1 *Title*

2

3 **Towards an easy generation of scientific three-dimensional models for**
4 **embedding into 3D PDF (Portable Document Format) files**

5
6
7
8
9

10 *Author & Affiliation*

11

12 1. Corresponding author:

13 Name: Axel Newe

14 Affiliation: Chair of Medical Informatics, Friedrich-Alexander-University Erlangen-Nuremberg, Erlangen, Germany

15 E-mail address: axel.newe@fau.de

16

17

18

19

20 *Abstract*

21   The Portable Document Format (PDF) allows for embedding three-dimensional (3D) models and is therefore particularly
22 suitable to exchange and present respective data, especially as regards scholarly articles. The generation of the necessary
23 model data, however, is still challenging, especially for inexperienced users. This prevents an unrestrained proliferation of 3D
24 PDF usage in scientific communication.
25   This article introduces a new module for the biomedical image processing framework MeVisLab. It enables even novice
26 users to generate the model data files without requiring programming skills and without the need for an intensive training by
27 simply using it as a conversion tool. Advanced users can benefit from the full capability of MeVisLab to generate and export
28 the model data as part of an overall processing chain.
29   Although MeVisLab is primarily designed for handling biomedical image data, the new module is not restricted to this
30 domain. It can be used for all scientific disciplines.

31

32 ## *Introduction*

33   Science produces a large amount of three-dimensional (3D) data, especially in the biomedical field. Although the

34 visualization of this data should be 3D as well to avoid a loss of information (Tory & Möller, 2004), almost all contemporary

35 visualization means (paper printouts, computer or television screens) only provide a two-dimensional (2D) interface. This

36 limitation makes it necessary to project the 3D data onto the available 2D plane, which results in the so-called "2.5D

37 visualization" (Tory & Möller, 2004). While there are many technical approaches to overcome this issue (stereoscopy,

38 anaglyphs, head-mounted displays), they all require special equipment and do not eliminate the problem that objects can

39 occlude each other if they lie on the same optical axis. A simple but effective solution is interaction: by changing the angle of

40 a 2.5D projection, depth perception is improved (Tory & Möller, 2004), and masked objects can be brought to sight. Finally,

41 the possibility to interact with the data representation might trigger the consumer's curiosity, which then may lead to a more

42 detailed exploration (Ruthensteiner & Heß, 2008).

43   The Portable Document Format (PDF), which is the de-facto standard for the exchange of electronic documents with more

44 than 500 million users worldwide (Adobe Systems Incorporated, 2014a), is the best way to exchange respective data. A PDF

45 file describes the layout of an electronic document and can comprise all necessary resources for its reproduction without the

46 need of external resources. Although there is a considerable number of publications in this field ((Ruthensteiner & Heß,

47 2008; Danz & Katsaros, 2011; Ziegler et al., 2011; Kumar et al., 2010; Vasilyev, 2010; Quayle et al., 2014; Sharp, 2014) and

48 others), and although even journals encourage authors to embed 3D data directly into their publications (Maunsell, 2010), the

49 usage of 3D-PDF has not yet found its way neither into the publishing routine nor into the clinical routine.

50   One reason might be that the generation of the necessary data can still be challenging, especially for the inexperienced.

51 This constitutes an inhibition threshold, which stands in the way of a further proliferation of 3D PDF usage in science and

52 medicine. In this article, a highly advanced version of a previously described tool for the generation of 3D data for

53 embedding into PDF (Newe & Ganslandt, 2013) is presented. It is available free of charge for all major operating systems,

54 can be used out-of-the-box for biomedical and other science disciplines, and requires no programming skills.

55

56 ## *Background and Related Work*

57 ### *Using 3D PDF for the Exchange of Scientific and Medical Data*

58   The Portable Document Format is a standard (ISO 32000-1:2008, (International Organization for Standardization (ISO),

59 2008)) for the definition and reproduction of electronic documents. It ensures independence from the creating, displaying and

60 printing hardware and software and fulfills all requirements for an interactive document as defined by (Thoma et al., 2010).

61 The specification is freely available and very well documented. Although it is an ISO standard, it can be downloaded and

62 used free of charge (Adobe Systems Incorporated, 2014b; Adobe Systems Incorporated, 2008).

63   The Adobe Reader (http://get.adobe.com/reader/otherversions/) is currently the only 100% standard compliant software

64 that allows to correctly display 3D models (meshes with solid or transparent surfaces, wireframes, line sets and point clouds)

65 embedded into PDF documents and to let the user interact with them (zooming, panning, rotating, selection of components).

66 By means of embedded scripting, animations and interaction with other components (e.g. control elements like clickable

67 buttons) of the respective PDF document are possible. Adobe Reader that is available for free for all major operating systems

68 (MS Windows, Mac OS, Linux).

69 Furthermore, respectively formatted PDF documents are particularly suitable for the representation and exchange of

70 medical data if compliant with the PDF Healthcare (PDF/H) standard published by the Association for Information and

71 Image Management (AIIM) and the American Society for Testing and Materials (ASTM) (Association for Information and

72 Image Management, 2008a; Association for Information and Image Management, 2008b).

73 In addition to that, Supplement 104 (DICOM Standards Committee, Working Group 6, 2005) of the DICOM (Digital

74 Imaging and Communications in Medicine) standard describes how to encapsulate PDF documents into a DICOM data

75 structure, so that they can be stored and exchanged using the appropriate DICOM Service Classes.

76

77 ***3D Model Data***

78 Two different file formats can be used to embed 3D models into PDF: the Product Representation Compact (PRC) format

79 and the Universal 3D (U3D) format. They are not arbitrarily exchangeable since they differ in some features (Visual

80 Technology Services Ltd., 2014a; Visual Technology Services Ltd., 2014b). PRC (Adobe Systems Incorporated, 2014c) is

81 the older format and published as ISO 14739-1 (International Organization for Standardization (ISO), 2012), but U3D seems

82 to have become more popular since it is available as export format for many 3D software tools. The U3D specification is

83 published by the Ecma International as the ECMA-363 (Universal 3D File Format) standard (ECMA International, 2007).

84 There are a number of tools and libraries available for the creation of either PRC or U3D files. Most of them are

85 commercial software, but open source solutions like MeshLab (http://meshlab.sourceforge.net/) are available. However,

86 using these tools needs a considerable amount of training. Furthermore, certain features those are of interest for scientific 3D

87 data like point clouds and line sets (polylines) are often neglected by these tools. Free libraries that provide the full feature

88 range are available, e.g. the Visualization and Computer Graphics Library (http://vcg.sourceforge.net/) or the U3D Reference

89 Implementation Library (http://u3d.sourceforge.net/). Barnes et. al. (Barnes et al., 2013) have presented a comprehensive

90 library that creates PRC data for scientific purposes. The drawback of using such libraries, however, is that they often require

91 programming skills. Furthermore they are only suitable for converting existing 3D data that need to be generated

92 intermediately using another software like Amira (http://www.vsg3d.com/amira/).

93

94 ***MeVisLab***

95 An alternative to 3D data processing applications and libraries is the use of MeVisLab (http://www.mevislab.de/, German

96 web address, but English language) since it combines the advantages of both. MeVisLab is an image processing framework,

97 developed by MeVis Medical Solutions AG and Fraunhofer MEVIS in Bremen, Germany. The core feature of MeVisLab is

98 its module concept: All included algorithms and functions are represented and accessed by "modules", which can be arranged

99 and connected to image processing networks on an intuitive graphical user interface (GUI) following the visual data-flow

100 development paradigm. These networks can then be converted with little effort into complete applications for a convenient

101 re-use. For simple tasks like creating or converting 3D model data, this requires no writing of software code.

102 MeVisLab is available for all major operating systems (MS Windows, Mac OS and Linux,

103 http://www.mevislab.de/download/) and offers a free license for use in non-commercial organizations and research

104 ("MeVisLab SDK Unregistered", (MeVis Medical Solutions AG & Fraunhofer MEVIS, 2014a)). The usage of MeVisLab is

105 explained in its easy-to-understand documentation (http://www.mevislab.de/developer/documentation/). Especially the

106 "Getting Started Tutorial" is recommended for newcomers. It can be accessed via MeVisLab itself (Menu "Help" → "Show

107 Help Overview" → "Getting Started") or as downloadable version (MeVis Medical Solutions AG & Fraunhofer MEVIS,

108 2014b). Further support can be obtained from an active online community (http://forum.mevis.fraunhofer.de/index.php).

109 The current version 2.6.1 of MeVisLab has included more than 1000 pre-defined standard modules. Another 1800

110 additional modules completely wrap the Insight Segmentation and Registration Toolkit (ITK, http://itk.org/) and the

111 Visualization Toolkit (VTK, http://vtk.org/), which makes the total module base very comprehensive.

112

Material & Methods

Creation of an Improved U3D Export Module

115 The standard distribution of MeVisLab comes with the WEMSaveAsU3D module, which is described in detail in (Newe &

116 Ganslandt, 2013). This module is capable of exporting triangular surface meshes to U3D file format and has proven to be

117 suitable for use in reporting of surgery planning results in clinical routine. However, it was limited to triangular meshes –

118 other geometry definitions could not be exported, although U3D allows for embedding point clouds and line sets (polylines)

119 as well. In addition to that, the definition of object model trees was not possible and the specification of object properties

120 (like name, color etc.) was somewhat cumbersome. Finally, the re-use of geometry data for multiple objects was not possible.

121 In order to compensate these shortcomings, a new Module named "SaveU3D" was created. The source code was written in

122 C++ using Microsoft Visual Studio 2010 and contains the full set of constant definitions (e.g. lighting attributes or material

123 attributes) of the ECMA-363 Standard. Although not necessary for the end-user, the code was extensively annotated in order

124 to simplify the understanding and the potential expansion of the implementation.

125 To facilitate the generation of the necessary object definitions, the final module was enriched by a convenience window

126 that allows for an easy assembly of the respective informations. This part was written in the Python programming language.

127

Validation of the New Module

129 The new SaveU3D module was validated against the old WEMSaveAsU3D module and the reference implementation of

130 the U3D standard (http://u3d.sourceforge.net/).

131 Using only features that the WEMSaveAsU3D module already supported (triangle mesh geometry, lighting, cameras), the

132 output files of the SaveU3D and WEMSaveAsU3D were equal.

133 The output files of the reference implementation and the SaveU3D module were binary compatible, i.e. both produced the

134 same geometry models after import into a PDF document.

135

Results

The SaveU3D Module

138 The new module produces ECMA-363 compliant U3D files that contain point clouds, line sets, triangle meshes and meta

139 data annotations. Each object that shall be exported can be specified using a simple description syntax that resembles the

140 well-known Extensible Markup Language (XML) (Figure 1, left). A Specification Generator (Figure 1, right) facilitates the

141 creation of the necessary specifications.

142 While the objects to be exported are specified directly in the GUI of the module, the underlying geometry data must be

143   provided by other modules. This can be modules that load existing data from a storage medium or modules that create the

144   data themselves. This concept gives the user the full flexibility to either re-use data that has been created using other software
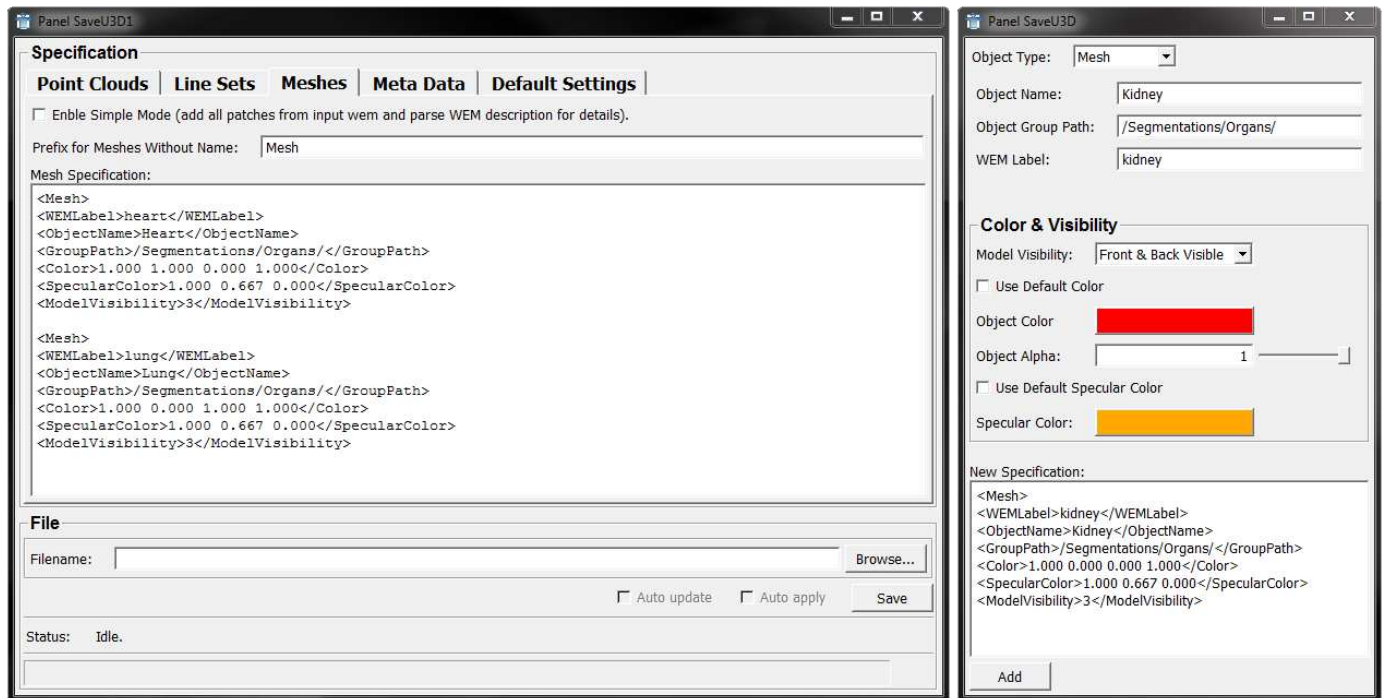
145   or to use MeVisLab itself to generate the data.

147   **Figure 1: Panels (Windows) of the SaveU3D module.** Left: Main panel of the U3D module where the object specifications are entered.

148   Right: Panel of the Specification Generator which facilitates the assembly of valid object specifications.

149

150   *Usage of the Module*

151   MeVisLab novices should read the "Getting Started" tutorial mentioned above to get familiar with the basic concepts of

152   MeVisLab and to learn how to create modules and how to assemble them to networks. Using the module itself requires no

153   programming. It simply needs to be created ("instantiated") using the MeVisLab GUI. A detailed description of the module

154   and its usage is available with the module documentation. An example network that demonstrates all features is also

155   available. The module documentation and the example network can be accessed by right-clicking any instance of a SaveU3D

156   module and selecting "Show Help" or "Show Example Network" from the context menu.

157   Two steps are required to export 3D objects: first, the geometry data must be connected to the inputs of the module, and

158   second, the objects must be specified using the module GUI. The specifications can be entered manually using the XML-like

159   Syntax or by using the Specification Generator. The latter can be opened by right-clicking the module and selecting "Show

160   Window" → "Specification Generator Panel" from the context menu. Deleting unwanted or erroneous specifications can only

161   be done directly in the GUI. The specification syntax is described in the module documentation.

162

163   *Point Clouds*

164   Point Clouds are the simplest type of objects. They only consist of points in 3D space. Therefore, the geometry data only

165   consists of a list of point positions that need to be connected to the "inPointPositions" input of the module.

166

Line Sets

167

Line Sets consist of nodes that are connected by edges. The geometry data must be provided by two lists: the positions of

168

the nodes ("inLinePositions" input) and the description of the edges ("inLineConnections" input), that indicates which nodes

169

(positions) are connected by an edge. The latter list can be omitted – in this case the connections are automatically calculated

170

by simply connecting each node with the next in the list.

171

172

Meshes

173

Meshes are the most complex type of objects since they consist of nodes, edged, faces, and some more attributes.

174

MeVisLab uses the Winged Edge Mesh (WEM) format (Baumgart, 1972) (Baumgart, 1975) to store meshes. Therefore, the

175

geometry data for meshes needs to be provided as a WEM and connected to the "inWEM" input. MeVisLab provides about

176

50 modules for the import, creation, manipulation and visualization of WEMs.

177

178

Availability

179

The source code

180

(http://sourceforge.net/p/mevislabmodules/code/HEAD/tree/trunk/Community/General/Sources/ML/MLPDF/ and

181

http://sourceforge.net/p/mevislabmodules/code/HEAD/tree/trunk/Community/General/Modules/ML/MLPDF/) of the

182

SaveU3D module is available at the MeVisLab Community Sources (http://mevislabmodules.sourceforge.net/), hosted by

183

Sourceforge.net. It is part of the MLPDF project and requires another community project (MLBaseListExtensions). Binary

184

versions of the modules for the current MeVisLab version 2.6(.1) and instructions how to add them to an existing MeVisLab

185

installation are provided as Supplemental S1. Binaries for future releases of MeVisLab can be requested from the author or

186

the MeVisLab community.

187

188

Discussion

189

An Easy-to-Use Tool

190

While the predecessor module WEMSaveAsU3D (Newe & Ganslandt, 2013) was already a big relief compared to other

191

solutions, the new SaveU3D module simplifies the generation of biomedical 3D models for embedding into PDF even

192

further. In addition to that, new geometry model types (point clouds and line sets) can now be exported using MeVisLab in

193

the same simple and user friendly way as meshes.

194

Line sets can be used for the visualization of nervous fiber tracking, vessel centerlines or as pointers to structures of

195

interest. Another use case is the interactive visualization of vectorcardiograms (VCG, Figure 2 and Supplemental S2).

196

Traditional methods of plotting VCGs onto a 2D surface come with an inherent loss of information unless a high number of

197

plots with different viewing angles is presented. Using Adobe 3D PDF technology, only one representation of the VCG data

198

needs to be included in a document and the user herself or himself can find the best way to display the respective graph

199

according to his or her question.

200

Finally, point clouds (or single points) can be used to mark or highlight points of interest (Figure 2 and Supplemental S2).

201

To stay with the example of VCGs: points or point clouds could be used to mark the amplitude values or to set fiducial

202

7

203 markers.
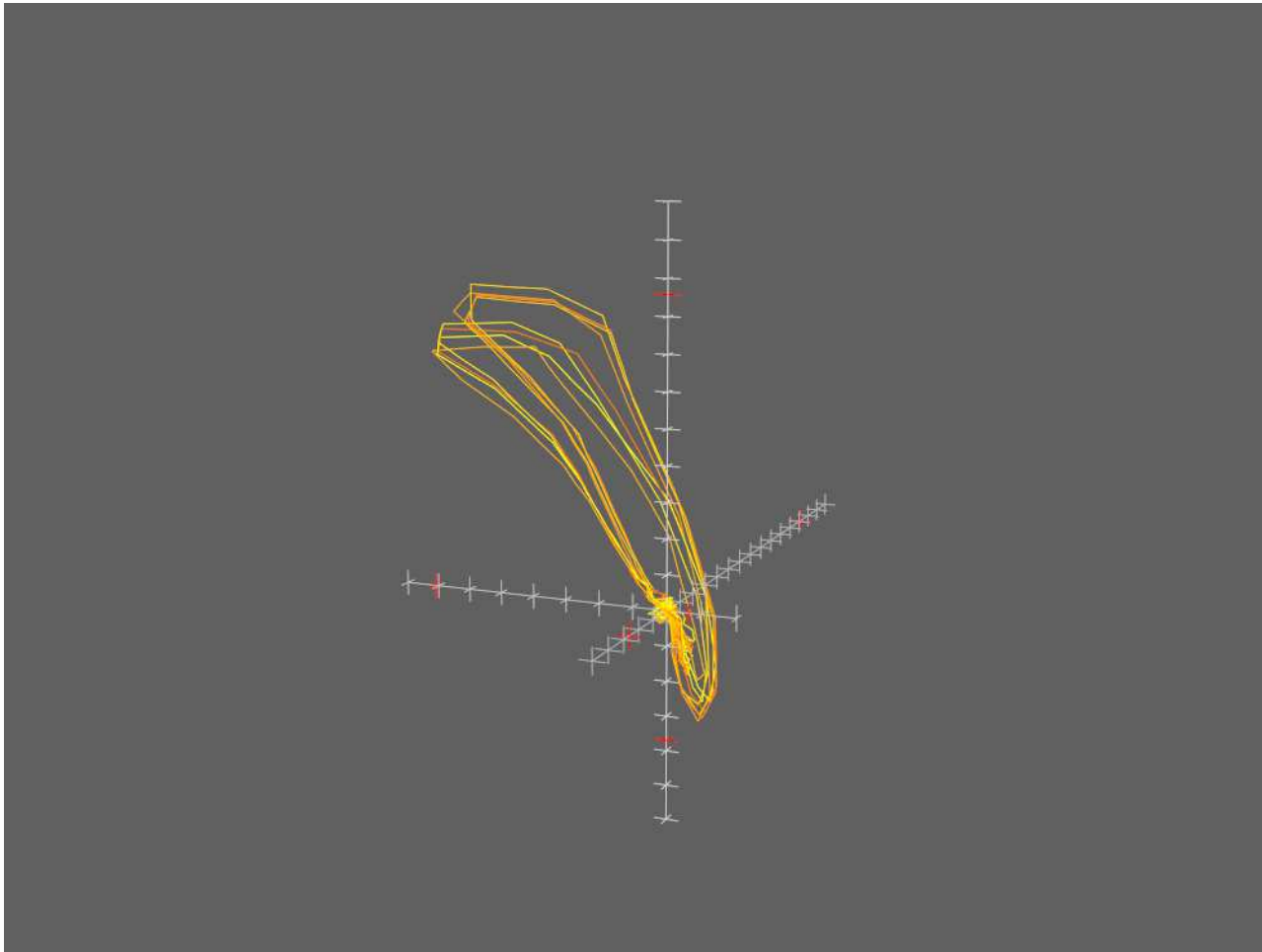
204
205 **Figure 2: Example of a 3D vectorcardiogram exported by SaveU3D module.** Shows an 8-beat vectorcardiogramm with fiducial
206 markers at the x-axis amplitude as displayed in Adobe Reader. A coordinate system is integrated into the 3D scene. **Click the image to**
207 **enable interactive mode**.
208

209   This support for point clouds and line sets is a unique feature of the SaveU3D module for MeVisLab, compared with other
210 integrated tools like MeshLab. Some libraries do support point clouds and line sets (e.g. S2PLOT (Barnes et al., 2013)), but
211 they require programming. The SaveU3D module works "out-of-the-box" and without the need to write any software code.
212 The generation of the geometry data can be handled within MeVisLab or be loaded from external sources, alternatively.
213 Therefore, this solution provides the possibility to make use of both approaches: on the one hand, the SaveU3D module could
214 be used as a simple conversion tool (Figure 3 and Supplemental S3); on the other hand, it can be used as final step in an
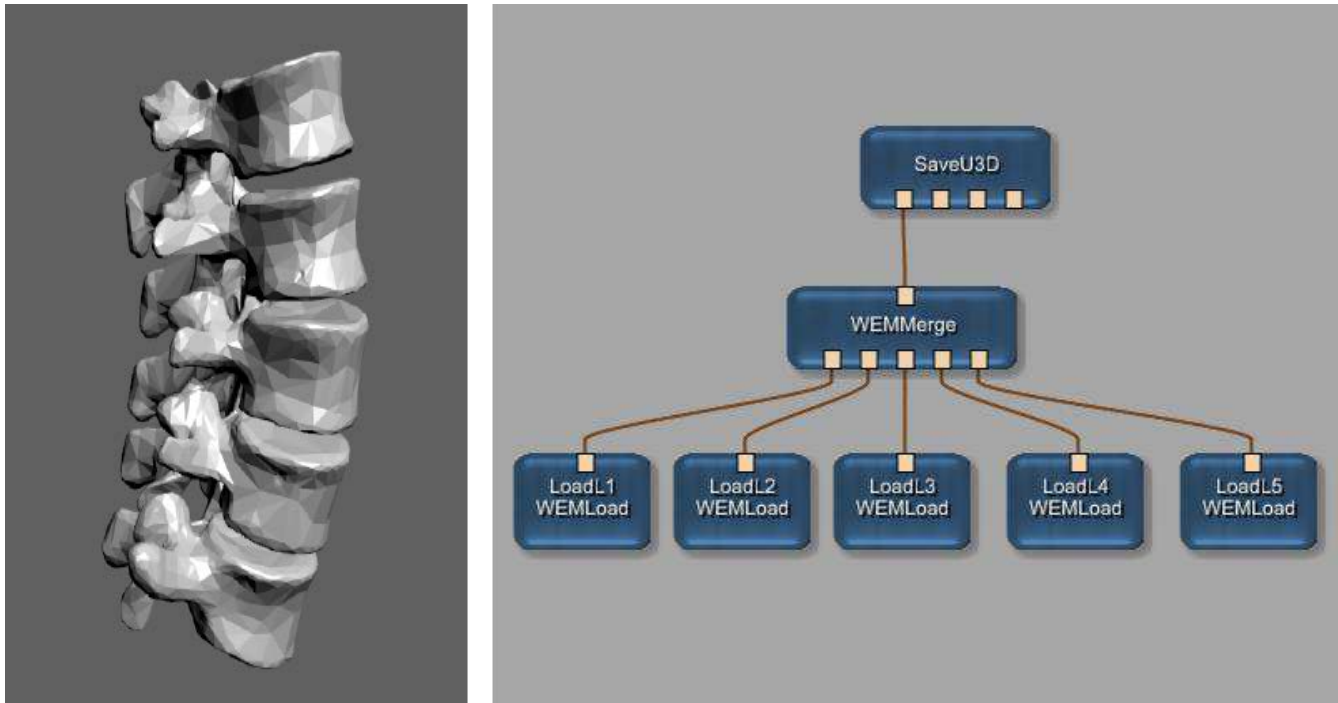215 arbitrarily complex image or data processing pipeline.

PeerJ PrePrints | http://dx.doi.org/10.7287/peerj.preprints.560v1 | CC-BY 4.0 Open Access | rec: 27 Oct 2014, publ: 27 Oct 2014

Figure 3: Example of 3D surface meshes converted by MeVisLab using the SaveU3D module. Left: The exported meshes as displayed in Adobe Reader. Right: The MeVisLab network used to load and to export the five meshes. The original mesh data was downloaded in Wavefront OBJ file format from BodyParts3D, The Database Center for Life Science **(Mitsuhashi et al., 2009)** and is licensed under Creative Commons Attribution-Share Alike 2.1 Japan. **Click the left image to enable interactive mode**.

MeVisLab is available for free and for all major operating systems (Windows, Mac OS and Linux). U3D models produced with the SaveU3D module can be processed by free PDF authoring tools like LaTeX (http://www.latex-project.org/) in conjunction with the media9 package (http://www.ctan.org/pkg/media9) or like the iText library (http://itextpdf.com/) to create the final PDF document.

Ongoing Development

The SaveU3D module will be extended. A major feature that is still missing is the application of textures onto models. Using textures would allow for creating simulated volume rendering visualizations. Although this simulated volume rendering would be limited to a fixed windowing, it would offer a new way of publishing biomedical 3D images.

Unfortunately, PDF does not support another feature of U3D: glyphs. Glyphs could be used to apply label text directly within the 3D scene, but since PDF ignores U3D glyphs, it is not planned to add support for glyph to SaveU3D. However, using textures for labeling objects in the 3D scene can serve as a workaround as shown in (Barnes et al., 2013). Especially PDFs with an educational purpose (e.g. for teaching anatomy to medical students) could benefit from an undoubtful labeling of structures with complex spatial relationships.

Additional Export Formats

SaveU3D is part of the MLPDF project. In the long term, this project shall provide all modules that are needed to create

239 PDF documents using MeVisLab. One of the next steps is the implementation of a module that exports 3D objects in PRC

240 format. Finally, the creation of actual PDF files is on the agenda for future development.

241   Another MeVisLab project deals with the implementation of the DICOM Surface Segmentation Storage SOP Class

242 (DICOM Standards Committee, Working Group 6, 2008). As soon as the respective modules for loading and saving DICOM

243 Surface Segmentation objects are available, the gap between generic DICOM segmentation results and their conversion into

244 files for embedding into PDF will be closed.

245

246   ***Beyond Biomedical Data***

247   Although it is their primary purpose, MeVisLab or the SaveU3D module are not limited to biomedical data. The 3D

248 objects used for Figure 3 could also be representations of rocks from geological sciences or chemical molecules. Lines or

249 point clouds as shown in Figure 2 could be derived from physics models or statistical distributions of any science discipline.

250

251 ## *Conclusion*

252   Modern science in general and the biomedical sciences in particular produce three-dimensional data at an increaing rate.

253 The Portable Document Format provides the means to distribute and visualize this data without the need for additional

254 dedicated software. The new SaveU3D module for MeVisLab presented in this article allows even novice users to generate

255 the necessary file format without requiring programming skills and without the need for an intensive training. Advanced

256 users can benefit from the full potential of MeVisLab to generate and export the model data to U3D as part of the overall

257 processing chain. Only one additional PDF authoring tool is then required to generate the final PDF document. For most uses

258 cases, a replacement of this authoring tool seems not reasonable since the ability to set text layout, process screenshots etc. is

259 an application domain of its own. Therefore, in most cases, the separation of model data generation and PDF authoring

260 cannot be avoided anyway.

261

262 *List of Abbreviations*

263 2D – Two-dimensional

264 2.5D –Three-dimensional reduced to two-dimensional

265 3D – Three-dimensional

266 AIIM – Association for Information and Image Management

267 ASTM – American Society for Testing and Materials

268 DICOM – Digital Imaging and Communications in Medicine

269 GUI – Graphical User Interface

270 ITK – Insight Segmentation and Registration Toolkit

271 PDF/H – PDF Healthcare

272 PRC – Product Representation Compact file format

273 SOP – DICOM Service-Object-Pair

274 U3D – Universal 3D file format

275 VCG – Vectorcardiogram

276 VTK – Visualization Toolkit (VTK)

277 XML – Extensible Markup Language

278

Competing interest statement

279

280 None declared.

281

282

Authors' contributions

283

284 AN engineered the software, conceived the study, drafted and wrote the manuscript.

285

286

Funding

287

288 This study received no funding.

289

290

Acknowledgements

291

292 De-identified VCG data by courtesy of Larisa G. Tereshchenko, Division of Cardiology, Department of Medicine, Johns

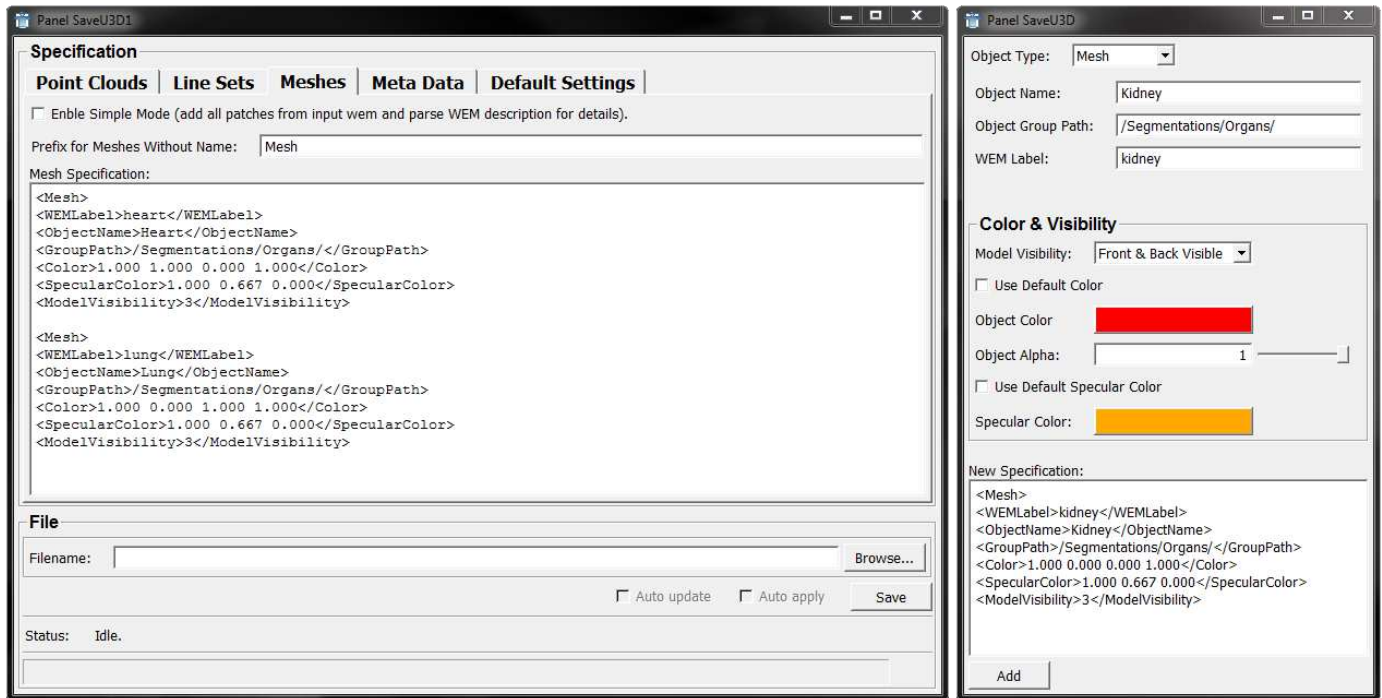293 Hopkins Hospital, Baltimore, Maryland, USA

294

295

References

Adobe Systems Incorporated. 2008. Document management — Portable document format — Part 1: PDF 1.7. *Available at http://wwwimages.adobe.com/content/dam/Adobe/en/devnet/pdf/pdfs/PDF32000_2008.pdf* (accessed: 2014-09-20). Archived at: http://www.webcitation.org/6S8xkrvPw.

Adobe Systems Incorporated. 2014a. Adobe - PDF: The Global Standard For Trusted, Electronic Documents and Forms. *Available at http://www.adobe.com/uk/pdf/* (accessed: 2014-09-20). Archived at: http://www.webcitation.org/6S8mi9nMv.

Adobe Systems Incorporated. 2014b. PDF Reference and Adobe Extensions to the PDF Specification. *Available at http://www.adobe.com/devnet/pdf/pdf_reference.edu.html* (accessed: 2014-09-20). Archived at: http://www.webcitation.org/6S8y0ShjG.

Adobe Systems Incorporated. 2014c. PRC Format Specification. *Available at http://help.adobe.com/livedocs/acrobat_sdk/9/Acrobat9_HTMLHelp/API_References/PRCReference/PRC_Format_Specifica tion/index.html* (accessed: 2014-09-20). Archived at: http://www.webcitation.org/6S91AzPzn.

Association for Information and Image Management. 2008a. AIIM and ASTM International Publish PDF Healthcare Best Practices Guide. *Available at http://www.aiim.org/Research-and-Publications/Standards/Articles/PDF-Healthcare* (accessed: 2014-09-20). Archived at: http://www.webcitation.org/6S8zLCnMW.

Association for Information and Image Management. 2008b. BEST PRACTICES - IMPLEMENTATION GUIDE FOR THE PORTABLE DOCUMENT FORMAT HEALTHCARE. *Available at http://www.aiim.org/documents/standards/PDF-h_Implementation_Guide_2008.pdf* (accessed: 2014-09-20). Archived at http://www.webcitation.org/6QkHzfRns.

Barnes DG, Vidiassov M, Ruthensteiner B, Fluke CJ, Quayle MR, McHenry CR. 2013. Embedding and Publishing Interactive, 3-Dimensional, Scientific Figures in Portable Document Format (PDF) Files. *PLoS ONE*, 8:e69446. DOI: 10.1371/journal.pone.0069446. PMID: 24086243.

Baumgart BG. 1972. Winged edge polyhedron representation. *Available at http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=AD0755141* (accessed: 2013-06-10).

Baumgart BG. 1975. A polyhedron representation for computer vision. In *Proc. of the May 19-22, 1975, national computer conference and exposition; ACM*. 589-596.

Danz JC, Katsaros C. 2011. Three-dimensional portable document format: a simple way to present 3-dimensional data in an electronic publication. *Am J Orthod Dentofacial Orthop*, 140:274-276. DOI: 10.1016/j.ajodo.2011.04.010. PMID: 21803267.

DICOM Standards Committee, Working Group 6. 2005. Digital Imaging and Communications in Medicine (DICOM) Supplement 104: DICOM Encapsulation of PDF Documents. *Available at ftp://medical.nema.org/medical/dicom/final/sup104_ft.pdf* (accessed: 2014-09-20).

DICOM Standards Committee, Working Group 6. 2008. Digital Imaging and Communications in Medicine (DICOM) Supplement 132: Surface Segmentation Storage SOP Class. *Available at ftp://medical.nema.org/medical/dicom/final/sup132_ft.pdf* (accessed: 2014-09-20).

ECMA International. 2007. Standard ECMA-363, Universal 3D File Format, 4th edition (June 2007). *Available at http://www.ecma-international.org/cgi-bin/counters/unicounter.pl?name=ECMA-363_4thedition&deliver=http://www.ecma-international.org/publications/files/ECMA-ST/ECMA-363%204th%20edition.pdf* (accessed: 2014-09-20). Archived at: http://www.webcitation.org/6QkI44nqn.

International Organization for Standardization (ISO). 2008. ISO 32000-1:2008 Document management -- Portable document format -- Part 1: PDF 1.7. *Available at http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=51502* (accessed: 2014-09-20). Archived at: http://www.webcitation.org/6SA93QkzD.

International Organization for Standardization (ISO). 2012. ISO/PRF 14739-1. Document management -- 3D use of Product Representation Compact (PRC) format -- Part 1: PRC 10001. *Available at http://www.iso.org/iso/catalogue_detail.htm?csnumber=54948* (accessed: 2014-09-20). Archived at: http://www.webcitation.org/6S91NLyHc.

Kumar P, Ziegler A, Grahn A, Hee CS, Ziegler A. 2010. Leaving the structural ivory tower, assisted by interactive 3D PDF. *Trends Biochem Sci*, 35:419-422. DOI: 10.1016/j.tibs.2010.03.008. PMID: 20541422.

344 **Maunsell J.** 2010. Announcement Regarding Supplemental Material. *Journal of Neuroscience*, 30:10599-10600.

345 **MeVis Medical Solutions AG & Fraunhofer MEVIS.** 2014a. MeVisLab - Versions and Licensing. *Available at*
346 *http://www.mevislab.de/mevislab/versions-and-licensing/* (accessed: 2014-09-20). Archived at:
347 http://www.webcitation.org/6SA6b5Nv0.

348 **MeVis Medical Solutions AG & Fraunhofer MEVIS.** 2014b. Getting Started - First Steps with MeVisLab. *Available at*
349 *www.mevislab.de/fileadmin/docs/current/MeVisLab/Resources/Documentation/Publish/SDK/GettingStarted.pdf* (accessed:
350 2014-09-20). Archived at: http://www.webcitation.org/6SADXigEF.

351 **Mitsuhashi N, Fujieda K, Tamura T, Kawamoto S, Takagi T, Okubo K.** 2009. BodyParts3D: 3D structure database for
352 anatomical concepts. *Nucleic Acids Research*, 37. DOI: 10.1093/nar/gkn613. PMID: 18835852.

353 **Newe A, Ganslandt T.** 2013. Simplified Generation of Biomedical 3D Surface Model Data for Embedding Into 3D Portable
354 Document Format (PDF) Files for Publication and Education. *PLoS ONE*, 8:e79004. DOI: 10.1371/journal.pone.0079004.
355 PMID: 24260144.

356 **Quayle MR, Barnes DG, Kaluza OL, McHenry CR.** 2014. An interactive three dimensional approach to anatomical
357 description — the jawmusculature of the Australian laughing kookaburra (Dacelo novaeguineae). *PeerJ*, 2:e355. DOI:
358 10.7717/peerj.355. PMID: 24860694.

359 **Ruthensteiner B, Heß M.** 2008. Embedding 3D Models of Biological Specimens in PDF Publications. *Microsc Res Tech*,
360 71:778-786. PMID: 18785246.

361 **Sharp AC.** 2014. Three dimensional digital reconstruction of the jaw adductormusculature of the extinct marsupial giant
362 Diprotodon optatum. *PeerJ*, 2:e514. DOI: 10.7717/peerj.514. PMID: 25165628.

363 **Thoma GR, Ford G, Antani S, Demner-Fushman D, Chung M, Simpson M.** 2010. Interactive Publication: The document
364 as a research tool. *Web Semantics*, 8:145-150. PMID: 20657757.

365 **Tory M, Möller T.** 2004. Human Factors in Visualization Research. *IEEE Transactions on Visualization and Computer*
366 *Graphics*, 10:72-84. DOI: 10.1109/TVCG.2004.1260759. PMID: 15382699.

367 **Vasilyev V.** 2010. Towards interactive 3D graphics in chemistry publications. *Theor Chem Acc*, 125:173-176. DOI:
368 10.1007/s00214-009-0636-7.

369 **Visual Technology Services Ltd.** 2014a. Universal 3D (U3D) Format. *Available at http://www.pdf3d.com/u3d.php*
370 (accessed: 2014-09-20). Archived at: http://www.webcitation.org/6SG7tiwNp.

371 **Visual Technology Services Ltd.** 2014b. PRC 3D Format. *Available at http://www.pdf3d.com/prc.php* (accessed: 2014-09-
372 20). Archived at: http://www.webcitation.org/6SG7yApdZ.

373 **Ziegler A, Mietchen D, Faber C, von Hausen W, Schöbel C, Sellerer M, Ziegler A.** 2011. Effectively incorporating
374 selected multimedia content into medical publications. *BMC Med*, 9:17. DOI: 10.1186/1741-7015-9-17. PMID: 21329532.
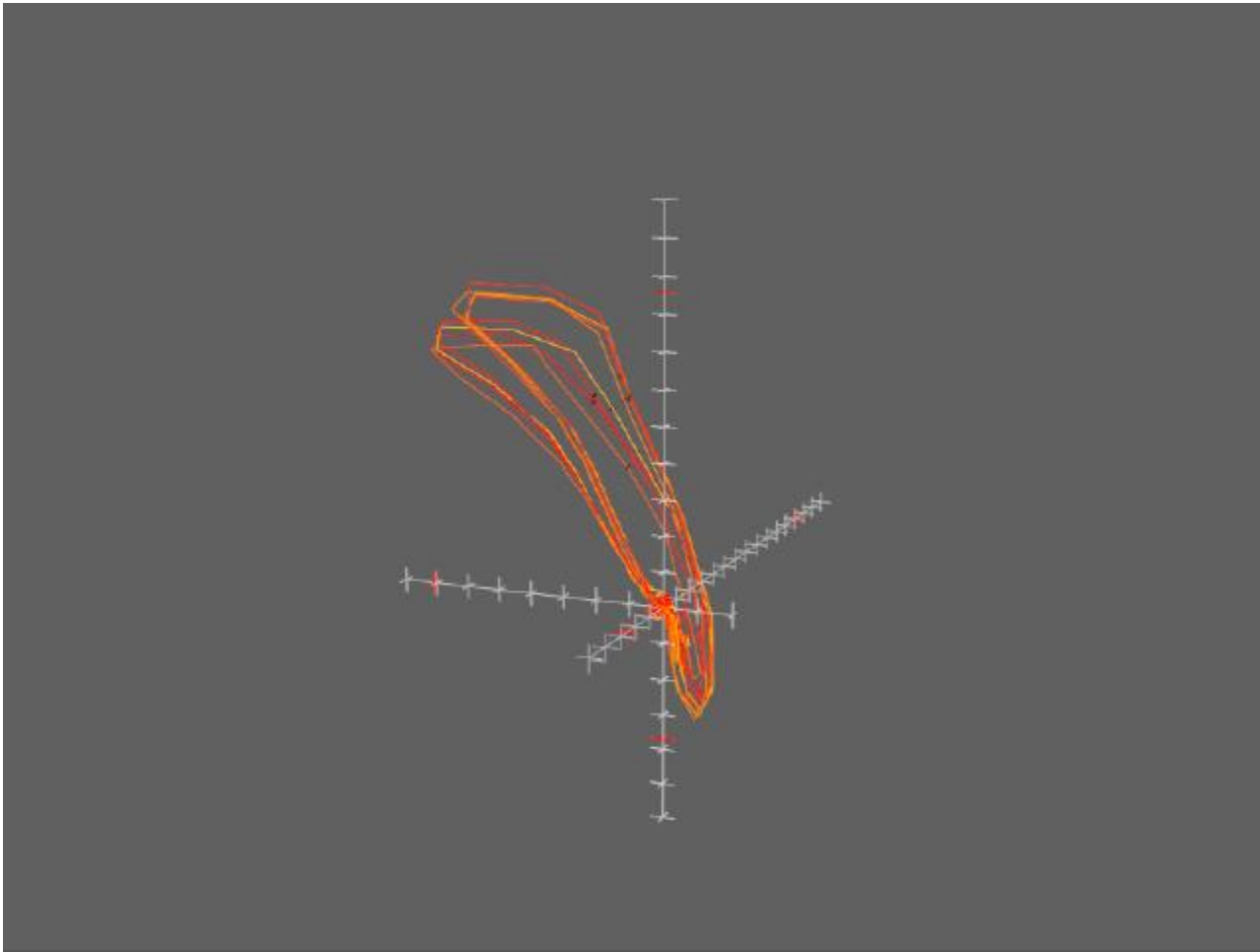
375

376

377　***Figures***

378

379　**Figure 1**

380

381
382
383　**Title**

384　Panels (Windows) of the SaveU3D module.

385

386　**Description**

387　Left: Main panel of the U3D module where the object specifications are entered. Right: Panel of the Specification Generator

388　which facilitates the assembly of valid object specifications.

389

390   **Figure 2**
391

392
393
394   **Title**

395   Example of a 3D vectorcardiogram exported by SaveU3D module.

396

397   **Description**

398   Shows an 8-beat vectorcardiogramm with fiducial markers at the x-axis amplitude as displayed in Adobe Reader. A

399   coordinate system is integrated into the 3D scene.

400

Figure 3
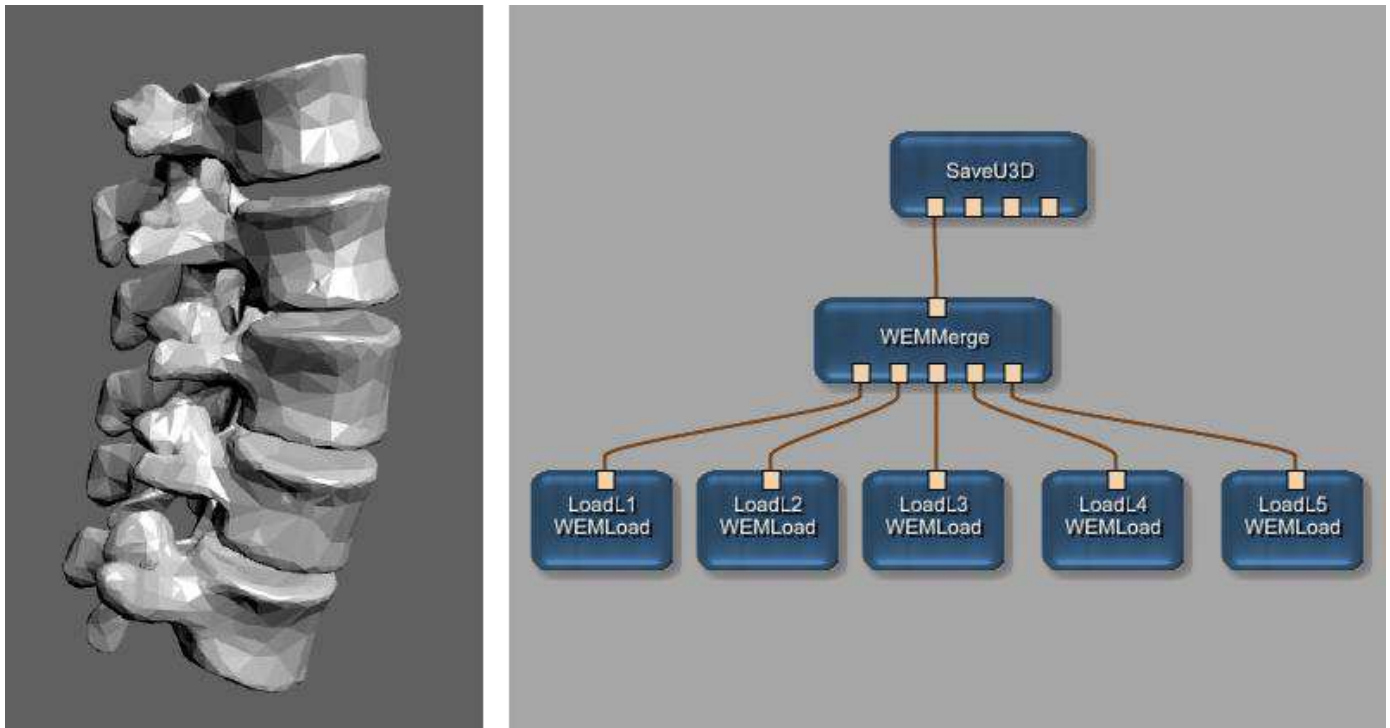
Title

Example of 3D surface meshes converted by MeVisLab using the SaveU3D module.

Description

Left: The exported meshes as displayed in Adobe Reader. Right: The MeVisLab network used to load and to export the five meshes. The original mesh data was downloaded in Wavefront OBJ file format from BodyParts3D, The Database Center for Life Science (Mitsuhashi et al., 2009) and is licensed under Creative Commons Attribution-Share Alike 2.1 Japan.

413 *Supplemental Information*
414
415 **Supplemental S1. "Package.zip".**

416 Binary files, module definition files and installation instructions. Using these files, the SaveU3D module can be added to an

417 existing MeVisLab 2.6(.1) installation without the need to compile the source files.

418

419

420 **Supplemental S2. "VCG-Example.zip"**

421 An example U3D file of a vectorcardiogram and the resulting 3D-PDF.

422

423

424 **Supplemental S3. "Vertebrae-Example.zip"**

425 An example U3D file of a lumbar vertebrae and the resulting 3D-PDF.

426

427