with 254 participants (students of nursing). The participants represented two full cohorts, i.e. there is no selection bias where only students with high affinity for new technology voluntarily took part. The students took a two hour lecture; one hour in a CAVE and another hour using the Powerwall to experience in total ten models, all representing complex spatial structures, such as the heart, the eye, and the ear. The knowledge gain, unfortunately, was not directly assessed. Instead, the students were asked whether they consider learning with the CAVE and the Powerwall appropriate and motivating and they had the impression that they improved their knowledge. On a scale from one to ten, the average answers are between 7.3 and 8.8. An interesting detail was that students taking part in the experiment in the morning consistently rated the VR system better (on average by 0.3) compared to those using it in the afternoon.

10.4. Discussion

We discussed selected studies that showed a positive effect of virtual anatomy. Indeed, most of the recent studies had this positive effect. This may be due to the fact that the underlying models are meanwhile more realistic and the amount of interactivity increased. We also mentioned a study that showed no significant difference in the learning effectiveness between the virtual anatomy group and a control group, e.g. [155]. To summarize the findings from evaluations within anatomy, it is very likely that for complex spatial regions and systems, such as the ear and the vascular system, interactive virtual anatomy systems based on very detailed anatomic models favor learning and deep understanding of spatial relations. However, not all students will benefit in the same manner and only a test with emphasis on spatial knowledge reveals the advantage. In summary, "evidence shows that learning anatomy using computer-based learning can enhance learning by supplementing rather than replacing the traditional teaching methods" [157].

While there is an impressive number of studies assessing the general effects of interactive 3D visualization, the specific value of techniques, such as clipping, virtual dissection endoscopic views, and focus-context views was not assessed. As a limitation of almost all evaluations, the knowledge gain is assessed in a test is only a surrogate for the actual imagination. Thus many authors, e.g. Nicholson et al. [3] require studies that analyze the external validity of such results, for example by analyzing the resulting competence in real cadaver dissection tasks. More research is necessary to better understand how to optimally integrate VA systems in the overall process of anatomy teaching. This research has to consider constraints, e.g. some institutions do not provide any cadaver dissection at all. This situation likely changes the optimal use of a VA system.

11. Concluding remarks

Many resources are available for students of medicine or related subjects for anatomy learning. Virtual anatomy systems with their emphasis on exploring shapes and spatial relations play an essential role. Powerful visualizations that support shape and depth perception, labeling and interaction techniques are the technical ingredients of virtual anatomy systems. Learning scenarios to be supported, learning and motivational strategies are the educational foundations. A large diversity of software libraries was used to create virtual anatomy systems. Currently, game engines, such as Unity, that support a wide range of input devices and interaction techniques, may be considered and were already used for a number of VA systems, e.g. [25].

In the scientific literature, there is no in-depth analysis of resources that are actually used by students, how they integrate the use of these resources with more traditional learning and which exploration features are particularly desired. Most virtual anatomy systems are not carefully integrated in the curriculum; their use is optional and the relevance of using them is not clear. The wide availability of VA systems indicates that at least a substantial portion of students employs them.

Outlook. The information space provided in VA systems is often limited to 3D models and related text. Diagrams, photos of dissections and video clips may be added and need to be carefully integrated. VA systems support explorative usage typically with only limited guidance. Based on experiences in many e-learning systems, powerful search and retrieval facilities need to be added. VA systems may have a long life-time and thus need to enable easy modification and extension of the *content*. This means, that the content is clearly separated from the software to display and navigate within that content.

We have seen that few systems support variational and functional anatomy. A strong demand for future research in these areas exists. The usefulness of virtual anatomy resources depends on the learner, e.g. her spatial ability. It may be investigated whether VA systems may adapt themselves to these abilities.

True virtual reality systems *may* enhance anatomy education, but are in its infancy. Considerable research is needed to explore the design space more systematically and evaluate possible solutions w.r.t. motivational aspects, and problems, such as motion sickness. Currently, a number of obstacles restrict the use of such systems. Since the development of VR glasses w.r.t. spatial resolution, field of view and comfort is still very rapid, it is expected that many opportunities arise for VR-based anatomy education.

There is a synergetic effect between patient education and anatomy education. As an example, the system by Saalfeld et al. [112] was originally intended to inform patients about their vascular disease and possible treatment options. More effort should be spent to directly support patient education as well, including substantial evaluations of their effect. A fresh new idea that may be beneficial for patient education was presented by Stoppel et al. [158] who produce hardcopies of volume visualizations and preserve a certain degree of interactivity.

An integration of realistic haptic feedback that conveys the different mechanical properties of soft tissue, vascular structures and bones would be a highly useful addition to VA systems. Several studies indicated that cadaver dissection is still perceived as more important than VA-based learning. This is likely due to the haptic interaction. While haptics was used in surgery simulation systems, anatomy education is based on different learning goals and constraints. VA systems need to be cheaper due to their larger audience. Thus, considerable effort is necessary to adapt haptic feedback to VA systems.

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