RESEARCH REPORT

ASE

Comparison of 3D Reconstructive Technologies Used for Morphometric Research and the Translation of Knowledge Using a Decision Matrix

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The use of three-dimensional (3D) models for education, pre-operative assessment, pre-surgical planning, and measurement have become more prevalent. With the increase in prevalence of 3D models there has also been an increase in 3D reconstructive software programs that are used to create these models. These software programs differ in reconstruction concepts, operating system requirements, user features, cost, and no one program has emerged as the standard. The purpose of this study was to conduct a systematic comparison of three widely available 3D reconstructive software programs, Amira®, OsiriX, and Mimics®, with respect to the software's ability to be used in two broad themes: morphometric research and education to translate morphological knowledge. Cost, system requirements, and inherent features of each program were compared. A novel concept selection tool, a decision matrix, was used to objectify comparisons of usability of the interface, quality of the output, and efficiency of the tools. Findings indicate that Mimics was the best-suited program for construction of 3D anatomical models and morphometric analysis, but for creating a learning tool the results were less clear. OsiriX was very user-friendly; however, it had limited capabilities. Conversely, although Amira had endless potential and could create complex dynamic videos, it had a challenging interface. These results provide a resource for morphometric researchers and educators to assist the selection of appropriate reconstruction programs when starting a new 3D modeling project. Anat Sci Educ 00: 000–000. © 2013 American Association of Anatomists.

Key words: three-dimensional modeling; reconstructive technologies; anatomy education; anatomy research; decision matrix; digital anatomy; medical education; image segmentation; morphometric research

INTRODUCTION

Since the advent of noninvasive and volumetric scanning devices like computed-tomography (CT) and magnetic resonance imaging (MRI), the use of three-dimensional (3D) computer-generated models for education, pre-operative assessment, pre-surgical planning, and measurement have become more prevalent (Rosse, 1995; Bale and Widmann, 2007; Humbert et al., 2008). Three-dimensional modeling may afford advantages over traditional techniques through complete visualization of complex anatomical morphology (Landes et al., 2006). Traditional two-dimensional (2D) imaging techniques, that involve superimposition or cross-sectional slices, are evolving into 3D modeling techniques, which

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create 3D reconstructed models from 3D volume acquisitions (Rosset et al., 2004).

Three-dimensional models enable more dynamic measurement capabilities, such as surface measurements and contours of 3D morphology, unlike traditional measurements that are linear and are typically taken on 2D scans (Waarsing et al., 2010). In addition, digitally reconstructed 3D models from patient-specific data may afford quantification and visualization of anatomical structures that are specific and unique to the patient (De Paolis et al., 2010).

To accommodate advances in technology, educators are adapting the educational techniques employed to teach health professionals morphology, measurement, and surgical skills. These educational activities are beginning to rely more heavily on the use of 3D models (Rosse, 1995; Bale and Widmann, 2007; Humbert et al., 2008). For learners, 3D models, sometimes termed virtual reality learning objects, may help the conceptualization of structures and their spatial relationships that are difficult to otherwise visualize (Vernon and Peckham, 2002; Trelease and Rosset, 2008). Through the utilization of the same 3D technologies and measurements used in medicine and medical education, the transition of transferring knowledge from clinical practice to learner becomes fluid.

An influx of 3D reconstructive technologies has become available recently, due at least in part, to the prevalence of high-performance computers possessing high processing speeds at a decreased cost (Haas and Fischer, 1997). These programs are developed for all levels of training, from the general public to medical professionals (Gehrmann et al., 2006). A variety of 3D reconstructive software programs have been created for scientific and educational use; however, no program has emerged as the standard. In addition, each program available varies greatly in its approach to reconstruction concepts (surface-rendered and/or volume-rendered), operating system requirements, features, and costs (Haas and Fischer, 1997; Landes et al., 2006).

As a result of the abundance of technologies available, studies have compared available software programs (Landes et al., 2006; Guyomarc'h et al., 2012; Matsumoto et al., 2012). However, no study has evaluated the overall advantages and disadvantages of commercially available medical imaging software programs and their features, such as 3D segmentation tools, measurement tools, and educational features. Amira®, OsiriX, and Mimics® are three programs that are commercially available, relatively cost effective, and commonly used for morphometric research, to build educational tools, and for preoperative assessment and pre-surgical planning (Mahaisavariya et al., 2004; Brandt et al., 2005; Tuan and Hutmacher, 2005; Wang et al., 2007; Kramer et al., 2008; Handzel et al., 2009; Lu et al., 2009; Nguyen and Wilson, 2009; Matsumoto et al., 2012; Qing et al., 2012; Rojas et al., 2012; Kim et al., 2013). Although these software programs have not been systematically compared, other authors have assessed different features of these programs independently. For instance, while examining automatic surface generated models, Guyomarc'h et al. (2012) suggested that Amira-based models were more aesthetically pleasing than those created with a software called TIVMI (Treatment and Increased Vision for Medical Imaging); however, the Amira-generated models yielded lower-precision reconstructions with limited reproducibility. Another study compared manual measurements taken on cadaveric pig knees to the reconstructed models of the same knees produced with OsiriX establishing that the reproducibility of the measurements were very high and the mean differences were negligible (Kim et al., 2012). Matsumoto et al. (2012) compared models of lung vasculature and reported no notable differences in the 3D models created at the segmental level and that all three programs, including OsiriX, were useful as a reference during surgery. One limitation to OsiriX was that the 3D model could not be altered after it was created. Finally, Tuan and Hutmacher (2005) compared Mimics to two other software, CTan and 3D Realistic Visualization, used in conjunction for bone tissue engineering. Mimics exhibited greater degrees of image manipulation, visualization, and editing functions than the other two programs. One disadvantage of Mimics, with regard to finite element modeling (FEM), is its inability to compute various structural bone parameters (used to assess trabecular bone structure) inherently; however, volume meshes are easily exported to be used in FEM software programs.

As suggested by the literature, no comprehensive, nor systematic, comparison of consumer-level reconstructive software exists that informs a wider audience of anatomical researchers and educators. Therefore, the purpose of this study was to conduct a systematic comparison of three widely available 3D reconstructive software programs, Amira, OsiriX, and Mimics, with respect to the software's usability in morphometric research and in education to translate morphological knowledge. Cost, system requirements, and inherent features of each program are compared. A decision matrix was used to objectify the comparisons of usability of the interface, quality of the output, and efficiency of tools. Decision matrices have not been used in comparing 3D reconstructive software programs previously, but may provide a novel method of deciding on a best-suited software program. For this study, two different weighting methods were used to reflect the needs of separate user bases, one to assess the morphometric research offerings and one to assess the educational features. Three-dimensional models can be used for an array of morphometric research and educational tools; this comparative exploration samples, demonstrates, and assesses the inherent features and tools available within each program.

METHODS

3D Reconstructive Programs

Three common software programs were chosen for the study: (1) Amira 5.2 (Mercury Computer Systems, Chelmsford, MA); (2) OsiriX, version 3.6 (Pixmeo, Geneva, Switzerland); and (3) Mimics, version 14.11 (Materialise, Leuven, Belgium). All three programs are widely available, cost effective, and commonly used for anatomical research and educational purposes. Amira generates accurate reconstructions of anatomical structures automatically, semi-automatically, or by manually identifying regions of interest from serial sections. Anatomical models produced in Amira are capable of dynamic interaction and stereoscopic projection. OsiriX was designed for radiologists and developed exclusively for the Mac OS X operating system. OsiriX is an open-source DICOM image processing workstation software. OsiriX is capable of viewing and manipulating digital anatomical data from various imaging modalities and quickly generating volume rendered anatomical structures. Mimics can view and manipulate digital anatomical data from various imaging modalities. The data can be manually segmented or can be generated via volume rendering. Mimics has strong measuring and engineering capabilities that allow users to work directly on the 3D model as well as a wide range of output formats.

The study components using Amira and Mimics were performed on a PC utilizing Microsoft Windows XP (64-bit) operating system (Microsoft Corp., Redmond, WA) with a 2.4-GHz Intel (R) Core (TM)2 Quad CPU (8 GB Ram). The OsiriX software was the 64-bit version on a Mac Pro, OSX, version 10.6.8 (Apple Computer, Cupertino, CA) with a 2 × 3.2 GHz Quad-Core Intel Xeon processors (16 GB Ram).

Decision-Makers

Six anatomists were used as decision-makers in this study. Three of the decision-makers were novices and three were experienced. The novice decision-makers were a diverse group who did not have extensive experience using 3D reconstructive software programs. The first novice decision-maker conducts educational psychology research analyzing skill acquisition in medical students and residents. The second novice decision-maker was a new MSc student who had not yet started research using 3D reconstructive technologies. The third novice decision-maker had extensive knowledge regarding the application of the 3D reconstructive technologies, both for educational and research purposes; however, this decision-maker had never used the programs personally and thus, did not have any technical knowledge of the programs. The other three decision-makers were experienced, with previous involvement conducting one or more morphometric or educational study using at least one of the 3D reconstructive software programs. The first experienced decision-maker has extensive knowledge of the application of 3D reconstructive technologies and has extensive experience creating 3D models and learning tools with Amira. The second experienced decision-maker has extensive experience and technical knowledge of Amira and other 3D programs. The third experienced decision-maker has extensive knowledge in the application of the 3D technologies and has experience conducting morphometric measurements using Mimics and Amira.

Assessment

A decision matrix was used to objectify the comparisons of the three programs by the decision-makers. A decision matrix is a concept selection tool commonly used in engineering (Al-Najjar and Alsyouf, 2003). Decision matrices inform a decision making process by transforming subjective rankings to meaningful scores. The matrix consists of a set of criteria, which are then ranked by decision-makers. The criteria are weighted according to their level of importance in making a decision. Once the decision-maker completes an assessment, the rankings are multiplied by their weighting factor to produce a final score (Müller and Büttner, 1994).

The software programs' websites were used to gather information regarding the available software features and costs; if necessary the companies were contacted. A user assessment form consisting of three sections was developed for the decision-makers to use when ranking the software. The sections were broad categories comprising multiple facets termed "criteria." The three sections included one category looking at the 3D modeling tools overall (10 criteria), and two subcategories that utilize 3D modeling in different ways, measurement tools (7 criteria), and educational features (6 criteria). Each criterion is ranked on a seven-point Likert scale. A seven-point scale was chosen because it provides a more accurate measure of a participant's true evaluation than five-point scales during unsupervised usability questionnaires when the participant must choose a whole number (Finstad, 2010). Each criterion also included a "not applicable"(N/A) box for decision-makers to use if a particular tool or feature was not available. In addition, each part of the assessment had a section for open-ended comments.

An instructional guide was created for each software program. The instructional guide consisted of a series of prescribed tasks for the decision-maker to complete before ranking the criteria. The tasks chosen for the study involved undertakings commonly performed when conducting morphometric research or creating a digital learning tool, such as: building 3D models; segmenting structures; utilizing the available measurement tools; building and exporting dynamic views of the model in the form of a movie (Nguyen and Wilson, 2009). The decision-makers then ranked these criteria based on the process of completing the task and not necessarily focusing on the outcome of the task. Each program's instructional guide outlined the same tasks and differed only by the available features and methodology of each program. Each decision-maker completed the program assessments in a different order to prevent exposure bias in the novice group. The experienced decision-makers also completed the assessments in a different order; however, as these decision-makers had prior experience with at least one of the 3D reconstructive programs available, exposure bias was not a concern.

Once the decision-makers' rankings were completed they were entered into the decision matrix where a weight was applied to the ranking for each criterion to establish the final score. Each criterion had its own weight that was established by classifying the importance of each criterion to each weighting scale: morphometric research weighting scale and educational features weighting scale. For example the measurement tools criteria were classified as important, whereas the educational features and esthetics of a model were classified as unimportant for the morphometric research weighting scale. The importance of each criterion was expressed as a percentage, which became the weight. To determine the final score of each criterion, decision-makers' ranks were multiplied by the weight to calculate the score.

Following analysis of all three programs, decision-makers completed a final questionnaire to evaluate their overall preference of program interface, 3D modeling features, measurement tools, and educational features. The questions were open-ended which allowed the decision-makers to answer freely.

RESULTS

Cost

Table 1 outlines the current market price for all three programs. The basic Amira package costs approximately $5,400.00. For Amira to accommodate large DICOM file data sets that are common in volumetric modeling, the "Amira Very Large Data" option is suggested, which is an additional $6,750.00. An annual maintenance fee of $1,080.00 for the base package and $1,350.00 for the Very Large Data package entitles the user to technical support and new product versions. OsiriX is the least expensive program,

Table 1.

Program Information and Features

	Amira 5.2	Osirix 3.6	Mimics 14.11
Cost	$5,400 Very large data option $6,750	Free for 32-bit $426 for 64-bit	$6,900 MedCad Module $5,175
System requirements	Windows–XP/Vista/7 Mac OS X–10.5/10.6/10.7 Linux	Mac OS X – 10.6 +	Windows – XP/Vista/7
Types of models	Surface-rendered Volume-rendered	Surface-rendered Volume-rendered	Surface-rendered Volume-rendered
Modeling features	Paintbrush, lasso, threshold, magic wand, scissors, contour fitting, interpolation, wrapping, smoothing, morphological filters, opening/closing, operations	Thresholding, grow region, brush, scissors	Thresholding, region growing, boolean operations, cavity fill, edit masks, multiple slice edit, morphology operations
Measurement features	2D and 3D length, angle, annotate, volume	2D length, oval, angle, rectangle, text, open polygon, pencil, point	2D and 3D measure distance, angle, diameter, density in rectangle, density in ellipse, annotations, CAD module objects, re-slicing, density
Educational features	Movie maker, exportation of models, stereo (anaglyph/ polarized)	Fly through (points of interest), exportation of models, stereo anaglyph	Exportation of models
Additional plug-ins/ modules available	Neuro option, microscopy option, developer option, molecular option, mesh option, virtual reality option, very large data option	Open-source software (many 3rd company plug-ins available)	3-matic module

with the 32-bit version available as free-ware and $426.00 for the 64-bit version for a single user. The base program for Mimics is $6,900.00, the MedCad module, which provides the user with more 3D measurement tools, is an additional $5,175.00. The Mimics license is perpetual; however, to receive program updates and program assistance the annual maintenance package is necessary at a cost of $900.00 per year.

Computer System Requirements

Table 1 lists the system requirements for the versions of the programs used in this study. Amira is supported by Windows XP, Vista, and Windows 7, Mac OS X 10.5 and higher, as well as Linux operating systems. OsiriX is a Mac only program and is supported by OS X 10.6 and higher. Finally, Windows XP, Vista, and Windows 7 support Mimics; however, it is recommended to use Windows Vista or Windows 7 with a minimum of 2 GB of Ram (8 GB Ram for large data sets).

Program Features

All programs have multiple features that assist in the creation of 3D anatomical models from a variety of raw data sources, segmentation, performing measurement, and creation of 3D learning tools. The program specificities and main features are outlined in Table 1.

Decision Matrix—Morphometric Research Weighting Scale Results

The morphometric research weighting scale applied greater emphasis to 3D modeling, perceived accuracy, and the availability of various measurement tools that can be applied to the created 3D model. The overall scores, for all criteria, indicate that Mimics is the leading program for morphometric research (Fig. 1). The scores from both the novice decision-makers and the experienced decision-makers were similar.

Examining only the criteria used to evaluate the 3D modeling features of the software both OsiriX and Mimics had high scores, whereas Amira scored lower comparatively (Fig. 2A). Once again, the novice and experienced decision-makers were similar in their scoring; however, the experienced decision-makers scored Amira slightly higher and scored OsiriX and Mimics slightly lower than the novice decision-makers. With respect to criteria questions used to evaluate the available measurement tools, Mimics was scored the highest and both novice and experienced decision-makers scored the programs similarly (Fig. 2B).

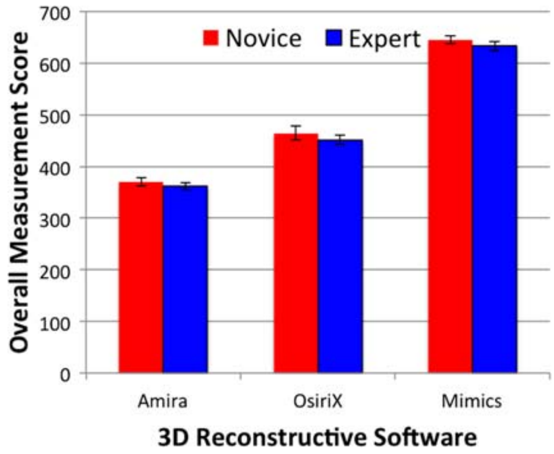

Figure 1.

Overall novice and experienced scores for each 3D reconstructive program using the morphometric research weighting scale ± SD.

Decision Matrix—Educational Features Weighting Scale Results

The educational weighting scale applied a higher emphasis to 3D modeling, ease of use, and available educational features. The overall scores, for all criteria, indicate that OsiriX is the leading program with Amira close behind for building 3D models for learning tools (Fig. 3). The scores from both the novice decision-makers and the experienced decision-makers were similar.

When examining the criteria that sampled 3D modeling features alone, OsiriX and Mimics were scored higher than Amira (Fig. 4A). The novice and experienced decision-makers scored Mimics very similarly, whereas the novices tended to score Amira lower and OsiriX higher than the experienced decision-makers. The measurement tool criteria were classified as having a lower importance and thus were weighted lower in the educational weighting scale; as a result these criteria had lower scores. Similarly to the results found with the morphometric research weighting scale, Mimics scored the highest for measurement tools and the novice and experienced decision-makers scored the programs the same (Fig. 4B). With regard to the criteria questions used to evaluate the programs' inherent educational features, both Amira and OsiriX were scored highly; however, OsiriX had higher scores than Amira (Fig. 4C). Mimics lack inherent educational features and was not rated in this section. Novice decision-makers rated Amira similarly to the experienced users, but rated OsiriX higher than the experienced users.

Open-ended Comments

All decision-makers provided comments on each section: 3D modeling, measurement tools, and educational features. The overarching themes from these comments are summarized in Table 2.

Preference Questionnaire

Overall preference results are shown in Figure 5. When asked which 3D program interface was preferred, four decision-makers (three novice and one experienced) chose OsiriX and two experienced decision-makers chose Mimics. In regards to 3D modeling, one experienced chose Amira, two decision-makers (one novice and one experienced) chose OsiriX, and three decision-makers (two novice and one experienced) chose Mimics as their preferred program. All decision-makers chose Mimics as their preferred program to conduct anatomical measurement. One experienced decision-maker chose OsiriX as the preferred program to create an educational tool. All of the other decision-makers said that they would use a combination of the three programs to create an educational tool. The other combinations were divided by which program the decision-maker preferred to use to create the 3D model and which program the decision-maker preferred for its educational features. These combinations are outlined in Table 3.

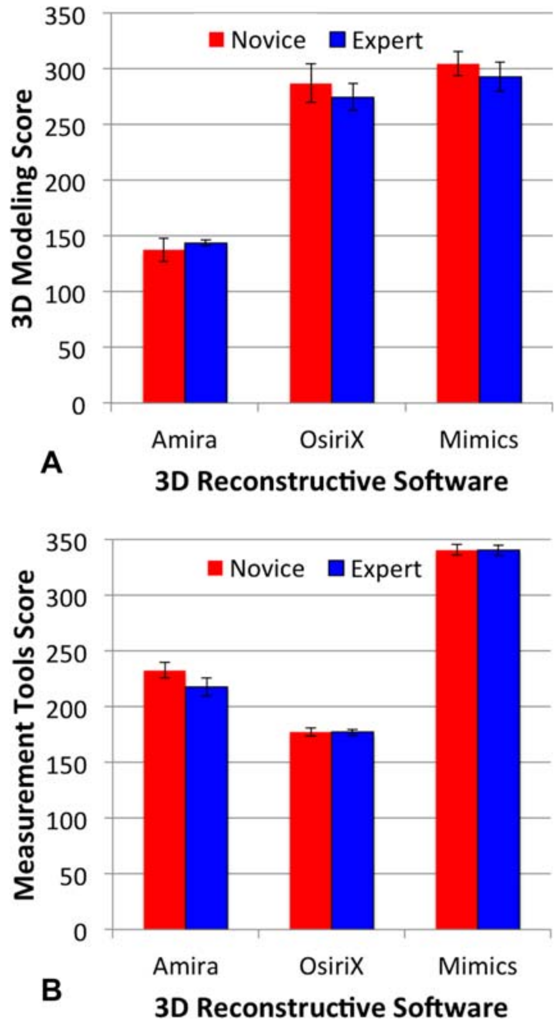

Figure 2.

Novice and experienced scores, for each 3D reconstructive program using the morphometric research weighting scale. (**A**) 3D modeling criteria; (**B**) measurement tools criteria.

DISCUSSION

The purpose of this study was to compare three widely available 3D reconstruction software programs, Amira, OsiriX,

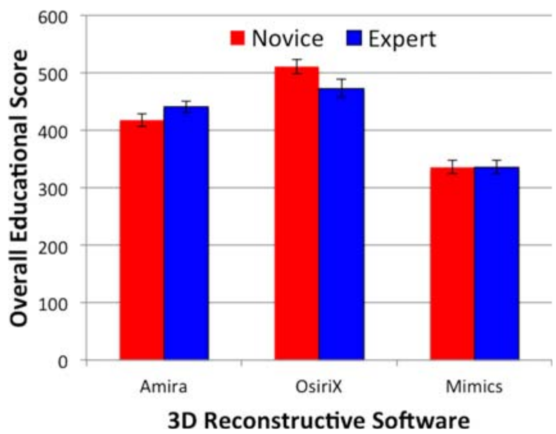

Figure 3.

Overall novice and experienced scores for each 3D reconstructive program using the educational features weighting scale.

and Mimics. Ranking of the software was performed with respect to the software's ability to be used in morphometric research and in education for the purpose of translating morphological knowledge. Each software program was ranked by both an experienced and novice cohort using an approach requiring users to perform specific tasks using standardized instructions tailored to each program.

Program Features

In terms of affordability, OsiriX is the least expensive program, with a free 32-bit version and $426.00 for a 64-bit version. OsiriX is an open-source program and thus third-party individuals can create their own plug-ins to manipulate the program to suit their personal research, clinical, and educational needs; this results in the basic OsiriX program being limited in its features, tools, and abilities. For a researcher or a person designing a learning tool, this may be a limitation, as he or she may want to use the basic program without spending time and effort designing a plug-in. Many third-party plug-ins are available to the public; however, most plug-ins are designed for very specific purposes and often are not suitable for general use. Conversely, Amira and Mimics have similar costs for the base program, have many similar innate features designed to assist in measuring and building 3D models, and Amira also has inherent educational features. Both Amira and Mimics have the ability to add on different options for specific uses at an additional cost.

Decision Matrix—Morphometric Research Weighting Scale

The morphometric research weighting scale placed heavier emphasis on 3D modeling, perceived accuracy of the anatomical model, measurement, as well as the availability and usability of the measurement tools (Table 4). Overall scores from the morphometric research weighting scale (Fig. 1), demonstrate that Mimics scored the highest, with OsiriX coming in second, and Amira scoring the lowest.

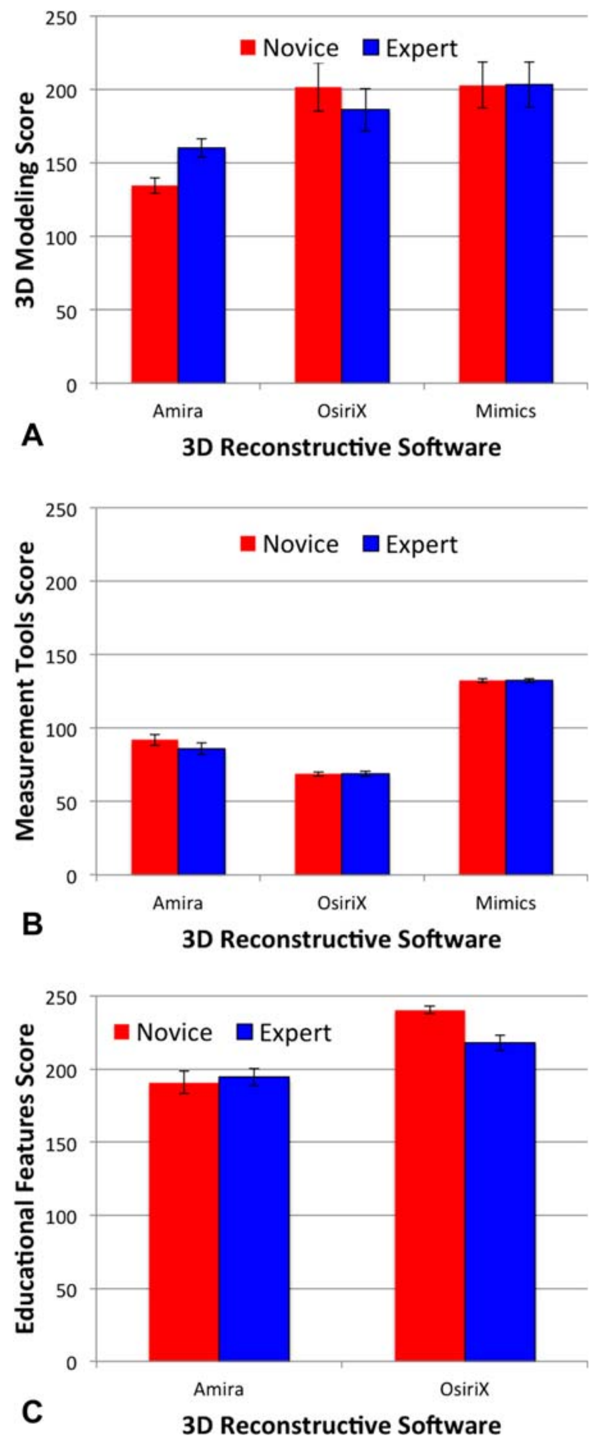

Figure 4.

Novice and experienced scores, for each 3D reconstructive program using the educational weighting scale. (**A**) 3D modeling criteria; (**B**) measurement tools criteria; (**C**) educational features criteria.

Morphometric Research Weighting Scale

3D modeling. The 3D modeling criteria questions, using the morphometric research weighting scale, resulted in Mimics scoring the highest with OsiriX trailing slightly behind (Fig. 2A). Amira scored quite low in this area. Mimics

Table 2.

Decision-Maker Comments Regarding Each 3D Reconstructive Software Program

	3D modeling	Measurement tools	Educational features
Amira	Advantages: -Lots of features and potential -Esthetically pleasing models Disadvantages -Not intuitive: -Time consuming	Disadvantages: -Cannot measure on 2D [data] slices -2D measurements are not bound to model -Seems to be a high error rate in placing 3D measures	Advantages: -High potential for making dynamic movies Making stereo models is easy Disadvantages: -Movie making interface is challenging -Quality of stereo anaglyph models is lower than expected
OsiriX	Advantages: -User friendly -Automated surface- and volume-rendered models are excellent quality and easy to make Disadvantages: -Manual segmentation models (ROIs) have lower than ideal quality -Cannot add material to the automated models	Advantages: -Easy-to-use -Helpful to have reference points that are visible in 2D and 3D Disadvantages: -Cannot perform measurements on 3D model -Limited tool choices and available tools preform simple actions	Advantages: -Easy-to-use -Movie is very smooth Disadvantages: -Stereo anaglyph is harsh -Movie capabilities are very limited
Mimics	Advantages: -Fast -Easy-to-use Disadvantages: -Time consuming to make a 3D model	Advantages: -User friendly -Excellent variety of measurement tools -Ability to map surfaces -CAD objects are powerful for measurements Disadvantages: -Difficult to accurately place measurements in 3D	Advantages: -Educational potential could be achieved with screen capture to demonstrate the anatomical structures -Additionally, the available measurement tools could be utilized to demonstrate clinical techniques and measurements.

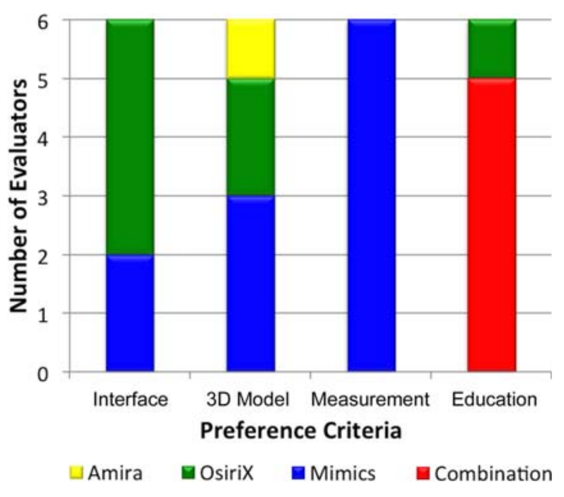

Figure 5.

Final questionnaire preferences regarding program interface, 3D modeling features, measurement tools, and educational features.

scored the highest due to the ease of use of its interface and wide availability of tools for segmenting. Manual segmentation of anatomical structures is time consuming in all programs; however, one experienced decision-maker mentioned that "... [segmenting] in all three programs was cumbersome but I found that Mimics had the best tools to help with the process." These findings are supported by Tuan and Hutmacher's study that found that Mimics afforded a greater degree of image manipulation, visualization, and editing functions, when compared to two other programs used for bone tissue engineering (Tuan and Hutmacher, 2005). OsiriXs high scores in the area of 3D modeling can be attributed to its user-friendly interface, time efficiency, and the high quality of the automatic surface- and volume-rendered models it creates. However, OsiriX did not achieve scores as high as Mimics because of its limited abilities in manual segmentation. Manual segmentation of structures can be achieved, in OsiriX, by creating a region of interest (ROI) model; however, the decision-makers found that these ROI models were lower quality than the automatic volume-rendered models. Another limitation to 3D modeling in OsiriX is that the automated models cannot be altered after they are created. Matsumoto et al. (2012) also found that the inability to alter the 3D model after creation was a major limitation in OsiriX,

Table 3.

Preference Criteria Combinations for Creating an Educational Tool

Decision maker	Build model	Educational features
Experienced 1	Mimics	Amira
Experienced 2	Amira	OsiriX
Experienced 3	OsiriX	OsiriX
Novice 1	Depends on the educational tool being created: (1) Amira for complex movies but interface is not intuitive and exporting is timely; (2) OsiriX for simple movies and exports	
Novice 2	Mimics	Amira or OsiriX
Novice 3	OsiriX	OsiriX for movies; Amira for blue/amber or polarized stereo

Table 4.

Criteria Importance Classification for the Morphometric Research Weighting Scale

Criteria	Morphometric research weighting scale
3D modeling	
Creating a surface-rendered model is easy	6.98
I perceive the anatomical accuracy of the surface-rendered model to be high	8.14
Creating a volume-rendered model is easy	5.81
I perceive the anatomical accuracy of the volume-rendered model to be high	8.14
Overall this software has useful 3D modeling tools for research purposes	8.14
I would use this software to build 3D models for research purposes	8.14
Measurement tools	
Utilizing the 2D measurement tools is easy	6.98
I perceive the 2D measurement tools to be accurate	8.14
Overall this software has useful 2D measurement tools for research purposes	8.14
Utilizing the 3D measurement tools is easy	6.98
I perceive the 3D measurement tools to be accurate	8.14
Overall this software has useful measurement tools for research purposes	8.14
I would use this software for clinical measurement research	8.14

when comparing OsiriX to two other programs, CTTRY and AW, with respect to their characteristics, advantages, disadvantages, and utility in the operating room. Amira's low scores in the area of 3D modeling appear to be due to its non-intuitive interface and the tools and features requiring time to achieve a desired outcome. One decision-maker commented that "[Amira] is useful and does output useful models but its interface and user controls are painstaking and challenging to operate; I would avoid using it despite its output quality." Another decision-maker stated "... the process to come to a surface generated 3D model is long and not intuitive with some steps not well demarcated. These poor work flow ergonomics make it long to get to a suitable/acceptable final product." Thus, due to their user-friendly interfaces and 3D modeling features Mimics and OsiriX scored high in the 3D modeling section of the Morphometric weighting scale; Amira's low scores, on the other hand, were a result of a challenging interface despite model quality.

Measurement tools. Mimics scored the highest with Amira and OsiriX scoring lower in the measurement tools category of the morphometric research weighting scale (Fig. 2B). Mimics' strong score in this area is a result of its variety of available measurement tools and its user-friendly interface. One decision-maker commented that: "the measurement tools are fantastic and not only appear to measure what I want but in some instances encourage new dimensions/perspectives to the data at hand." Another decision-maker commented on a specific measurement tool available stating that: "the ability to map convex and concave [anatomical] structures is invaluable for clinical/research activities." Amira scored quite a bit lower than Mimics but slightly higher than OsiriX. Once again the lower scores were due, at least in part, to the challenging program interface but there were also some comments surrounding the disadvantages of the measurement tools themselves, such as "[not being able to make] measurements on 2D slices is a limitation to research" and "the 3D [measurements], though anchored [unlike the 2D measurements] are ill-representations of anatomical measures as they fail to align with surface contour and are thus, greatly hindered." OsiriX was scored the lowest of the three programs. The decision-makers found that the measurement tools were easy-to-use but that they were limited and only performed simple actions. Another major disadvantage in OsiriX was that the measurements could only be performed on the 2D slices and not on the 3D model itself. Mimics scored higher than OsiriX and Amira, in the area of

Table 5.

Criteria Importance Classification for the Educational Features Weighting Scale

Criteria	Educational features weighting scale
3D modeling	
Creating a surface-rendered model is easy	7.07
Esthetics of a surface-rendered model are pleasing	6.06
I perceive the anatomical accuracy of the surface-rendered model to be high	5.05
Creating a volume-rendered model is easy	2.02
Esthetics of a volume-rendered model are pleasing	1.01
I perceive the anatomical accuracy of the volume-rendered model to be high	1.01
Overall this software has useful 3D modeling tools for educational purposes	7.07
I would use this software to build 3D models for educational purposes	7.07
Measurement tools	
Utilizing the 2D measurement tools is easy	3.03
I perceive the 2D measurement tools to be accurate	3.03
Overall this software has useful 2D measurement tools for research purposes	3.03
Utilizing the 3D measurement tools is easy	3.03
I perceive the 3D measurement tools to be accurate	3.03
Overall this software has useful measurement tools for research purposes	3.03
I would use this software for clinical measurement research	3.03
Educational features	
Quality of the movie function is high	7.07
Utilizing the movie function is easy	7.07
Quality of the stereo capabilities is high	7.07
Utilizing the stereo capabilities is easy	7.07
Overall this software has useful 3D educational features for creating learning tools	7.07
I would use this software to create an educational tool	7.07

measurement tools, because of the variety and versatility of the measurement tools available.

Decision matrix—educational weighting scale. The educational weighting scale was designed to assess the inherent educational features of the program, such as making movies and visualizing models in stereo 3D. Any program that creates 3D models may be used as parts of an educational tool via exporting snapshots or screen capture images; however, for the current study, only inherent movie making and stereo 3D tools were assessed. The educational weighting scale applied a higher emphasis on aesthetics and ease of use (Table 5). Depending on the audience and the learning objectives, a 3D model does not necessarily need to be an accurate representation of the raw data; however, it must appear to be the appropriate anatomical structure and the models must be easy to make for it to be worthwhile for an educator to take the time to create a 3D model as a learning tool. Although the "perceived anatomical accuracy" criterion was given a lower importance classification, it was not removed from the educational weighting scale, because surgical training tools would require high anatomical accuracy. Thus, the necessity for anatomical accuracy depends on the educational tool being created. The educational weighting scale assessment criteria were divided into three categories: 3D modeling, measurement tools, and educational features. The criteria assessing measurement tools were included in the educational weighting scale with a lower importance classification. Measurement tools were included because learning tools created with 3D anatomical models can be used to transfer knowledge of clinical measurements, diagnoses, and treatments, and thus the measurements themselves can be visualized within the learning tool. However, the actual measurements taken on a demonstrative model might be less critical than those used in actual clinical practice. Overall results for the educational weighting scale are displayed in Figure 3. OsiriX scored the highest with Amira trailing slightly behind and Mimics scored the lowest. OsiriX's high scores can be attributed to the program's easy-to-use features and interface. Mimics' low scores likely result from its lack of movie making or stereo 3D functions; however, it was rated high in both the 3D modeling and measurement tool sections. It should be noted that Mimics does have the ability to screen capture and record a video. However, visualization of this recording is only available within the Mimics program itself and exporting of this video would require third-party software to capture it for export.

Educational Weighting Scale

3D modeling. In analysis of criteria pertaining to the evaluation of 3D modeling performance, both OsiriX and Mimics accumulated high scores (Fig. 4A). Both the novice and experienced decision-makers scored Mimics similarly, whereas the novice decision-makers scored OsiriX slightly higher than the experienced decision-makers. Mimics' high scores can be attributed to the program's user-friendly interface and its variety of segmentation tools. OsiriX's easy-to-use interface and the aesthetics of the program's automated surface- and volume-rendered 3D models resulted in high scores in the area of 3D modeling. Because a user cannot manually alter the automated models and the limited manual segmentation/model creation in OsiriX likely attributed to the experienced users bestowing a lower 3D modeling score to OsiriX than the novices. Amira was rated the lowest of all three programs in the 3D modeling section. Although, the decision-makers were pleased with the 3D models created in Amira, the scores dropped due to the challenging segmentation process and interface. The experienced decision-makers rated Amira higher than the novice decision-makers, likely due to previous workflow experience that these users had with Amira and other 3D reconstructive software programs. Similar to Guyomarc'h et al. the decision-makers were satisfied with the aesthetics of the models that Amira creates (Guyomarc'h et al., 2012).

Measurement tools. The results of the measurement tools category of the educational weighting scale mirrored those of the morphometric research weighting scale, with Mimics scoring highest and OsiriX scoring lowest (Fig. 4B). The reasons behind these scores are the same as the reasons described above from the morphometric research weighting scale results. They differ only in the increased or decreased weight based on perceived importance; thus, resulting in lower overall scores.

Educational features. For assessing the programs' inherent educational features, OsiriX scored the highest followed by Amira. Although Mimics was not scored in this section because it lacked inherent educational features, one decision-maker commented on its educational potential; "I think with some creativity and screen capture, the educational value of demonstration with anatomical specimens [created in Mimics] could be achieved. Even more demonstrative would be the wonderful measurements available in this software to both anatomists and clinical colleagues." OsiriX's high scores are attributed to the program's user-friendly interface and easy-to-use movie and stereo functions. Although easy-to-use, OsiriX's movie function is limited by its ability to only record simple actions and its inability to include 2D slices within the recording. In addition, the decision-makers found OsiriX's stereo function to be unforgiving on the eyes. Some of the comments addressed these advantages and disadvantages: "if the generated models made it to the desired quality, the educational and demonstrational possibilities increase as the rapidity and ease of use is high"; "it is easy to create a movie; however, it is very limited in what you can do with the video". Amira's scores were high, but lower than OsiriX's scores. Amira scored high because the program has seemingly unlimited potential in terms of complexity and dynamism of movies and stereo models. However, the scores did not surpass OsiriX's scores due to the challenging interface of the movie-making function. One decision-maker commented on this stating, "this software has boundless potential but the interface challenges are far too great and too frequent to be useful to a researcher, professor, or clinician. Using it is painful. Though final products could be useful in teaching, most educators lack the time investment that understanding this program demands for even basic use."

From the results discussed earlier, the overall program preferences were not surprising. Both OsiriX, with four votes, and Mimics, with two votes, were the programs of choice for interface. For 3D modeling, two decision-makers chose OsiriX, three chose Mimics, and one experienced decision-maker, with prior experience with Amira, chose Amira. All six decision-makers chose Mimics for the preferred program to conduct morphometric research. The preferred program for creating a learning tool was not as obvious. One decision-maker chose OsiriX; however, the other decision-makers did not make a definitive choice, stating they would prefer to use a combination of programs as opposed to a single program. The combinations of programs are listed in Table 3. These combinations tended to avoid using Amira to create the 3D model, due to the challenging interface, and would use either Amira or OsiriX for their educational features depending on the task at hand.

This study aimed to provide a general comparison of the features, usability, and quality of output of three different 3D reconstructive software programs available to a wide set of potential users. Although the assessment was designed to cover the majority of the features required for general morphometric research and learning tool design, it was limited in that it did not include all available features in each program. This study did assess the variety, usefulness, ease of use, and perceived accuracy of the available measurement tools. However, not testing the accuracy or precision of the models and measurements, by reconstructing a model of known dimensions, was a limitation. Previous studies assessing precision and accuracy have compared some of these software programs to other available programs (Guyomarc'h et al., 2012; Kim et al., 2012). Comparing the precision and accuracy of the widely available programs assessed in this study would be an asset; however, that was beyond the scope of this particular study.

CONCLUSION

In conclusion, Mimics was determined to be the best suited for a variety of morphometric research projects. Mimics is user-friendly, creates anatomical models easily, and has a variety of useful measurement tools available. For creating educational learning tools the results were less clear. If the data being used is high quality and can create automatic surface- or volume-rendered models of desired quality, OsiriX could be easily used to develop learning tools. Operators can easily create simple, high-quality movies from 3D representations of anatomical structures. If the learning tool designer is interested in manually segmenting complex structures, wants to create complex dynamic videos, and has time to learn an intricate program, then Amira would be the best choice. This comparison may be used as a resource for morphometric researchers and educators to select the appropriate reconstruction program when starting a new 3D modeling project.

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