

RESEARCH ARTICLE

Comparing the critical features of e-applications for three-dimensional anatomy education[☆]



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ABSTRACT

Anatomical e-applications are increasingly being created and used in medical education and health care for the purpose of gaining anatomical knowledge. Research has established their superiority over 2D methods in the acquisition of spatial anatomy knowledge. Many different anatomy e-applications have been designed, but a comparative review is still lacking. We aimed to create an overview for comparing the features of anatomy e-applications in order to offer guidance in selecting a suitable anatomy e-application.

A systematic search was conducted. Data were retrieved from the 3D model designs (realism), software aspects and program functionality.

The non-commercial e-applications focused on small body regions and received an average score of 3.04 (range 1–5) for model realism. Their average score on program functionality was 8.8 (range 0–14). The commercial e-applications covered the entire human body and received an average score of 2.85 (range 1–5) for model realism. Their average score on program functionality was 10.4 (range 0–14).

Non-commercial anatomy e-applications received higher scores on realism and facilities like performing a virtual dissection, while the commercial anatomy e-applications offer a much wider range of anatomical structures available and they showed higher scores on program functionality. These scores gave good insight of the e-applications' possibilities, and may help future users to make an informed choice among the large number of available e-applications.

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1. Introduction

Human anatomy as a basic medical science has been a fundamental component of medical education for centuries, relevant for all health care specialties (Older, 2004). It is widely agreed that competent doctors need to have an adequate knowledge of anatomy (Turney, 2007). Anatomical knowledge is essential to examine patients, make diagnoses and communicate findings to patients and medical professionals. Medical students must learn to identify relevant structures in the human body and create a three dimensional (3D) understanding of the body with insight

into the topographical relationships between anatomical structures (Sugand et al., 2010).

Although supervised cadaver dissection, examination of prosected specimens, and two-dimensional (2D) teaching tools all aim at improving spatial understanding of complex anatomy, reaching this goal has been proven difficult (Miller, 2000). It has been claimed that 3D images are considered useful teaching tools, especially in recalling anatomical knowledge requiring spatial ability (Hoyek et al., 2014; Mitrousias et al., 2018). The use of multimedia has become common worldwide and 3D presentations of information are being increasingly used in medical education and health care (Sugand et al., 2010). Modern anatomy teaching increasingly includes the use of multimedia presentations and radiological images, in addition to more traditional educational procedures such as cadaver dissection and depicting surface anatomy.

In a recent meta-analysis of the educational effectiveness of three-dimensional visualization technologies (3DVT) in teaching anatomy, Yamine and Violato (2015) compared these with traditional methods such as lectures, blackboard drawing, or textbooks.

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They concluded that students studying anatomy by using 3DVT achieved higher levels of factual anatomy knowledge. The 3DVT approaches showed superiority over 2D methods, in particular over 2D digital images, in the acquisition of spatial anatomy knowledge, insight and understanding (Yammine and Violato, 2015).

Several commercial anatomy e-applications, e.g. Zygote Body[®] (Zygote Body), Visible Body[®] (Visible Body) and Primal Pictures[®] (Primal Pictures) were created using real sectional images to provide an accurate and detailed 3D anatomical model of the human body. Despite the existence of these e-applications, many departments of anatomy and surgery have started to create their own 3D models together with software (non-commercially available e-applications) to support anatomy teaching (Attardi and Rogers, 2015). Possible explanations are specific requirements in 3D model regions, different software properties and the lack of any comparative reviews of existing e-applications. Both Friedman (1994) and Cook (2005) suggested that research is required to compare features of computer-based instructional systems. As a result, with the emergence of many more anatomical e-applications, the urgency increased for a review. There is a wide range of e-applications for anatomy teaching departments today, but there are very few guidelines how to choose among them.

For the purpose of comparing the features of e-applications (both those developed commercially and non-commercially), two approaches can be discerned. One is to review anatomy e-applications described in literature, particularly those that report on their features and effectiveness, and the other is to examine commercial anatomy e-applications directly. We decided to do both. The first by evaluating published studies testing virtual 3D visualizations (including 3D computer animated/dynamic graphics, and 3D learning environments such as virtual reality (Nowinski et al., 2009)) used in undergraduate and/or postgraduate medical or health students or among health care professionals and noting their properties. The second approach was carried out by selecting popular, commercial anatomy programs and examining these, in order to get their properties as well.

The aim of this study was to compare characteristics of e-applications for 3D anatomy to offer guidance in selecting an anatomy e-application when three-dimensional visualizations is desirable for studying gross anatomy of the whole body or more specific areas, or for preparing surgical procedures. This was done by creating 2 groups of e-applications (those developed commercially and non-commercially) and rating them on their characteristics.

2. Material and methods

2.1. Search and selection

To obtain a list of anatomy e-applications, we conducted a search of MEDLINE through the PubMed interface, EMBASE and Cochrane in September 2017. The search strategy was based on the DDO approach (DOMAIN, DETERMINANT, OUTCOME (DDO)). We screened for articles in which virtual 3D visualization for anatomy education was discussed and tested with medical students. The search strategy involved the following combinations of key words: (“3D” AND “imaging”) AND (“medical” AND “students”) AND (“education” AND “method”). Synonyms for the search terms “3D imaging”; “medical students” and “education methods” were used (Table 1). Duplicates were excluded. Titles and abstracts were screened on relevance for inclusion. If, after screening on both title and abstract inclusion remained doubtful; full text screening was performed. Only reports of original study data were included. All titles and abstracts were screened by authors MZ and EK applying our inclusion and exclusion criteria as listed in the flowchart (Fig. 1).

Table 1
Search strategy.

Database	Search string
Pubmed (148 articles found) & Cochrane (87 articles found)	(Three dimensional imaging[tiab]) OR (Three dimensional imagings[tiab]) OR (3D[tiab]) OR (3D imaging[tiab]) OR (3D imagings[tiab]) OR (Computer-assisted three dimensional imaging[tiab]) OR (Computer-assisted 3D imaging[tiab]) OR (Computer-assisted three dimensional imagings[tiab]) OR (Computer-assisted 3D imagings[tiab]) OR (Computer-generated three dimensional imaging[tiab]) OR (Computer-generated 3D imaging[tiab]) OR (Computer-generated three dimensional imagings[tiab]) OR (Computer-generated 3D imagings[tiab]) AND (education[tiab]) OR (training[tiab]) OR (teaching[tiab]) AND (medical[tiab] AND (student[tiab] OR students[tiab])) (Three dimensional imaging:ab,ti) OR (Three dimensional imagings:ab,ti) OR (3D:ab,ti) OR (3D imaging:ab,ti) OR (3D imagings:ab,ti) OR (Computer-assisted three dimensional imaging:ab,ti) OR (Computer-assisted 3D imaging:ab,ti) OR (Computer-assisted three dimensional imagings:ab,ti) OR (Computer-assisted 3D imagings:ab,ti) OR (Computer-generated three dimensional imaging:ab,ti) OR (Computer-generated 3D imaging:ab,ti) OR (Computer-generated three dimensional imagings:ab,ti) OR (Computer-generated 3D imagings:ab,ti) AND (education:ab,ti) OR (training:ab,ti) OR (teaching:ab,ti) AND (medical:ab,ti) AND (student:ab,ti OR students:ab,ti)
Embase (388 articles found)	(Three dimensional imaging:ab,ti) OR (Three dimensional imagings:ab,ti) OR (3D:ab,ti) OR (3D imaging:ab,ti) OR (3D imagings:ab,ti) OR (Computer-assisted three dimensional imaging:ab,ti) OR (Computer-assisted 3D imaging:ab,ti) OR (Computer-assisted three dimensional imagings:ab,ti) OR (Computer-assisted 3D imagings:ab,ti) OR (Computer-generated three dimensional imaging:ab,ti) OR (Computer-generated 3D imaging:ab,ti) OR (Computer-generated three dimensional imagings:ab,ti) OR (Computer-generated 3D imagings:ab,ti) AND (education:ab,ti) OR (training:ab,ti) OR (teaching:ab,ti) AND (medical:ab,ti) AND (student:ab,ti OR students:ab,ti)

Virtual 3D anatomy had its origin between 2000 and 2005 (Cook, 2005); to ensure that the same actions can be performed on all e-applications; only publications after 2005 were included. Animal studies; systematic reviews; case reports; articles not in written in English; German or Dutch; and articles without full text access were excluded for further evaluation. Reference lists of included studies were cross-checked to identify additional studies that might have been missed by the electronic search.

There are also a number of commercially available anatomy e-applications that include interactive 3D computer models of the body's structures which we did not find in Medline et al. To obtain a list of e-application characteristics as complete as possible, we decided to analyze this type as well (Lewis et al., 2014; Mitrousias et al., 2018): after searching the internet for “anatomy e-applications”, seven well-known commercial anatomy e-applications (Anatronica, Biodigital, Netter 3D Anatomy, Primal Pictures, Visible Body, Zygote Body, 3D4Medical) were downloaded (either free-versions or demo-versions on a Microsoft windows PC/android tablet device) and evaluated, using a Dell Optiplex 9020 desktop (Windows 7 64-bit, Intel Core i5 processor, 16 GB RAM, GeForce GT 730 graphics engine).

2.2. Study assessment and data extraction

The relevance of articles was assessed by examining the sections describing details of objectives and context of the study. The characteristics of eligible e-applications from the selected studies were divided into three main categories: (i) 3D model design (realism), (ii) software aspects and (iii) program functionality. Articles describing not all three categories of characteristics were excluded. After screening full text, data from the e-applications of the included articles were processed by reading the articles and studying the included images. The same characteristics from the

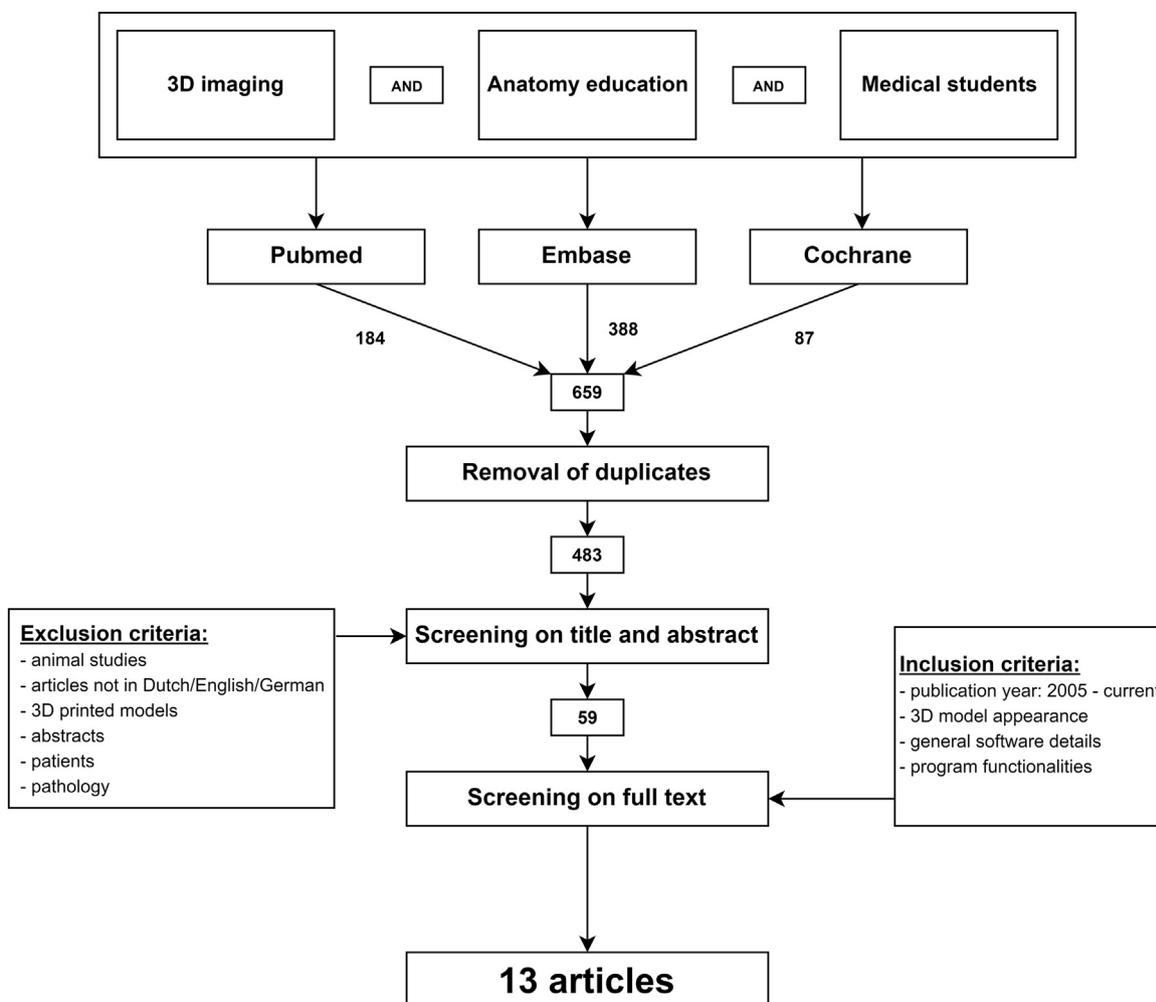


Fig. 1. Flowchart.

commercial anatomy e-applications were processed by both MZ and EK manually testing the trial-versions of the e-applications that could be downloaded for free.

MZ and EK independently rated the model realism on a scale 1–5. This was done by comparing the appearances (aesthetics, resolution and visual clarity/colors) in the developed model by either rating the added models images in the articles and by using the commercially available trial versions. A model using very simple shapes (tube- and oval-like objects) and lacking any details, either in colors or in visual clarity, was assigned the lowest score, i.e. '1'. A model with either less simplistic shapes but still lacking details in color/visual clarity or with simple shapes but more details in color/visual clarity got assigned the score '2'. When both aspects (less simplistic shapes and more details in color/visual clarity) are present, the 3D model got assigned the score '3'. Exceptional development, i.e. close to realism, of either the shapes or the visual details got assigned the score '4'. And an e-application containing an anatomical 3D model as realistic in both shapes and visual details as possible, got assigned the highest score, i.e. '5'. Furthermore, 3D models with a limited number of anatomical regions were scored on realism the same way as a 3D model of the entire human body; i.e. the realism score is not affected by the number of anatomical regions present.

These guidelines were used to determine the models realism score (intermediate scores were given as well). The final score was calculated by taking the average of MZ's and EK's ratings. Reliability

was tested by calculating Pearson correlation coefficients as a measure for interobserver agreement. The software aspects details were subdivided in: anatomical regions, the origin of medical data, operating system, development date, costs, future plans and research with medical students. Anatomical regions were used to globally describe what the 3D model consisted of. Future plans and testing the model in the target study population were excluded for the commercial anatomy e-applications.

The program functionalities were subdivided in: rotation, displacement, zooming in, clickable structures, changeable transparency, anatomical descriptions and virtual dissection: these categories were supposed to provide the main source of information for each application. Rotation, displacement and zooming in are general functionalities to control the 3D model. Clickable structures and changeable transparency (which is used to see what is behind selected structures) are both methods to work interactively with the 3D model. Anatomical descriptions are used to transfer anatomical information to the user, and a virtual dissection, i.e. dragging or clicking away items to expose underlying structures, is an advanced functionality for studying anatomy. MZ and EK independently rated these seven program functionality subcategories on a scale 0–2 (Table 2 shows the ratings for each specific characteristic), the final scores were calculated by taking the average of MZ's and EK's ratings. A total program functionalities-score was calculated (0–14) by adding the seven subcategory scores.

Table 2
Characteristics of the program functionality.

Feature	Response options: scores
Rotation	<ul style="list-style-type: none"> Unable to rotate the models/view the models from different vantage points: 0 Only possible to view the models from different vantage points: 1 Able to rotate the models without limitations: 2
Displacement	<ul style="list-style-type: none"> Unable to move the models/structures: 0 Only possible to move the models/structures by predefined displacement: 1 Able to move the models/structures without limitations: 2
Zooming	<ul style="list-style-type: none"> Unable to zoom in/out of the models/structures: 0 Only possible to zoom in/out of the models/structures with limitations: 1 Able to zoom in/out of models/structures without limitations: 2
Clickable structures	<ul style="list-style-type: none"> Unable to click on structures for selection: 0 Not all structures are selectable by clicking: 1 All structures can be selected by clicking: 2
Changeable transparency	<ul style="list-style-type: none"> Unable to change objects/structures transparency: 0 Objects/structures transparency can only be changed in combined structure-groups: 1 The transparency of objects can be fully adapted: 2
Anatomical information	<ul style="list-style-type: none"> No additional anatomical descriptions present: 0 Only the anatomical names displayed/no additional descriptions for every structure: 1 Additional anatomical descriptions present for all structures: 2
Virtual dissection	<ul style="list-style-type: none"> Unable to perform a virtual dissection: 0 Some (not all) structures can be removed to perform a virtual dissection: 1 All structures can be removed to perform a virtual dissection: 2

3. Results

3.1. Search and selection

From the systematic search, a total of 659 articles was obtained. After removal of duplicates, 483 articles remained; these were evaluated by screening titles and abstracts. A flowchart of the selection procedure is presented in Fig. 1. Application of exclusion criteria and an additional search from article references resulted in a total of 59 unique articles. After screening those on full text and taking the inclusion criteria into consideration, 13 articles were considered for final inclusion in this review. No useful articles were found by cross-referencing and no additional terms were added to the original search string.

3.2. Study assessment

In the 13 included studies a total of 13 different anatomy e-applications were described. All studies were conducted in tertiary educational institutions with committed medical programs.

Adding the publicly known commercial anatomy e-applications that were evaluated, resulted in a total list of 20 different anatomy e-applications.

Table 3 represents an overview of the characteristics of all the non-commercial anatomy e-applications.

3.3. Realism

Concerning the appearances, there were many differences among the models. In one study (Ng et al., 2015) an e-application

was used to focus on relations between structures and it contained simple shapes and connections between structures. The opposite was seen in two e-studies (Nowinski, 2017; Zilverschoon et al., 2017) where e-applications were created containing a 3D model as realistic and complete as possible. The realism of the other e-applications was assigned an intermediate score. Screenshots of a model with the lowest, intermediate and highest score are included to give an impression (Fig. 2a). The average model realism score of the 13 different non-commercial anatomy e-applications was 3.04 (range 1–5). The interobserver agreement (MZ/EK) was high: the Pearson correlation coefficient was 0.895.

3.4. General software details

The anatomical structures the models represented varied greatly. In three studies (Allen et al., 2016; Li et al., 2014; Nowinski, 2017) a model of a human brain was used, in three other studies (Keedy et al., 2011; Lu et al., 2010; Shin et al., 2013) the focus was on a model of organs of the abdomen and in six studies a specific body region was tested (pelvic (Temkin et al., 2006), ear (Ng et al., 2015), eye (Glittenberg and Binder, 2006), extremities (Battulga et al., 2012; Zilverschoon et al., 2017), heart (Jerath et al., 2011)). In one application (Fang et al., 2017) a 3D model of a complete set of male and female anatomical structures was created and tested.

The Visible Human dataset (The Visible Human Project) was used in two studies (Allen et al., 2016; Shin et al., 2013) as source material to create a 3D model and in two other studies (Fang et al., 2017; Li et al., 2014) cross-sectional images of the Chinese Visible Human dataset (Zhang et al., 2006) were used. In five studies (Jerath et al., 2011; Glittenberg and Binder, 2006; Keedy et al., 2011; Lu et al., 2010; Shin et al., 2013) a 3D model was created from anonymized (patient) CT datasets and in three studies (Battulga et al., 2012; Jerath et al., 2011; Ng et al., 2015) the 3D model was made without a pre-existing dataset. Finally, in one study (Zilverschoon et al., 2017) cross-sectional images of a human hand were used.

The required operating system needed to use an e-application varied between models. Some e-applications exclusively work on a Microsoft Windows based system (Li et al., 2014; Nowinski, 2017), Mac OS based system (including iPad) (Jerath et al., 2011; Ng et al., 2015) or are only web-based (internet) (Allen et al., 2016; Battulga et al., 2012; Keedy et al., 2011; Temkin et al., 2006). Other e-applications are usable on multiple operating systems, running on both Microsoft Windows and a Mac OS based system (Shin et al., 2013; Fang et al., 2017), running on both a Microsoft Windows based system or a web-based approach (Lu et al., 2010), or accessible on all operating systems (Zilverschoon et al., 2017). In one study (Glittenberg and Binder, 2006), the information regarding the required operating system could not be found. Mobile application versions for the use on tablets were not available for these 13 e-applications. Touch screen functionality was integrated in two e-applications (Ng et al., 2015; Lu et al., 2010), this feature was not mentioned for the other e-applications.

Five e-applications (Jerath et al., 2011; Glittenberg and Binder, 2006; Keedy et al., 2011; Lu et al., 2010; Temkin et al., 2006) discussed in these studies were developed before 2010, the other e-applications were created in 2010 or later. In six studies (Jerath et al., 2011; Glittenberg and Binder, 2006; Fang et al., 2017; Li et al., 2014; Nowinski, 2017; Shin et al., 2013) mention was made that the e-application could be downloaded for free. The other seven studies did not mention the cost of working with the e-application; hence, information on this important feature was missing.

First-year undergraduate medical students were involved in four studies (Battulga et al., 2012; Keedy et al., 2011; Ng et al., 2015; Lu et al., 2010) to test an e-application, in one study (Allen et al., 2016) the e-application was tested with second

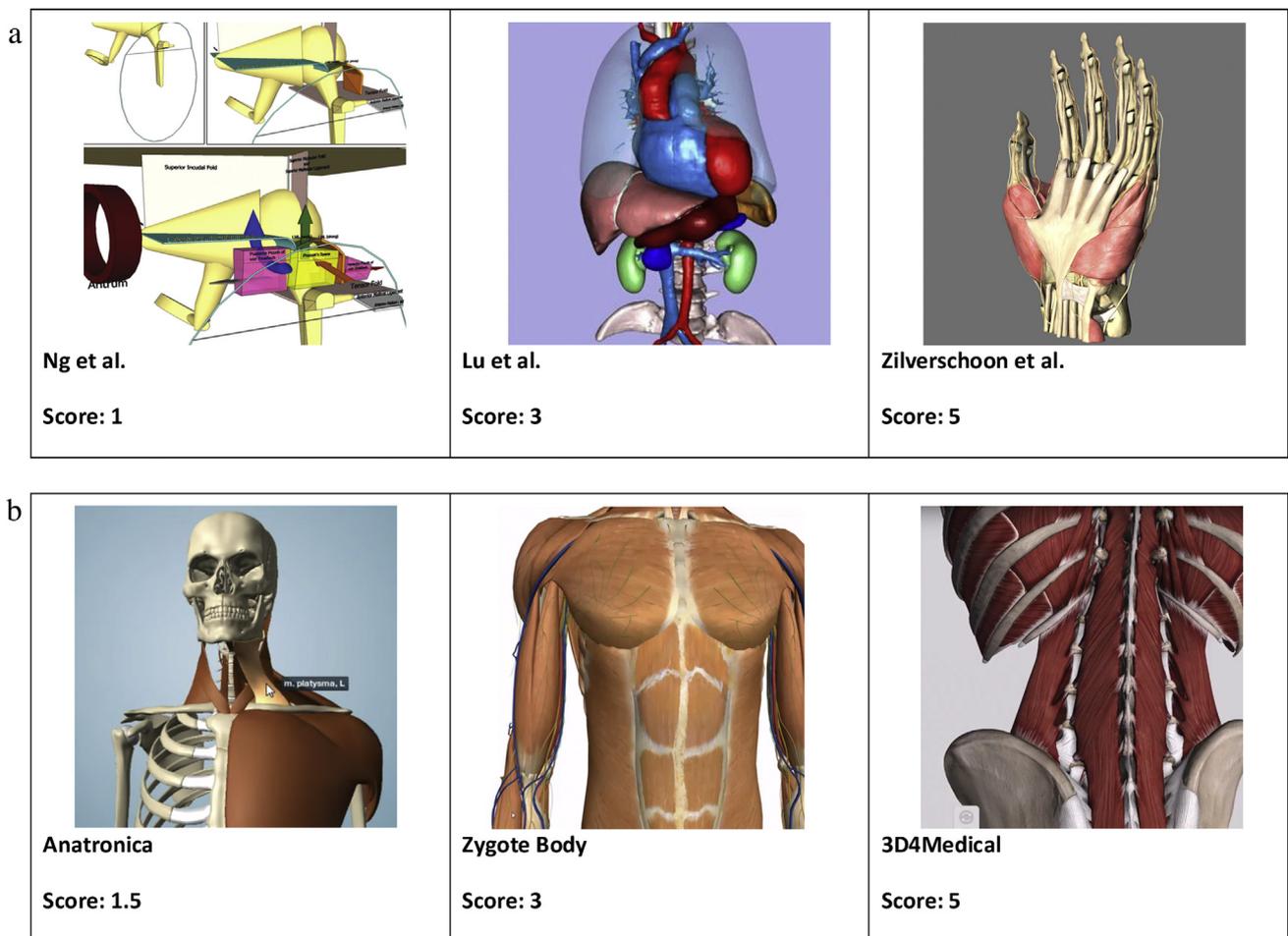


Fig. 2. (a) Example realism-scores of non-commercial anatomy e-applications. (b) Example realism-scores of commercial anatomy e-applications.

year undergraduate medical students and postgraduate residents (in anaesthesia/cardiology/cardiac surgery and in ophthalmology) were involved in two studies (Glittenberg and Binder, 2006; Jerath et al., 2011). In general, in those studies (Allen et al., 2016; Battulga et al., 2012; Fang et al., 2017; Glittenberg and Binder, 2006; Keedy et al., 2011; Lu et al., 2010; Ng et al., 2015) that tested an anatomy e-application with medical students, the students' responses were positive enough to recommend that 3DVT should be used for increasing the quality and efficiency of anatomy education. It also has a positive effect on demonstrations of complex topics in order to make the teaching of anatomy more interesting and relevant to clinical medicine. In the remaining six studies the e-application was not tested in the target student population. In five studies (Battulga et al., 2012; Jerath et al., 2011; Lu et al., 2010; Li et al., 2014; Shin et al., 2013) no future plans concerning the e-application were mentioned, in the other eight studies the follow-up plans were described, varying between expanding the e-application functionalities (Temkin et al., 2006; Fang et al., 2017; Keedy et al., 2011; Glittenberg and Binder, 2006), creating additional 3D models (Zilverschoon et al., 2017; Nowinski, 2017; Allen et al., 2016) and explaining examination of the long term benefits (Ng et al., 2015).

3.5. Program functionality

Rotation facility was limited in four e-applications to specific predefined views (Jerath et al., 2011; Glittenberg and Binder, 2006; Keedy et al., 2011; Temkin et al., 2006); those 3D models could not

be viewed from every angle. Rotating the model was not limited in any of the other e-applications, so it could be rotated freely in every angle. Six e-applications had displacement restrictions (Jerath et al., 2011; Glittenberg and Binder, 2006; Keedy et al., 2011; Ng et al., 2015; Li et al., 2014; Temkin et al., 2006), the user was not able to move the anatomical objects freely. Three e-applications had limited zooming facilities (Ng et al., 2015; Li et al., 2014; Temkin et al., 2006), and three other e-applications did not have any zooming options at all (Glittenberg and Binder, 2006; Jerath et al., 2011; Keedy et al., 2011).

In four e-applications (Jerath et al., 2011; Glittenberg and Binder, 2006; Ng et al., 2015; Lu et al., 2010), the user could not select structures by clicking and in two e-applications clicking facilities were limited (Allen et al., 2016; Li et al., 2014) (not all visible structures were clickable). In the other e-applications, all structures could be selected by mouse clicking. The transparency of objects could be fully altered in two e-applications (Zilverschoon et al., 2017; Fang et al., 2017), enabling to better view areas behind those structures. In five e-applications (Battulga et al., 2012; Jerath et al., 2011; Lu et al., 2010; Nowinski, 2017; Shin et al., 2013), objects transparency could only be changed in combined structure-groups or by presets, the other e-applications did not include the ability to change the transparency of objects at all.

Anatomical descriptions providing additional anatomical information were present in all e-applications; however, in three e-applications (Allen et al., 2016; Glittenberg and Binder, 2006; Shin et al., 2013) these were limited to displaying the anatomical names. Performing a virtual dissection on the model (by manu-

ally removing structures) was only possible in two e-applications (Nowinski, 2017; Zilverschoon et al., 2017). The total scores on program functionality reached a value between 3 (lowest (Glittenberg and Binder, 2006)) and 14 (highest (Zilverschoon et al., 2017)), with an average score on program functionality of 8.8 (scale 0–14).

Table 4 represents an overview of the characteristics of all the commercial anatomy e-applications.

3.6. Realism

In every commercial anatomy e-application, a 3D model containing all the different structures of the entire human body was used, and in general the same geometrically designed shapes were seen. However, the differences were, compared to the non-commercial anatomy e-applications, less distinctive. Differences in realism of the models were seen, ranging from strongly reduced/overly simple (Netter 3D Anatomy; Anatronica) to realistic (Primal Pictures; 3D4Medical), both in geometry and visual details. Screenshots of a model with the lowest, intermediate and highest score are included again (Fig. 2b). The average realism score of the seven different commercial anatomy e-applications is 2.85 (range 2–4). The interobserver agreement (MZ/EK) was high: the Pearson correlation coefficient was 0.919.

3.7. General software details

All commercially available anatomy e-applications contained a model of the entire male and female body, and some (Primal Pictures; Zygote Body; 3D4Medical) included additional modules of specific, more detailed body regions (for example: an enlarged detailed model of the eye-region). The origin of all e-applications can be traced back to the Visible Human Project (The Visible Human Project), which implies they are all based on the same source. Two e-applications (Netter 3D Anatomy; Zygote Body) were exclusively designed for a web-based working environment and could only be accessed that way. One e-application (Primal Pictures) is accessible on table devices and a web-based working environment, and four e-applications (Visible Body; 3D4Medical; BioDigital; Anatronica) are usable on multiple operating systems, running on both a Microsoft Windows based system, on a Mac OS based system (including iPad) or on tablet devices. Touch screen functionality was present in all e-applications.

The latest version of all e-applications dates from 2017. The cost of working with the e-application varied considerably. Four e-applications (Netter 3D Anatomy; BioDigital; Anatronica; Zygote Body) had a basic or 'lite' version, free to use, and a professional version (with annual subscription costs ranging from €4.30 to €48.00 annually). Two e-applications (Visible Body; 3D4Medical) could be purchased in subsections or as a whole (costs varying between €0.99–€32.99 per component) and one application (Primal Pictures) was only accessible by paying a monthly subscription fee (a student (for the general 3D human body model) 12 month subscription rate of €95.00 and non-student (many highly detailed 3D models of specific body parts) 12 month subscription rate of €230.00).

3.8. Program functionality

The software characteristics contained fewer differences than seen in the non-commercial available e-applications, all e-applications are user friendly, interactive, and self-explanatory. In two e-applications (Anatronica; Zygote Body) the user could not fully rotate or move the objects, in the other e-applications no limitations in rotating or displacement were experienced. Zooming options were available in all e-applications.

In one e-application it was not possible to select different structures by mouse clicking (Netter 3D Anatomy); this could be done in all other e-applications. Anatomical descriptions were lacking in one application (Netter 3D Anatomy), whereas this feature was fully present in all other e-applications. Performing a virtual dissection of the model was possible in one e-application (Anatronica), albeit to a limited extent (not all structures could be removed). A virtual dissection was not available in the other tested e-applications.

The total scores on program functionality reached a value between 7 (lowest (Netter 3D Anatomy)) and 12 (highest (3D4Medical)), with an average score on program functionality of 10.4 (scale 0–14).

3.9. Summarizing

Table 5 gives an overview of the most important characteristics of both commercially available and non-commercially available anatomy e-applications discussed in this article.

4. Discussion

The characteristics of the 20 different electronic applications for 3D anatomy that were examined in this study provides a source of information when selecting a suitable anatomy application when three-dimensional visualization is desirable. The non-commercial anatomy e-applications received a higher average score in terms of realism, while the commercial anatomy e-applications received a higher total score on program functionality.

4.1. Realism

The separate ratings by MZ and EK, from which the final realism scores were calculated, did not differ much from each other, the substantial interobserver agreement measurements (Pearson Correlation: 0,895 & 0,919) confirm that. Only a few minor differences were seen which resulted in half points (Battulga et al., 2012; Nowinski, 2017; Temkin et al., 2006; Anatronica; BioDigital; Primal Pictures; Visible Body). A medical student trying to master basic structures of a human body region has less need for a highly realistic, detailed model and may learn more from a simplified model; avoiding details can make it easier for the user to conceptualize the anatomic structures and spaces. However, post-graduate students in a surgical specialty who must process detailed information about a specific body part require a more realistic, detailed 3D model. Another explanation for the difference in realism is the source material and software used to create the 3D models. CT scans from the Visible Human dataset/Chinese Visible Human dataset contain abundant information, which has been converted into realistic 3D models including small visible anatomical structures, using cross-sectional images (Zilverschoon et al., 2017). High-resolution CT scans (Nowinski, 2017) can create even smaller or more detailed anatomical structure representations. A critical question is to what extent the quality can be compromised. With the proper development software and fast computers this can be achieved without too much trouble. Hollow surface models have smaller file sizes than volume models and can be rendered with high resolution textures to create realistic 3D models. Expert software developers with considerable technical insight can assist in creating realistic 3D models with fewer limitations. All commercially available anatomy e-application 3D models and a number of the 3D models (Zilverschoon et al., 2017; Nowinski, 2017; Fang et al., 2017) listed in Table 3 have been developed with assistance of application publishers: a team of expert software developers put to work on creating the e-application, resulting in the creation of realistic 3D models. Given the development of electronic devices over

Table 4
Commercial anatomy e-applications.

Application name	Model realism: simple(1)–realistic (5)	Software aspects				Program functionality								
		Anatomical regions	Operating system	Development date	Costs	Model rotation	Model displacement	Zooming in/out	Clickable structures	Changing transparency	Anatomical information	Virtual dissection	Total program functionality score (0–14)	
Anatronica	1,5	- Nearly all male and female anatomical structures	iPad Android Microsoft Windows Mac OS	Latest version 2017	- Basic version: free - Pro version: \$4.99–\$19.95	1	2	2	2	1	2	1	11	
Biodigital	2,5	- Nearly all male and female anatomical structures	iPad Android Microsoft Windows Mac OS	Latest version 2017	- Basic anatomy: free - Professional grade detail: \$4.00/month	2	2	2	2	1	2	1	12	
Netter 3D Anatomy	2	- Nearly all male and female anatomical structures	Web-based	Latest version 2017	- Basic version: free - Pro version: \$4.99–\$19.95	2	2	2	0	1	0	1	8	
Primal Pictures	3,5	- Nearly all male and female anatomical structures (up to 20 body system modules)	Web-based iPad Android Windows mobile	Latest version 2017	- Student 12 month subscription €95.00 - Non-student 12 month subscription €230,00	2	2	2	2	1	2	0	11	
Visible Body	2,5	- Nearly all male and female anatomical structures	iPad Android Microsoft Windows Mac OS	Latest version 2017	€0.99–€27.99	2	2	2	2	0	2	0	10	
Zygote Body	3	- Nearly all male and female anatomical structures (additional content for paid subscriptions)	Web-based	Latest version 2017	- Lite: free - Premium: \$4.00/month - Professional: \$98.00/month	1	1	2	2	1	2	0	9	
3D4medical	5	- Nearly all male and female anatomical structures (up to 4 body system and 12 body regions modules)	iPad Android Microsoft Windows Mac OS	Latest version 2017	€0.99–€32.99	2	2	2	2	2	2	0	12	

Table 5
e-Applications summary.

Comparative studies/ application name	Complete human body	Model aesthetics: simple(1) –realistic (5)	Total program functionality score (0–14)	Last known update	Costs	Web-based	Microsoft Windows	Mac OS	Mobile
Allen et al. (2016)	No, model of the brain	3	8	2011	Unknown	Yes	Unknown	Unknown	Unknown
Battulga et al. (2012)	No, model of the shoulder	3,5	11	2011	Unknown	Yes	Unknown	Unknown	Unknown
Fang et al. (2017)	Yes	4	12	2015	Free for students	Unknown	Yes	Yes	Yes
Jerath et al. (2011)	No, model of the heart	3	5	2007	Unknown	Unknown	Unknown	Yes	Unknown
Glittenberg and Binder (2006)	No, model of the oculomotor system (eye)	2	3	unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Keedy et al. (2011)	No, model of the abdomen	2	6	2006	Unknown	Yes	Unknown	Unknown	Unknown
Li et al. (2014)	No, model of the brain	3	7	2013	Free	Unknown	Yes	Unknown	Unknown
Lu et al. (2010)	No, model of the thorax and abdomen	3	9	2008	Unknown	Yes	Yes	Unknown	Unknown
Ng et al. (2015)	No, model of the epitympanum (ear)	1	6	2012	Unknown	Unknown	Unknown	Yes	Unknown
Nowinski et al. (2009)	No, model of the brain	4,5	13	2017	Free	Unknown	Yes	No	Unknown
Shin et al. (2013)	No, model of the pelvic and perineum	3	10	2010	Free for students	Unknown	Yes	Yes	Unknown
Temkin et al. (2006)	No, model of the abdomen	2,5	7	2005	Unknown	Yes	Yes	Yes	Unknown
Zilver Schoon et al. (2017)	No, model of the hand	5	14	2017	Unknown	Yes	Yes	Yes	Yes
Anatronica	Yes	1,5	11	2017	- Basic version: free - Pro version: \$4.99– \$19.95	Yes	Yes	Yes	Yes
Biodigital	Yes	2,5	12	2017	- Basic anatomy: free - Professional grade detail: \$4.00/month	Yes	Yes	Yes	Yes
Netter 3D Anatomy	Yes	2	8	2017	- Basic version: free - Pro version: \$4.99–\$19.95	Yes	Yes	Yes	Yes
Primal Pictures	Yes	3,5	11	2017	- Student 12 month subscription €95,00 - Non-student 12 month subscription €230,00	Yes	Yes	Yes	Yes
Visible Body	Yes	2,5	10	2017	€0.99–€27.99	Yes	Yes	Yes	Yes
Zygotte Body	Yes	3	9	2017	- Lite: free - Premium: \$4.00/month - Professional: \$98.00/month	Yes	Yes	Yes	Yes
3D4medical	Yes	5	12	2017	€0.99–€32.99	Yes	Yes	Yes	Yes

the course of the past two decades, it is no surprise more recent models are more realistic and represent more detailed anatomical structures than older models (Temkin et al., 2006; Glittenberg and Binder, 2006). However, even when we compare only the commercial anatomy e-applications, which are all dating from 2017 and based on the same data, we found the realism scores not to be all that high.

4.2. General software details

In most of the studies in Table 3, a specific model of an anatomical region that warrants a high degree of detail was created (either by developers using their own data or by using data from the Visible Human dataset (The Visible Human Project)/Chinese Visible Human dataset (Zhang et al., 2006)), rather than a 3D model of the entire human body (as seen in all e-applications from Table 4). These e-applications of specific anatomical structures were created to develop more effective methods of demonstrating and teaching complex topics for specific educational purposes; those can be useful for medical students who are studying anatomy in this region for specific courses, so creating the remaining parts of the human body was unnecessary. Hence, many developers apparently decided not to create additional models of other parts of the human anatomy. Though most non-commercially available anatomy e-applications run on either Microsoft Windows or Mac OS (mobile devices are not always included), all commercially available e-applications run on both Microsoft Windows and Mac OS, including mobile devices. Web-based access is made available for some e-applications (which allows running the e-application on most systems), but for the remaining e-applications it is still unclear if they will run on every operating system.

And as far as costs are concerned, we see that all non-commercial anatomy e-applications are either free to use or that costs are not indicated (because there are no sales plans), while it is common for the user to pay a (small) amount to use the full version of a commercially available anatomy e-application. Therefore, a limited budget can influence the choice for a final e-application.

4.3. Program functionality

The separate ratings by MZ and EK, from which the final realism scores were calculated, were comparable. The differences in program functionality generally seem to reflect the age differences of the e-applications: those from the last 1–2 years in general have a higher total score on program functionality than e-applications developed in the previous decade; they contain more advanced features, like the facility of changing objects transparency, simple touch/tapping gestures, and identifying structures with virtual pins and performing a virtual dissection. Earlier e-applications more often contained separate instructional videos to explain actions, of which the actions can now be performed by the user. The average total score on program functionality among commercial anatomy e-applications (10.4) is higher compared with the non-commercial e-applications (8.8). Like the realism score, the total score on program functionality among the commercial e-applications varies considerably; apparently not every feature is seen as equally important by the software developers. In general, features like model rotation, zooming and clickable structures do not differ greatly. A bigger difference is seen in both the options of model displacement and to adapt transparency, in which many non-commercial e-applications fall short. These differences could be explained by the level of technical expertise used while creating the e-application: the help of expert software developers can integrate these functionalities to a better extend. Anatomical descriptions are present in most e-applications; both the commercial and non-commercial anatomy e-applications provide a good

amount of anatomical descriptions. As yet, only three commercially available e-applications (Anatronica; BioDigital; Netter 3D Anatomy) allow the user to perform virtual dissection, and still only to a limited extent; in contrast, two non-commercial e-applications (Zilverschoon et al., 2017; Nowinski, 2017) do provide this facility in a more sophisticated way. The difference could be explained by the fact that performing a virtual dissection is seen as a fairly specific feature, which especially can be useful for medical students practicing surgery in this region. This is not the main goal of most anatomy e-applications, so there is no direct need to integrate this feature. One could argue that if an e-application provides the ability to virtually dissect then there may be no requirement for stand-alone changeable transparency (because the user could theoretically achieve the same). However, in the e-applications studied, the presence of these features appeared to be independent from each other (3D4Medical; Zygote Body; Primal Pictures; Fang et al., 2017).

4.4. Recommendation

When properly integrated into medical education (Yamine and Violato, 2015), anatomy e-applications will motivate participants to study a complex anatomical structure (Battulga et al., 2012; Keedy et al., 2011; Estevez et al., 2010). Beerman et al. concluded that 3D imaging significantly improved students' identification of complex surgical liver anatomy (Beermann et al., 2010) and Estevez et al. (2010) showed that 3D physical modeling activity is an effective method for teaching spatial relationships of brain anatomy and will better prepare students for visualization of 3D neuroanatomy.

We used text and 2D figures embedded into a PDF for assessment of the non-commercial e-applications, on the other hand we were able to use the 3D software trial versions for assessment of the commercial e-applications. The latter enable a more detailed evaluation, so this methodological bias made us decide not to compare both groups (commercial versus non-commercial) but to offer guidance in selecting an anatomy e-application for both groups separately.

It is difficult to obtain a proper impression of the functionalities of an anatomical e-application without actually testing it; the total score on program functionality can assist teachers and faculty who consider buying an e-application in deciding on the best choice. If the e-application is used in a general anatomy course, commercially available e-applications generally appear to be satisfactory; all anatomical structures are represented, their total scores on program functionality are above average and they will run on every operating system. In addition to the program functionality score, some other aspects should be considered: the realism of the 3D model, and the costs. The ability to perform a virtual dissection can be of added value as well. When students are required to learn fine details of specific anatomical structures, using one of the non-commercial anatomy e-applications can be interesting (because a commercially available e-applications may be too broad/superficial). For example, in two studies an advanced model of the brain (Nowinski, 2017) and hand (Zilverschoon et al., 2017) was developed that can bring additional information compared to commercially available e-applications in this area. As far as costs are concerned, it can matter whether money can be invested or whether it should remain completely free of charge. The required operating system may also affect the choice to be made; some of the non-commercially available anatomy e-applications basically force the users to either use Microsoft Windows or Mac OS, while all commercially available e-applications allow the user to choose freely. Nonetheless, the number of options of different non-commercially anatomy e-applications is small because in those e-applications the focus was only on specific body regions and it is unclear whether any further development is planned to create additional 3D models.

None of the published studies in which virtual 3D visualizations are tested examined the use of anatomical computer programs or e-applications that are currently commercially available on the market (*Anatronica*, *Biodigital*, *Netter 3D Anatomy*, *Primal Pictures*, *Visible Body*, *Zygote Body*, *3D4Medical*). We argue that materials produced to meet the needs of teachers and students contribute added value for successful implementation. These 3D models also better relate to the clinical context, the content and the educational level, and were developed from authentic material and not specifically adjusted. This helps students to understand that anatomic structures are featured by biological differences and add value to the students' learning process (a significant factor that stimulates learning is reported to be the experience of variation and differences (Cook et al., 2008)). Further development of advanced 3D visualizations should take into account what students find difficult. A valuable next step would be to test the efficiency of the individual e-applications in the students' learning processes and compare them to the total scores on program functionality, in future studies this may be further evaluated and refined for wider applicability. An aspect that can be included as well is whether specific groups of target students (e.g., pre-graduate, postgraduate, resident) value the realism, general software details and program functionalities differently.

5. Conclusion

Virtual 3D anatomy e-applications are increasingly used in anatomy education. Several models have been developed, some of which are commercially available. Although a number of commercially available anatomy e-applications have been released, many educators still develop their own 3D anatomy models tailored to their own needs, only increasing the list of available anatomy e-applications. We compared 13 non-commercial and 7 commercial anatomy e-applications on realism, general software details and program functionality. While non-commercial anatomy e-applications received higher scores on realism and the access of specific software abilities (like performing a virtual dissection), the commercial anatomy e-applications offer a much wider range of anatomical structures available and they performed better on program functionality. Both the realism-scores and the total scores on program functionality score can help future users to make an informed choice among the large number of available e-applications.

6. Future work

Currently there are more anatomical e-applications on the market, many developed by individuals or small companies, which emphasize creating more realistic 3D models than the ones discussed in this review. However, no research data is available of these. So a more critical evaluation of different 3D products is necessary to make an even better and more complete guide for selecting a suitable anatomy application when an additional three-dimensional visualization is desirable.

Authors' contributions

MZ and BE contributed to the initial conception and design of this study, MZ started this project and performed the systematic search together with EK. MZ and EK assembled the tables with different characteristics. MZ wrote the first draft of the manuscript, all authors contributed the concept or design of the study and to the final version of the manuscript.

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