

Research Article

Democratizing Virtual Surgical Planning of Mandibular Reconstruction with Fibular Free Flap: A Feasibility Study Comparing Open Source and Commercial Software

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Abstract

Especially Virtual Surgical Planning (VSP) and Additive Manufacturing (AM) have become indispensable for surgical procedures. VSP allows surgeons to use Digital Imaging and Communications in Medicine (DICOM) images to virtually plan upcoming complex surgeries by using Computer Assisted Design (CAD)/Computer Assisted Manufacturing (CAM) software. It has been shown that preoperative VSP improves surgical accuracy, leads to a faster procedure and reduces surgical costs. Moreso, AM creates the ability to produce patient-specific anatomical models and Surgical Cutting Guides (SCG) which made complex facial surgical reconstructions more predictable. For SCGs and 3D anatomical models, Stereolithographic (STL) data is used. An STL file describes a raw, unstructured triangulated surface by the unit normal and vertices of the triangles using a three-dimensional Cartesian coordinate system.

Keywords: Mandibular reconstruction; Fibular free flap; CAD; Virtual oncological resection

Introduction

In the last decades, several important technological innovations were cemented in the daily clinical practice of Oral and Maxillofacial Surgery (OMFS). Especially Virtual Surgical Planning (VSP) and Additive Manufacturing (AM) have become indispensable for surgical procedures. VSP allows surgeons to use Digital Imaging and Communications in Medicine (DICOM) images to virtually plan upcoming complex surgeries by using Computer Assisted Design (CAD)/Computer Assisted Manufacturing (CAM) software. It has been shown that preoperative VSP improves surgical accuracy, leads to a faster procedure and reduces surgical costs [1-3]. Moreso, AM creates the ability to produce patient-specific anatomical models and Surgical Cutting Guides (SCG) which made complex facial surgical reconstructions more predictable. For SCGs and 3D anatomical models, Stereolithographic (STL) data is used. An STL file describes a raw, unstructured triangulated surface by the unit normal and vertices of the triangles using a three-dimensional Cartesian coordinate system [4]. Anatomical STL files must be accurate because any deviation in the file will cause a deformity of the additively manufactured model and thus induces inaccuracies during surgery [5].

By using VSP and SCGs, mandibular reconstructions with autologous osteomyocutaneous free flaps became more predictable, increased accuracy and resulted in reduced operating time. The autologous osteomyocutaneous Fibular Free Flap (FFF) is the

most frequently used vascularized bone graft for mandibular reconstructions. Alternatives exist such as the Deep Iliac Crest Flap (DCIA) or scapular free flap [6,7]. During surgery, the affected mandibular bone is removed or osteotomized, and replaced with a FFF for functionality, aesthetics, and facial contouring [8]. Not only the bony structures are transplanted but also skin, muscles and blood vessels can be included. SCG are designed on the bony surfaces of the patient and guide the surgeon's saw or drill, immediately obtaining the correct angles and size of the osteotomy parts [9,10].

A major drawback of VSP is the surgeon's learning curve to acquire the necessary CAD/CAM skills, which also entails a large financial educational cost. A second disadvantage is that Commercially Available Software (CAS) packages often come with a considerable price. The price is often determined by the development cost and associated intellectual patents. There are OSF software packages available that can be used for free, but these are unfortunately not always approved for medical use. Due to the open-source nature of these software programs the source code is available for everyone and adjustments or innovative additions can thus be made by the users [11]. CAD/CAM software is often surface based (STL) and based on different mathematical principles (triangle use), making it possible to imitate certain VSP actions with similar CAD techniques. To date, few studies have been conducted into the feasibility of such OSF, in everyday surgical use or as an educational alternative for young surgical residents [5].

In this study, the feasibility of VSP of a mandibular reconstruction with a FFF with open-source software was compared to commercially available software (golden standard).

Materials and Methods

Oncological cases

In this study three consecutive patients with oncologic resection of the mandible and immediate reconstruction with a vascularized FFF were included. All patients were diagnosed with a T4 Oral Squamous Cell Carcinoma (OSCC) with mandibular invasion and received adjuvant radiotherapy. All cases were preoperatively planned with

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Materialise Mimics Innovation Suite 25 software (Leuven, Belgium) by the chief surgeon R.C. The VSP was used as a reference throughout the study. The report adheres to the tenets of the Declaration of Helsinki. Written informed consent of the patient was obtained.

VSP workflow principles in mandibular reconstruction

VSP of the surgical resection and mandibular reconstruction was divided into three categories according to the use of the different software programs: DICOM image segmentation, virtual oncological resection, mandibular reconstruction and design of SCGs (Figure 1).

DICOM images of CT scans consist of Hounsfield Units (HU), which do not contain anatomical information. The segmentation process highlights anatomical regions as Regions of Interest (ROIs) on the DICOM images. These ROIs are then optimized and transformed in STL files. In the case of a mandibular reconstruction with a vascularized FFF, the cranium, mandible and fibula are segmented. After segmentation, virtual anatomical models of the patients are generated and used for VSP. There are two major phases in the mandibular reconstruction planning. Firstly, the osteotomy planes of the oncological mandibular resection determined by the oncological margins (virtual oncological resection). Secondly, the placement and orientation of the FFF in the remaining parts of the mandible (mandibular reconstruction). Finally, patient specific SCGs are designed and manufactured with a 3D printer to transfer the preoperative planning into the operating theatre.

An inexperienced student (B.R.) was trained to use the Materialise software by the surgeons (R.C., M.U.) using available guidelines, hands-on lessons, and visits to the operating theatre in order to better understand the advantages and limitations of the surgery. Afterwards the VSP of mandibular resection and reconstruction with FFF was replicated using OSF.

The CAS (Mimics inPrint®, Proplan CMF® and 3-matic®) is CE marked and FDA approved for medical use. Therefore, the Materialise® software was considered the gold standard in this study. 3D Slicer is an OSF and multi-platform software package widely used for medical, biomedical, and related imaging research [12]. Blender is the OSF and community-driven 3D creation suite [13] (Figure 1). This OSF workflow was converted into a practical guideline and a number of educational videos in order to make this workflow reproducible and thus suitable for education (See supplementary files, <https://www.youtube.com/@rombaut4678>).

Workflow commercially available software-golden standard

Segmentation of DICOM images with materialise mimics Inprint®: Materialise Mimics InPrint® is a software package capable of segmentation of DICOMs which can be converted into STLs following a specific workflow (Figure 2). Based on the gray values in the DICOMs (e.g. Hounsfield units for CT scans) voxels are highlighted and selected by using certain thresholds. In the case of mandibular reconstruction, a threshold of 500 HU-3000 HU is used. After removal of artifacts created after thresholding, the segmented or colored voxels are divided into anatomical structures using the split tool (e.g., cranium, fibula, ...). Finally, the colored voxels (voxel-based) are converted into a shell or surface.

Virtual oncological resection and reconstruction with Materialise ProPlan CMF®: Following the segmentation process, a virtual STL model of the patient was obtained. Materialise ProPlan CMF® uses specific algorithms to virtually osteotomize and reconstruct the mandible. The VSP for a mandibular reconstruction using a FFF is divided, as previously described, in two main steps: osteotomy and reconstruction.

The virtual oncological resection was designed at the defined surgical resection margins on the anatomical parts of the skull. The osteotomies were constructed by planes, determined by three selected points on the mandible. After adaptation of the position and orientation, perpendicular to the mandible, the osteotomies are applied separating the mandible into healthy and oncological parts (Figure 3).

Next, the mandibular reconstruction with FFF is planned (Figure 3). By marking a reconstruction, a line on the osteotomized mandible, the software automatically calculates the dimensions and position of the fibula parts, hereby taking into account the distance to the malleolus process and between the fibula parts. These parts can be repositioned, rotated and vascularization inverted. Visual verification and accuracy towards the original DICOMs are possible as shown in Figure 3.

Design of surgical cutting guides with Materialise 3-Matic®: The design of mandibular and fibular cutting guides follows similar processes. SCGs design follows identical CAD processes (Figure 4). After the virtual oncological resection, the osteotomy planes are defined. The surgeons in this study preferred the use of cutting boxes,

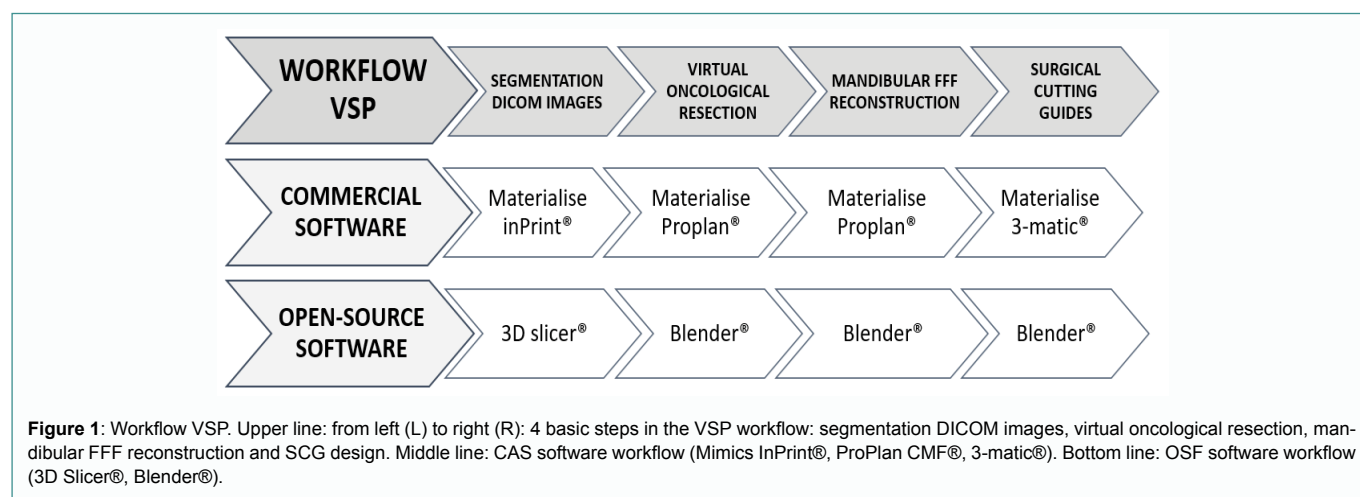


Figure 1: Workflow VSP. Upper line: from left (L) to right (R): 4 basic steps in the VSP workflow: segmentation DICOM images, virtual oncological resection, mandibular FFF reconstruction and SCG design. Middle line: CAS software workflow (Mimics InPrint®, ProPlan CMF®, 3-matic®). Bottom line: OSF software workflow (3D Slicer®, Blender®).

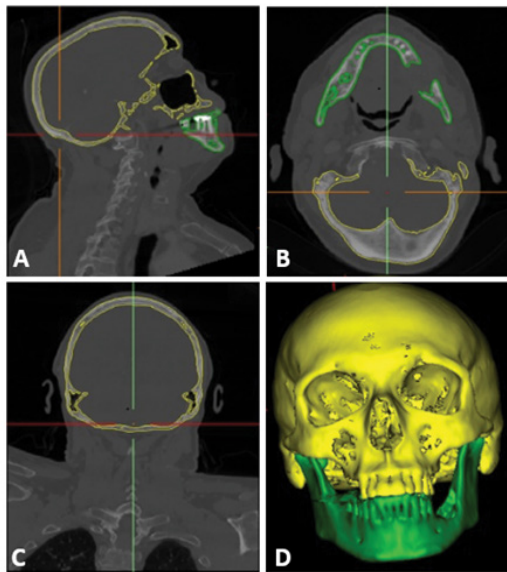


Figure 2: Segmentation using Materialise Mimis InPrint®. In yellow: segmented cranial ROI. In green: segmented mandibular ROI. A) Sagittal view CT scan. B) Axial view CT scan. C) Coronal view CT scan. D) 3D projection of ROI's. On the DICOM images (A-B-C), the borders of the 3D object are represented in the same colors as in the 3D ROI projection (D). (ROI=Region of Interest).

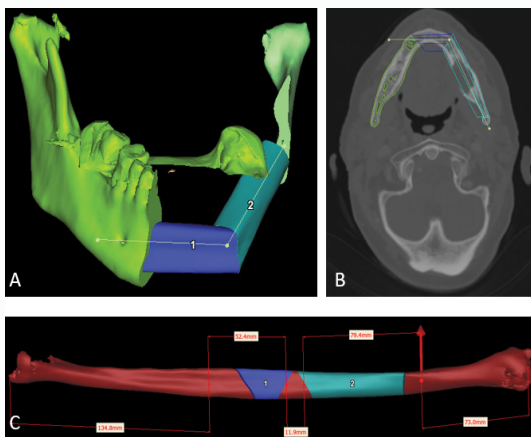


Figure 3: VSP using Materialise Proplan CMF®. A) Virtual representation of the post-operative mandibular reconstruction. In green: the remaining mandible and condyles. In blue: the osteotomized parts of FFF. B) The result of the VSP shown on the axial CT image. C) FFF with projections of two planned osteotomies on the parts to reconstruct the FFF (Remark: the mentioned distances are automatically calculated by the software). In brown: Fibula. In blue: the osteotomized parts for the mandibular FFF reconstruction. (VSP=Virtual Surgical Planning; FFF=Fibular Free Flap).

which were designed by performing a wrap-procedure of 2.0 mm around the defined osteotomy plane. A base plate (thickness of 2.0 mm) was designed respecting anatomical landmarks (mandibular angle, tooth position and/or position of the malleolus). Both the cutting box and base plate were merged and the osteotomy plane and anatomical structures subtracted with a clearance of 0.3 mm.

Workflow open-source freeware

Segmentation of DICOM images with 3D Slicer®: The same principles as mentioned in 2.3.1 adhere to segmentation of the DICOM images in 3D Slicer; however thresholding in this software

needs to be performed manually. 3D models of the fibula, cranium and mandible are created, using the island tool. The scissors tool was used to adjust problematical regions such as connections between upper and lower teeth (Figure 5).

Virtual oncological resection and reconstruction with Blender®: Before virtual oncological resection can be performed, the location of the tumor must be examined on CT images. Therefore, the executor searches for anatomical landmarks on the STL-files (e.g. tooth, mandibular incisura...) for optimal osteotomy plane placement to obtain free oncological margins. The method is comparable to real life surgery. The osteotomy planes are defined by a virtual plate which was positioned and orientated until the correct position for the osteotomy was obtained.

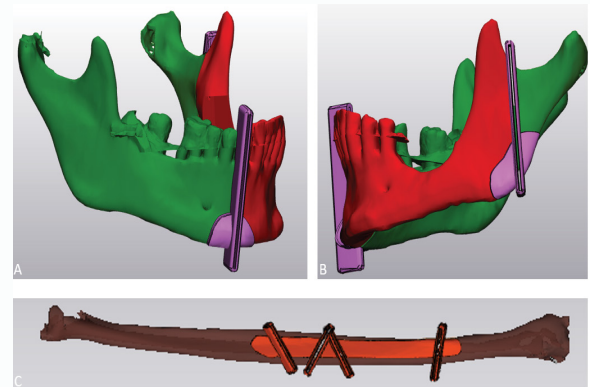


Figure 4: Surgical cutting guides designed with Materialise 3-Matic. In green: 'Healthy' mandibula parts after virtual oncological resection. In red: Oncological resection. In pink: Mandibular SCGs. In brown: Fibula bone. In orange: SCG for fibula osteotomies. A) Right side of the mandibular osteotomy with SCG in place. B) Left side of the mandibular osteotomy with SCG in place. C) Right fibula with SCG (SCG : Surgical Cutting Guide).

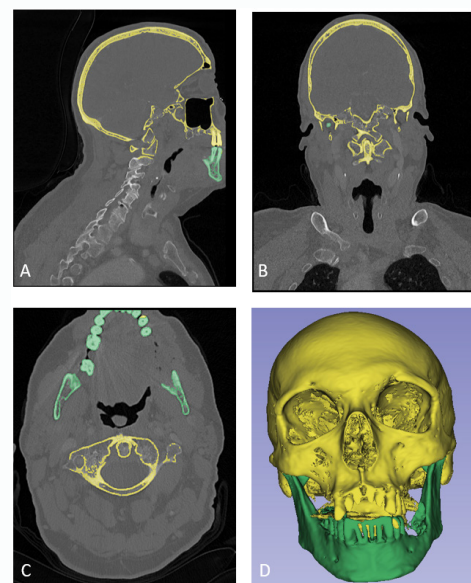


Figure 5: Segmentation using 3D-slicer®. In yellow: segmented cranial ROI. In green: segmented mandibular ROI. A) Sagittal view CT scan. B) Coronal view CT scan. C) Axial view CT scan. D) 3D projection of ROI's. On the DICOM images (A-B-C), the borders of the 3D object are represented in the same colors as in the 3D ROI projection (D) (ROI=Region of Interest).

Following virtual oncological resection, the FFF is positioned in the mandible (Figure 6). Armatures are used to rotate the FFF in the mandible. Armatures are structures to which other objects can be attached. Thereafter, the attached objects (e.g. fibula) can be rotated and moved relative to each other, like a hinge. At the start, line segments are drawn to estimate the armature size. When a correct position of the FFF is found, the cutting planes are added to divide the FFF into segments. Afterwards the FFF segments are rotated back in their original fibular position for the SCG design.

Design of surgical cutting guides with Blender®: The same principles are used for the SCG compared to the CAS workflow (Figure 7). A base plate and cutting boxes using the defined osteotomy planes are created. Using After merging the designed parts the SCGs is subtracted from the corresponding mandibular and fibular parts.

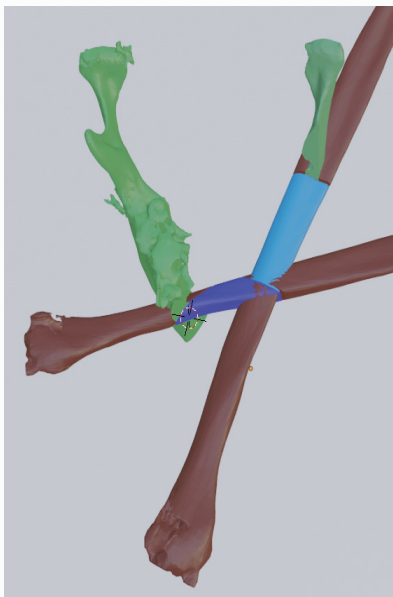


Figure 6: Virtual Surgical Planning (VSP) in Blender. In green: remaining mandible after virtual oncologic resection. In blue: Osteotomized fibula parts positioned into the mandible. In brown: transposed fibula for mandibular reconstruction.

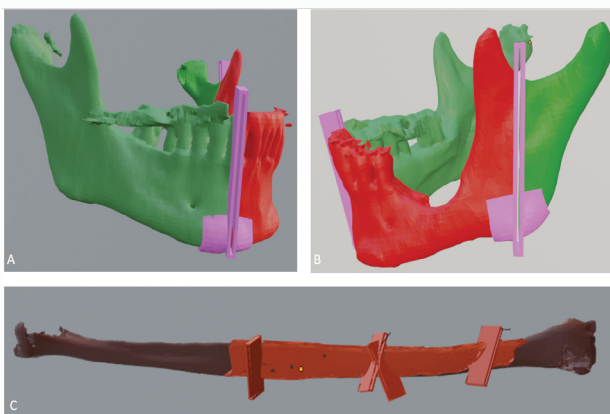


Figure 7: Designed SCG with Blender®. In green: remaining mandible after virtual oncologic resection. In red: oncologic resection. In pink: mandibular SCGs. In brown: Right fibula. In orange: fibular SCG. A) Right side of the mandibular osteotomy with SCG positioned on the corpus. B) Left side of the mandibular osteotomy with SCG positioned on the mandibular angle. C) Right fibula with SCG.

Study design

Five craniomaxillofacial residents, all inexperienced in VSP, received an educational training in VSP with the golden standard CAS (Materialise Mimics InPrint®, ProPlan CMF®, 3-Matic®) software and the OSF software (3D-slicer®, Blender®), using the abovementioned instructional videos, hands-on training and written guidelines from its author (B.R.) (educational session). After one educational tutorial, CMF residents were asked to perform the same VSP independently (performing session). All instructions were available to use during the performing session. The sessions took place in group (5 CMF trainees and 1 instructor (B.R.)) and were organized twice a week (one session OSF and one session CAS on different day), every week during 4 weeks (educational session and 3 performing sessions for the 3 oncological cases).

The educational and performing sessions of the following VSP steps were monitored: virtual oncological resection, mandibular FFF reconstruction, design of SCGs and the overall duration. Due to technical issues (computing power of the available hardware in this study) the duration of segmentation (Mimics InPrint® vs. 3D Slicer) was not taken into account in this study.

The software packages were compared in terms of duration (number of minutes required per step) and efficiency (number of Mouse Clicks (MC)). The duration was measured with a standard stopwatch of an iPhone SE 2020 series (Apple, Cupertino, USA) and the MCs, were tracked and recorded with a digital counter (Click Counter®, SourceForge, San Diego, USA).

Results

Descriptive analysis of oncological cases

Table 1 includes population parameters of the oncological population.

Comparison of virtual oncological resection

As shown in Table 2, a CAS planning session took $8 \text{ min} \pm 3 \text{ min}$ with $163 \text{ MCs} \pm 44 \text{ MCs}$. In OSF, the average performing sessions took $14 \text{ min} \pm 5 \text{ min}$ with 239 ± 104 . The education session took 10 min and 13 min respectively for CAS and OSF.

Comparison of virtual mandibular reconstruction with Fibula Free Flap (FFF)

Table 3 represents the comparison of the mandibular FFF reconstruction in OSF with CAS. Table 3 A shows the duration over the initial educational session and the learning curve over 2 sessions in the performing session. In Table 3 B, the MCs needed to make the reconstruction in both workflows are presented. Table 3 C shows the mean values accompanied by Standard Deviation (SD). The mean time to realize a fibula reconstruction after one educational training session in CAS (Materialise ProPlan CMF®) is $6 \text{ min} \pm 1 \text{ min}$ and takes on average $198 \text{ MCs} \pm 71 \text{ MCs}$. In OSF (Blender®) it takes $45 \text{ min} \pm 10 \text{ min}$ and $715 \pm 315 \text{ MCs}$ to complete the mandibular FFF reconstruction. There was a steep learning curve for OSF (educational session), but in the following performing sessions the duration was

Table 1: descriptive overview of the oncological cases used in the training courses. M: Male; F: Female; OSCC: Oral Squamous Cell Carcinoma; L: left; R: right

Gender	Age	Pathology	Resection	Reconstruction
M	72	OSCC	Corpus + L ramus	Fibula R
M	63	OSCC	Corpus + R ramus	Fibula L
F	75	OSCC	Corpus + R ramus & condyle	Fibula L

Table 2: Virtual oncological resection: comparison of OSF versus CAS A) & B) Histograms comparing the duration and efficiency of OSF and CAS. C) Table with the actual data (mean and standard deviation).

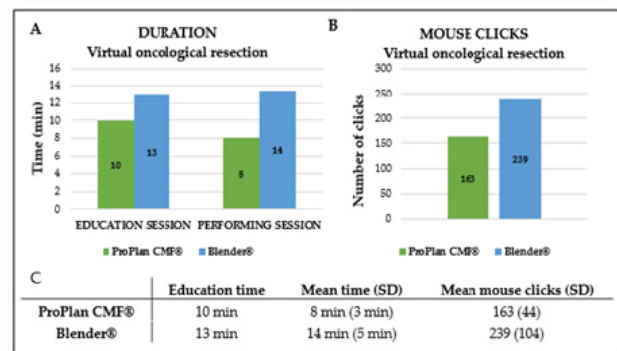


Table 4: Design of SCGs: comparison OSF versus CAS A) & B) Histograms comparing the duration of OSF and CAS. C) Table with the actual data (mean and standard deviation).

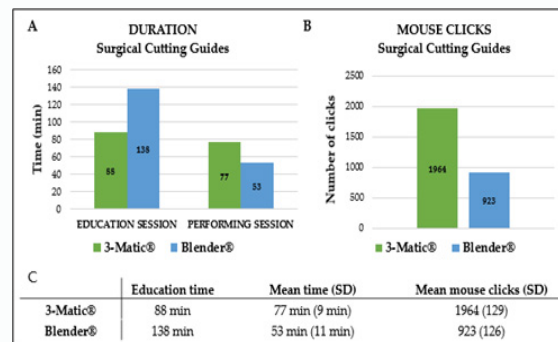


Table 3: Mandibular FFF reconstruction: comparison of OSF versus CAS A) & B) Histograms comparing the duration of OSF and CAS. C) Table with the actual data (mean and standard deviation).

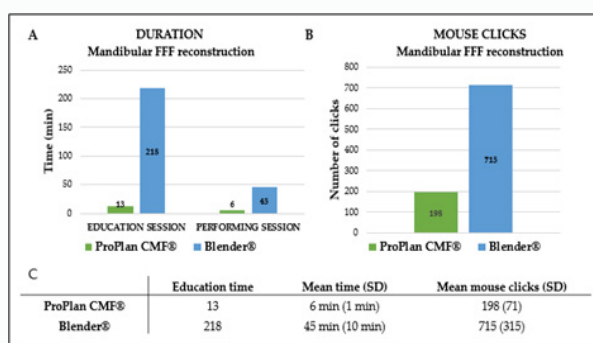
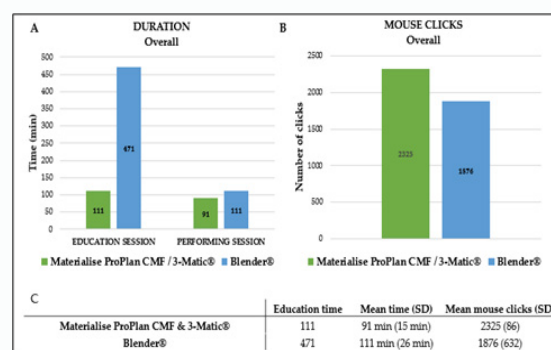


Table 5: Total time comparison OSF versus CAS A) & B) Histograms comparing the duration of OSF and CAS. C) Table with the actual data (mean and standard deviation).



decimated and a difference of 7 minutes was noticed between CAS and OSF.

Design Surgical Cutting Guides (SCG)

Table 4 represents the data comparing the design of SCGs in CAS and OSF. The CMF participants needed 77 min \pm 11 min and 53 min \pm 13 min using CAS (Materialise 3-Matic®) and OSF (Blender®), respectively. The number of MCs was on average 1964 MCs \pm 174 MCs for CAS (Materialise 3-Matic®) and 923 MCs \pm 218 MCs for OSF (Blender®).

Feasibility of the total workflow

Table 5 visually indicates data concerning the total OSF and CAS workflow. On average, it took 91 min \pm 15 min and 2325 MCs \pm 86 MCs for the entire workflow with the golden standard CAS software, as for the OSF workflow, it took 111 min \pm 26 min and 1876 \pm 632 MCs. Although the initial OSF educational sessions took five times the amount of the CAS sessions, CMF residents were able to lower the working time in the following performing sessions to 111 min, compared to 91 min CAS respectively.

Discussion

The current study is one of the first studies to attempt to validate the feasibility between OSF and CAS in mandibular FFF reconstruction. Although the study population is small, these results show that OSF is a feasible alternative for VSP for clinical and educational purposes. In literature, the comparison between VSP and OSF workflows are already described, however, a major disadvantage remains the lack of

thorough guidelines on how these VSP's have been realized [5,14-17].

One article includes tutorial videos on how to perform VSP on mandibular reconstruction with FFF [11]. The current study was able to use an updated OSF version, capable of using more interesting tools leading to more accurate and more predictable VSP. Firstly, an offset could be created during the final subtraction phase of the designed SCG from the anatomical model (e.g. mandible, fibula). The offset ensures a freeway space for mandibular and fibular soft tissues, avoiding pitching. Secondly, this study added educational videos explaining the basic controls of Blender®, giving the user a step-by-step protocol on how to realize SCGs. Thirdly, recent updates added certain novel tools (e.g. 'snapping' tool, 'shrink-wrap' tool) allowing for immediate object fitting to other objects, as such simplifying SCG design in comparison to previous described workflows [11].

The biggest advantage of CAS is the simplicity and speed of the workflow. The use of clear patterns and functions makes the software very intuitive. In comparison, 3D Slicer® is more difficult, and it takes several tutorials to get acquainted. Another main disadvantage is that this software often crashes or shows bugs. The reason of the crashes is that it needs a higher polycount to determine the object leading to bigger file sizes consuming more processing power (CPU and GPU). The lack of 2D verification of the segmentation on the DICOM images in Blender®, is a disadvantage. On the other hand, the obligation to search anatomical landmarks in VSP, is very comparable to real life surgery and obliges the surgeon to not blindly trust the produced SCGs.

During the study, CMF residents needed more time to get used to the control mechanism of Blender and had to learn short keys, leading to a steeper learning curve. Also, the use of hinges and defining the osteotomy planes in the FFF is quite time consuming in the beginning. After the initial educational session, a strong reduction in time spent on mandibular FFF reconstruction and designing time of SCGs.

The general principles for both the OSF and CAS workflow are similar. Blender® proved to be a viable alternative for the design of SCG. But, in general VSP for mandibular reconstruction with FFF leans in favor of CAS. Firstly, in OSF there is a lack of DICOM image verification. Secondly, working with the armatures for the fibula is suboptimal compared to the automatic positioning of CAS. Thirdly, the angles and proportions of all parts are visualized in OSF but making mistakes leads to starting over from step one. This study is the beginning of the exploration of the open-source landscape of programs and its possible benefits in VSP.

Conclusion

This study examines the feasibility of performing a mandibular reconstruction with a fibular free flap using OSF (3D-Slicer® and Blender® compared to a golden standard commercially available software package (Materialise®). Our results indicate that virtual surgical planning with OSF is comparable in terms of duration, but the CAS software package is more efficient and has certain workflow advantages. Further research is necessary to explore the OSF possibilities in resident training and its clinical applicability in order to democratize VSP.

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