Analysing the accuracy of segmented bimaxillary osteotomies with the OrthognathicDistanceCalculator

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Table of Contents

Abstract

In this research, the surgical accuracy of segmented bimaxillary osteotomies is analysed to evaluate the amount of success of this surgical procedure and to give insight in points of improvement. The analysis is done by calculating the differences of teeth positions between a 3D planning and a postoperative 3D model. These differences are analysed with a new method called the OrthognathicDistanceCalculator. The OrthognathicDistanceCalculator is an improved 3D cephalometry method that nullifies the human error present in conventional 3D methods. The error of the OrthognathicDistanceCalculator was calculated to be 0.000000mm, which means that it is 100% accurate.

The analysis was done on 6 patients that all had bimaxillary osteotomies, which included 2- or 3-segmented Le Fort I osteotomies and conventional or Createch fixation plates. The surgeries were done at the University Medical Centre Groningen (UMCG) from 2020 to 2021. The results were obtained from the displacements of the individual segments and the widening of the dentures.

Only one out of six patients had no clinically significant segment displacement and widening differences between the 3D planning and the postoperative 3D model. The low success rate of 16.7% implied that segmented bimaxillary osteotomies are performed rather poorly. Dextral, posterior and inferior displacement seem to be prevalent more often than sinistral, anterior and superior displacement in bimaxillary osteotomies.

Introduction

A proper denture has, besides being an important part of the digestive system, been a representation of youth, health and beauty for centuries [1]. Neanderthalic teeth with scratches on them have been found, which indicate that dental care was already present around 130,000 years ago. The realignment of crooked teeth was first described by Aulus Cornelius Celsus over 2000 years ago, which was done by putting pressure on the teeth by hand [2].

Nowadays, a large part of the population has (had) braces to correct for crooked or misaligned teeth. According to the Dutch Association of Orthodontists, 45% of the Dutch population below 18 years old wears braces [3]. This percentage is very high, because crooked dentures can be detrimental functionally, aesthetically and socially. According to a study done by American sociologist Frances Cooke MacGregor, even small deformities to the dentofacial area can have a large impact on the psychological wellbeing of people [4]. He even concluded that ''defects of the face can be one of the most tragic handicaps a person can have'' [4].

While some people only have crooked teeth, others have anomalies to the bony tissues of the dentofacial area. These anomalies are called dentofacial deformities and can be caused by trauma, or simply be congenital. Dentofacial deformities often lead to malocclusion. Malocclusion is a deformity in which the teeth of the maxilla (upper jaw) and the mandible (lower jaw) do not align properly, such as an overbite, underbite or open bite [5]. Correction of these malocclusions is often required due to the psychological impact and the functional impairment. Whilst small deformities of up to 4mm can be corrected with braces, in more extreme cases orthognathic surgery has to be done [5].

Prior to surgery, clinical observations and measurements of the countenance have to be done and are incorporated in the treatment plan. Often this treatment plan is a combination of presurgical orthodontic treatment, orthognathic surgery and post operational orthodontic treatment. The presurgical orthodontic treatment is done to reposition the teeth optimally with respect to the individual jaw. If the jaws are planned to be repositioned in multiple segments, space between the teeth can be introduced orthodontically to clear the way for the bone saw [5].

Just before the surgery, a CT scan can be made from which a preoperational 3D model can be derived. An intraoral scan is also made and replaces the teeth of the pre operational model to improve the quality of the dentures. A virtual surgery can be done on this 3D model to plan the repositioning of all the bony structures, which results in a 3D planning model. The amount of movement of each segment is documented and the surgeons try to mimic this repositioning as accurately as possible. The surgery is done, and a post operational CBCT scan is made to be able to evaluate the surgery and possibly use the model data for research purposes. Postoperative orthodontics are done to check the occlusion regularly.

Often the premolars are not yet in contact with the premolars of the other jaw which can be corrected with orthodontics [5].

Each case of malocclusion is different, so multiple approaches to correct it are possible. Orthognathic surgery can be done on only the maxilla or the mandible and optionally the chin, but sometimes a combination is necessary to properly correct the dentofacial deformities. An orthognathic surgery where both the maxilla and the mandible are being repositioned is called a bimaxillary osteotomy. A bimaxillary osteotomy consists of multiple surgical techniques namely: a Le Fort I osteotomy is used to reposition the maxilla (in multiple segments), a bilateral sagittal split osteotomy is used to reposition the mandible and an osseous genioplasty can be
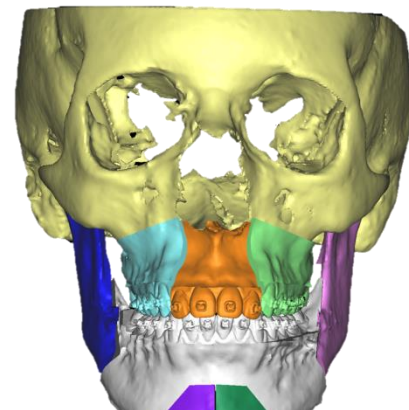

Figure 1: A 3D planning of a segmented bimaxillary osteotomy

used to reposition the chin [5]. In Figure 1, a 3D planning is shown of a segmented bimaxillary osteotomy with the aforementioned surgical techniques.

A splint can be used during the surgery to align the teeth of the maxilla and mandible. It is basically a dental impression that should ensure that the teeth are aligned when the bony segments are cut loose.

Fixation of the bony segments can be done with titanium screws with conventional titanium plates or custom plates like those made by Createch. Conventional plates come in standard shapes and sizes that can be bent by hand during the surgery to fit the specific patient. Createch plates are custom made, based on the 3D planning model to fit the specific contours of the dentofacial structures. The accuracy of these Createch plates has been analysed by Kraeima et al. in non-segmented bimaxillary osteotomies [6].

The accuracy of segmented bimaxillary osteotomies has however not been researched thoroughly. This leaves us with the question: How accurate are segmented bimaxillary osteotomies performed surgically? This question could be answered by figuring out how close the position of the teeth are postoperatively compared to the 3D planning. A lot of researches only look into the accuracy of a surgery, but it is also important to know: How accurate is the used analysation method? This research will be focussed on 2- or 3-segmented Le Fort I osteotomies in bimaxillary osteotomies. The accuracy of the mandible is not being analysed as the large range of motion makes it possible for the mandible to be in different positions while making the CBCT scans. This complicates the analysation of the positional differences.

Evaluating the results of the surgery is important for improvement, especially if the surgery needs to be redone. The only way to do this is to compare the 3D planning model with the post operational 3D model obtained from the pre and post operative CBCT scans respectively. As the goal of such surgical interventions is to relocate the jaws to correct for malocclusion, the position of the teeth are important landmarks to investigate. The differences in mm between the teeth in the 3D planning and the postoperative model can show if the surgery was completed successfully if the accepted clinical significance of <2.0mm established by Proffit et al was achieved [7]. The UMCG however, strives for a more precise error of about 0.5mm.

Currently at the UMCG, a program called ProPlan CMF 3.0 is used to prepare the post operational 3D model and analyse how it differentiates from the 3D planning. Firstly, the DICOM data from the CBCT scan is transformed into 3D models. Secondly, the intraoral scans are superimposed on the lesser quality dentures of the 3D models, which means that the teeth are aligned based on the model surfaces. Thereafter, the preoperational model is segmented to make the 3D planning. Finally, the 3D planning and the postoperative models can be superimposed onto each other by matching the characteristic surface areas of the eye sockets and forehead. This means that the surfaces of the skulls of the 3D planning and the post operational 3D model are in the same position. The distance analysis can then be done by manually drawing lines between the 3D planning and the post operational model, also known as 2D cephalometry. However, the quality of a CBCT scan is not very high as can be seen in Figure 2, thus estimations of tooth positions have to be made. These human errors lead to inconsistent and unknown inaccuracies, which is why a different analysis method should be used.
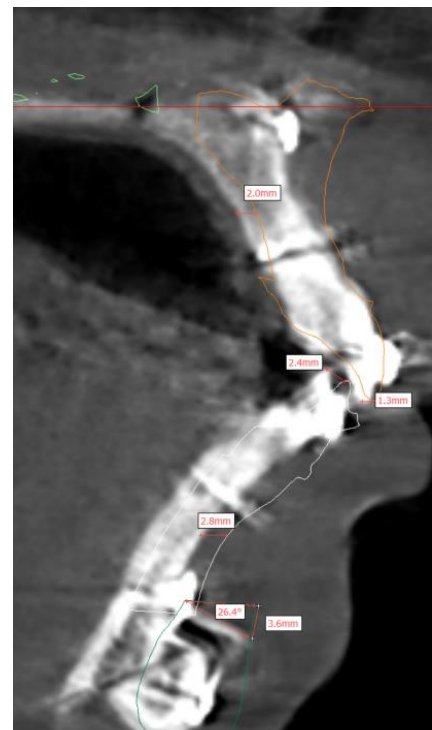

Figure 2: Measurements done in ProPlan

Materials and methods

Requirements and wishes

Before the research could be started, requirements should be drawn up to be able to pick the analysis method. The requirements were:

- The method should be available at the UMCG, meaning that the analysis method is free to use, or a licence to use this analysis method is already in possession.
- The accuracy of the analysis method should be documented or traceable.
- The method should be usable on segmented osteotomies specifically.

There were also some wishes that would be nice to implement. The wishes were:

- The analysis method should be easy to use, so no or a limited amount of training is required.
- The new analysis method should mesh with the currently used model preparation method at the UMCG.
- A full post operational difference analysis should be executed faster with this new analysis method than the method used before.

Literary research

A literary research was done to find a method that can analyse the accuracy of bimaxillary osteotomies. PubMed was used to search for relevant articles and 13 methods were found. These 13 methods were evaluated and categorised on: how they did the superimposition of the 3D models, what the analysis method entailed, the pros and cons of the method, how accurate this method claimed to be, how this method could be applicable for this research, if the described method is publicly available or not and additional comments about the method or article were written down. The overview of this research can be found in Table 1.

Analysed methods

Method	superimposition (surface or voxel based)	Analysis method	Pro's	Con's	How accurate is the method/ are the results?	Applicability in our research	Availability of methods or software	Comments
Orthognathic analyser method on model in Maxilim with voxel based matching technique [8]	voxel based, On characteristics of the skull	Triangle devised out of cephalometric landmarks placed on each bone segment. coordinates translated in orthognaticanalyser to clinically relevant data	user friendly interface results in clinically relevant data. Accuracies known!	surface based matching is better to counteract surface artefacts.	mean error < 0.25 mm correlation coefficients (> 0.97)	Could be used if more cephalometric landmarks are placed as more segments are created	Maxilim: can't find it OGA: 3DMedX requires licence	Usable with surface based superimposition (but less accurate results) Landmark error reduction is key!
Total face approach 3Dcephalometry method [9]	Not specified	linear measurements from axial, sagittal and coronal reference planes to landmarks	Method does not depend on head posture	retrospective allocation	>1.4mm It is not clear if these discrepancies are confident intervals or differences from the mean etc.	Not used to superimpose. Only to do cephalometry	No licence required	Tool used to measure symmetry consistently Method seems to be just a calculation of the occlusal

								plane location.
Regional based voxel registration [10]	voxel based	Trans-formation matrix	excellent accuracy	Only usable for rotational translations	excellent, but not specified what excellent actually means	too little information to be useful	Software unknown	Whole document not available
Matching optimal symmetry plane (MOSP) method [11]	voxel based median plane (OSP)	calculates an optimal symmetry plane by determining the greatest count of paired voxels.	Better results in test group	Does not work with tumours	0.2mm root mean square	Might not be relevant as cases are not planned with OSP method	Software only available for collaborative research	Used pre surgically, not to check afterwards. Tests done between treatment and control group
Tooth moving (MED software, OrthoAnalyze) [12]	voxel based matching	Moving each individual tooth from virtual setup to final outcome and calculate results with algorithm (SARME)	Accuracy method was validated	6 steps necessary for evaluation	0.3mm to 0.48mm accuracy and 7.97 to 10.26 degrees	Could be usable in our research as it also uses STL files	OGA: 3DMedX requires licence	They move every single tooth while the maxillary segments should remain the same

combination of ITK-snap & 3D Slicer [13]	Voxel based, matched on grayscale values in ITK-Snap	navigation axial slicer in ITK-snap and evaluation of transparent overlays in 3D Slicer software	Voxel based (can be automated), free to use, colour coded maps available	Training required, takes 3 hours i.s.o. a few minutes	unclear	Training might be too laborious to integrate in this research	ITK-snap and 3D Slicer are both free open source programs	3D Slicer might be an interesting tool to take into consideration.
OnDemand3D [13]	voxel based	Measuring distances on the sagittal planes in Ondemand3D	analysis is easy to do	Licence	unclear	Can be used easily but you'll never be certain about the accuracy	OnDemand3D requires a licence	Does not seem to pose any benefits over using Proplan3D
combination of OnDemand3D, 3D Slicer and ShapePopulation Viewer [13]	voxel based	Colour map based on Euclidean distances	colour map uses scalars and vectors colour maps		Not clear, ShapePopulation Viewer was used for the calculations.	Using colour coded maps might be great to evaluate T2	OnDemand3D requires a licence, 3D Slicer is free, ShapePopulation Viewer is a free extension of 3DSlicer	We might be able to use Proplan3D to do the superimposition and 3D Slicer/SPV for a codemap Need vtk files for this

CT stability assessment VSA assessment [14]	Voxel based	VBR transformation matrices	colour maps used	not clear how to do this	excellent 0.44mm	Used in 3 piece Le Fort I osteotomy	Software unknown	method/ software not clear at all
Comparison of surface and voxel based registration in Mimics [15]	voxel and surface based	CT Bone Wizard	Surface based was more accurate!	Analysis method unclear	surface-based registration error was clinically irrelevant (1.83% and 0.18 mm), voxel-based registration error was clinically relevant (5.44% and 0.52 mm).	Only relevant to find out what might be a better superimposition method	Mimics requires licence	No comments
Evaluation of surgical-orthodontic treatment [16]	Multiple	Review of multiple analysis methods	A lot of options to choose from	Only show study accuracy, not the analysis methods	>4 degrees and >2 mm except for gonion.	Not relevant. Only show that studies are accurate, not why.	Unknown as multiple unknown programs were used	No comments
ProPlan CMF 3.0 used at the UMCG	surface based matching	Measuring distances and angles by hand in Proplan3D	Easy to do	Expensive licence	human error, unclear	Can be used easily but you'll never be certain about the accuracy	Licence is available	No way to validate results in ProPlan

A 3-Dimensional Approach for Analysis in Orthognathic Surgery— Using Free Software for Voxel-Based Alignment and Semi-automatic Measurement [17]	voxel based matching	3D slicer and ITK snap	free	Should take a lot of time	Really accurate! <0.1mm and 0.1 degrees	Useful if proplan licence is not available	free software	No comments

Table 1: An overview of the methods that were researched in the analysis method

Chosen method

ShapePopulationViewer

The method suggested by Dot et al. was chosen to do the analysis with [13]. They suggested using the free programs called ITK-Snap and 3D-Slicer for the analysis. They made a full video series in which step-by-step tutorials explained how to use this method. An extension in 3D Slicer called ShapePopulationViewer allows the user to visualise the differences between the 3D planning and the post operational 3D model in a colourmap as can be seen in Figure 3.
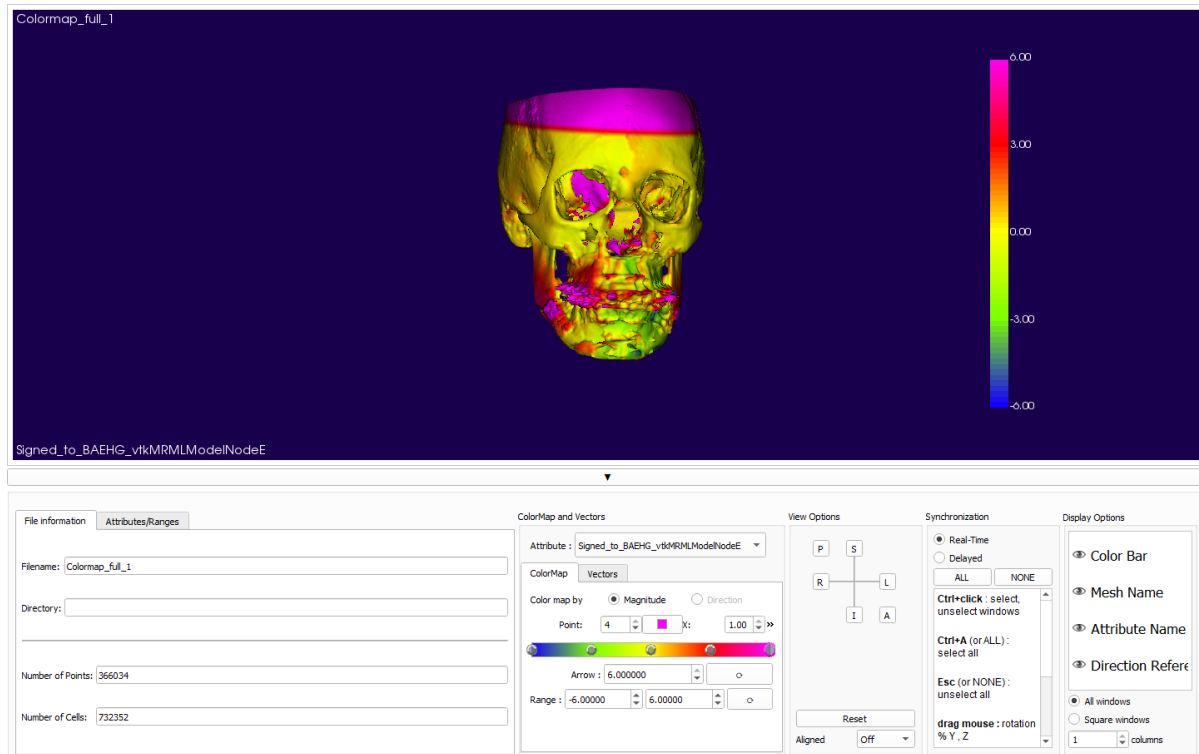

Figure 3: A colourmap made in ShapePopulationViewer

The option to visualise the data and the fact that the program was free to use, were the main reasons that this method was chosen. In the proposed method ITK-Snap was only used for the preparation of the 3D models and the analysis was done with ShapePopulationViewer. This method does deviate quite a bit from ProPlan, as ITK-Snap uses voxel based registration to superimpose the models, which has shown to be less accurate than surface based matching, also used in ProPlan [15]. The preparation of the 3D models also takes a staggering 3 hours per patient in ITK-Snap, as opposed to about half an hour in ProPlan. Since ShapePopulationViewer cannot differentiate between the methods used to superimpose the 3D planning and a postoperative 3D model, surface based matching can also be used. Thus, ITK-Snap was replaced by ProPlan to do the preparation of the 3D models. This also meant that the wish was fulfilled that the new analysis method should mesh with the currently used model preparation method at the UMCG.

A problem with ShapePopulationViewer was that the data was only available in the colourmap. This meant that the legend had to be used to visually extract data which is not accurate. As 3D Slicer is an open source program it allows the user to access the source code of the program. This was made use of by writing a Python script to extract data in mm by placing a markup node (a coordinate point snapped to the surface of the 3D model). The coordinates of this markup node were matched with the corresponding 3D model

coordinate and thus the difference in distance. This meant that validation and case analysis could now be done.

Unfortunately, the distance values extracted from ShapePopulationViewer did not correspond to the distance values from the 2D cephalometric analysis in ProPlan at all. It turns out that ShapePopulationViewer does not measure model differences from point to point, but measures from a chosen point on one model to the closest point on the other model. This means that if your selected point is on the apex of a tooth, the corresponding point will most likely not be on the apex of the tooth of the other model, as that will not be the closest point per se. The colourmap from ShapePopulationViewer would have been a nice way to visualise the data, but since the distances are not calculated correctly, this method cannot be used for this research.

The OrthognathicDistanceCalculator

As ShapePopulationViewer could not be used for this research a different method had to be used. However, 3D Slicer is an open source program that allows users to run a Python script, which was the inspiration to write a new analysis method. This new method is based on 3D cephalometry and can be used with any superimposition method. This means that ProPlan can be used to prepare the 3D models. The new method called the OrthognathicDistanceCalculator has code written to improve the consistency of 3D cephalometry by calculating the location of the apex of the tooth closest to the placed markup node and placing a new found markup node. It does this by placing an invisible sphere around the placed markup node and looks for the lowest z-coordinate within this sphere. In Figure 4 it can be seen that even though the placed markup node

dx	dy	dz
0.586914	0.155918	-0.23145

Figure 4: A 3D model of a tooth with found and placed markup nodes

seems to be close to the apex of the tooth it is still over 0.5 mm away from the apex. The radius of this sphere is called the error rectification radius (R) and can be adjusted to change the accuracy. Whenever the apex of the tooth is located within the sphere around the placed markup node, it will always place a newly found markup node exactly on the apex of the tooth as can be seen in Figure 4. This basically nullifies the human error if the apex of the tooth is within the sphere around the placed markup node. The differences between the teeth locations on the 3D planning and the post operational 3D model are calculated by subtracting the coordinate values of the found markup nodes on the post operative model from the found markup nodes on the 3D planning. The widening between the molars and the cuspids is also calculated and all the difference values are automatically saved in a CSV file.
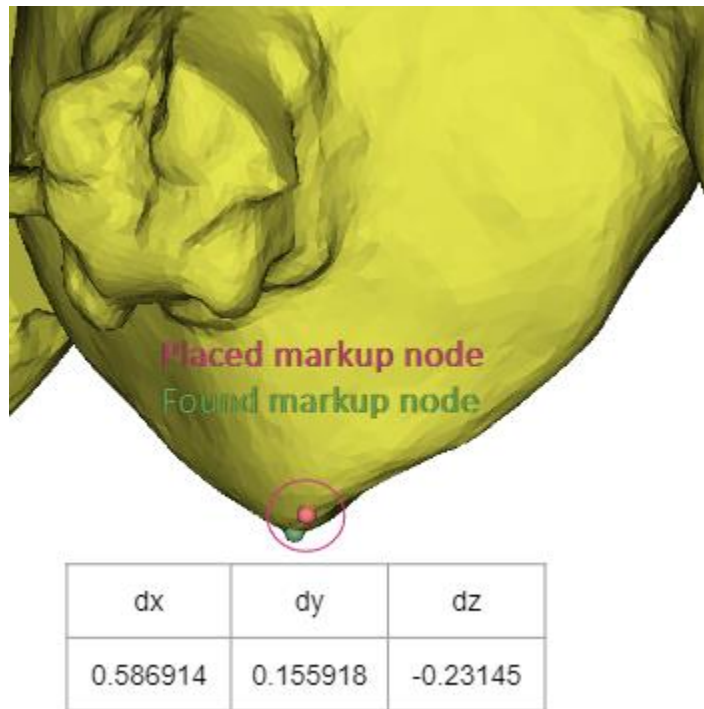
The OrthognathicDistanceCalculator Python script

The full Python script of the OrthognathicDistanceAnalyser is written down below. Parts of the code will be explained in green to show its purpose. A # at the start of a sentence means that this line is not part of the code that runs the script. The entire code can be copied and pasted in Python to run or edit it.

```python
# The OrthognathicDistanceCalculator
import numpy as np
from datetime import datetime


def find_peaks(markup_node, model_data, jaw, R=1.0):
    found_points = []

    for i in range(markup_node.GetNumberOfControlPoints()):
        F1=np.array([.0, .0, .0])
        markup_node.GetNthControlPointPosition(i, F1) # makes an array of zeros where values can be inserted

        diff = np.linalg.norm(model_data - F1, axis=1)
        in_sphere = model_data[diff < R] # looks at if the difference between the coordinate of the chosen markup and every coordinate of the model is smaller than the sphere with error rectification radius R and puts them in a list

        if jaw == 'maxilla':
            lowest = in_sphere[np.argmin(in_sphere, axis=0)[2]] # Replace [2] with: x=[0], y=[1] or z=[2] to change the axis used to find the lowest coordinate
            found_points.append(lowest) # Chooses the point from the sphere list with the lowest z coordinate as the found point
        elif jaw == 'mandible':
            highest = in_sphere[np.argmax(in_sphere, axis=0)[2]] # Replace [2] with: x=[0], y=[1] or z=[2] to change the axis used to find the highest coordinate

            found_points.append(highest) # Chooses the point from the sphere list with the highest z coordinate as the found point
        else:
            print('Please change the jaw type to maxilla or mandible', jaw)

    return np.array(found_points) # places all of these coordinates in the array

def find_delta_and_save(plan_node_name, post_node_name, outfile, R=1.0, jaw='maxilla'):
    F_plan = getNode('F_plan') # calls the coordinates of the placed markup nodes on the 3D planning
    F_post = getNode('F_post') # calls the coordinates of the placed markup nodes on the post operational model

    if F_plan.GetNumberOfControlPoints() != F_post.GetNumberOfControlPoints():
        print('F_plan and F_post should have an equal number of fiducials!')
```

```
    return;

  try:
    found_plan = getNode('Found_plan')
    found_post = getNode('Found_post')
  except slicer.util.MRMLNodeNotFoundException: # gives an error if the node does not exist
    found_plan       =       slicer.mrmlScene.AddNewNodeByClass('vtkMRMLMarkupsFiducialNode',
'Found_plan')
    found_post       =       slicer.mrmlScene.AddNewNodeByClass('vtkMRMLMarkupsFiducialNode',
'Found_post')
# looks for the found markup node maps, calls the coordinates if they already exist and makes them if
they do not already exist

  model_plan_node = getNode(plan_node_name)
  model_post_node = getNode(post_node_name)

  model_plan_data = arrayFromModelPoints(model_plan_node)
  model_post_data = arrayFromModelPoints(model_post_node)

  points_plan = find_peaks(F_plan, model_plan_data, jaw=jaw, R=R)
  points_post = find_peaks(F_post, model_post_data, jaw=jaw, R=R)  # new found coordinates

  updateMarkupsControlPointsFromArray(found_plan, points_plan)
  updateMarkupsControlPointsFromArray(found_post, points_post) # updates coordinates in slicer

  delta = points_plan - points_post # coordinate difference calculation between the found markup nodes
on the 3D planning and the post operational 3D model


  molaris_diff = (points_plan[0] - points_plan[11])-(points_post[0] - points_post[11])
  cuspids_diff = (points_plan[3] - points_plan[8])-(points_post[3] - points_post[8]) # widening calculation
  widening = [molaris_diff, cuspids_diff]

  with open(outfile, 'w') as f:
    f.write('label,dx,dy,dz\n')
    for i,d in enumerate(delta):
      f.write(f'F-{i+1},{d[0]},{d[1]},{d[2]}\n')
    for x,d in enumerate(widening):
      f.write(f'W-{x+1},{d[0]},{d[1]},{d[2]}\n') # organises the difference data in a CSV file


OUTFILE = datetime.now().strftime('ODC_%Y-%m-%d_%H.%M.%S.csv') #generate filename with date

find_delta_and_save('planning_model', 'postoperational_model', R=1.0, outfile=OUTFILE, jaw='maxilla')
# change STL the filenames, the radius and which jaw is being researched here
# first planning then post op
```

copy and paste the following (without the #) in the python interactor to execute the script:
exec(open('Orthognathicdistancecalculator.py', 'r').read())

make sure that Orthognathicdistancecalculator.py is saved in: C:\Users\[your username]\AppData\Local\NA-MIC\Slicer 5.0.2
Your data files with the calculated distances can also be found in that file location.

A step-by-step plan to analyse a bimaxillary osteotomy

This research requires the installation of two programs: ProPlan CMF 3.0 and 3D Slicer in which several actions have to be done to be able to research the data, which are described in more detail below.

First, the DICOM files of the post operational scans have to be converted to STL files. This can be done in both ProPlan and 3D Slicer. The postoperative model quality is quite bad due to scatter. To resolve this issue, the intraoral teeth scan has to be superimposed on that model in ProPlan. Thereafter, the STL files of the planning segments have to be merged into one file, which can be done in ProPlan as well. After completing the STL files, the planning and the postoperative scan can be superimposed onto each other by aligning characteristic features of the skull, which is also done using ProPlan. Finally, the STL files can be imported in 3D Slicer and markup nodes can be placed on the teeth. Running the Python script of the OrthognathicDistanceCalculator will automatically generate a CSV file that contains all the measurements. The steps are written in more detail below.

A video has also been made that shows how to do the analysis with the OrthognathicDistanceCalculator [18]. The video shows that the analysis can be done in 3 minutes and 20 seconds. The preparation of the 3D models is not included in this video.

From DICOM to STL in ProPlan

- Open ProPlan CMF 3.0
- Go to: Import Images and select the DICOM files
- Press select, Convert and OK
- Go to: Segmentation
- Step 1: Create new 3D, Next
- Step 2: Set a custom threshold range for the grayscale to select the tissue of interest. Adjust it so that only the bone tissue is coloured as can be seen in Figure 5 Press Next.
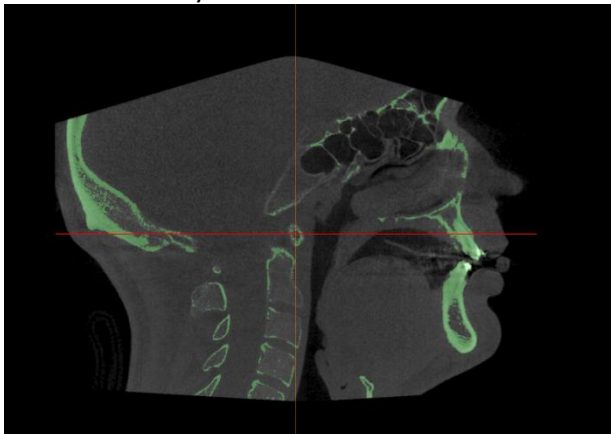

Figure 5: Grayscale adaptation in ProPlan

- Step 3: Select bone region of interest which in this case is the maxilla region. A small red dot is placed as can be seen in Figure 6. Press Next. All tissues that are not connected to the small red dot will now be deleted by ProPlan as can be seen in Figure 6.
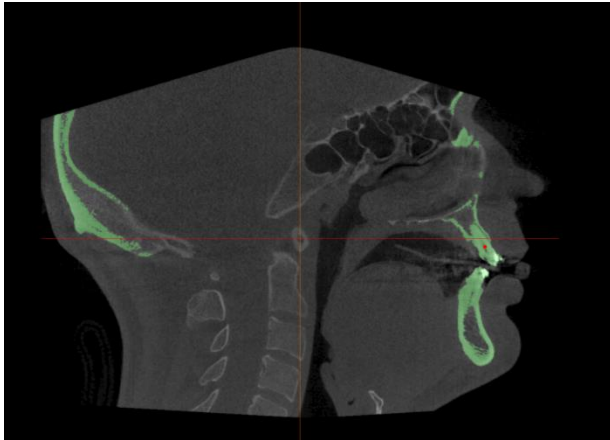
Figure 6: Bone region selection in ProPlan

- Step 4: Remove the mandible with the lasso tool as shown in Figure 7. Press Remove Selection and press Next.
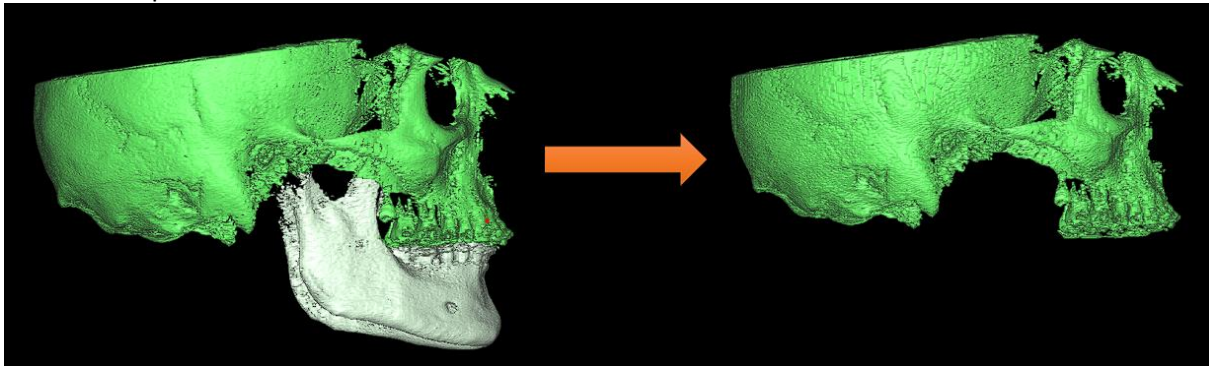

Figure 7: Removal of the mandible in ProPlan

- Step 5: Set name to: [patient name]_maxilla_[plan or post] (or whatever you'd like to name it). Press Finish.
- Press Finish. Select the object by ticking its box, Press Compress model and press Calculate.
- On the bottom left of the program, the Objects List can be found. Select the file, press export model as seen in Figure 8 marked in yellow. Export as STL file in the desired folder.
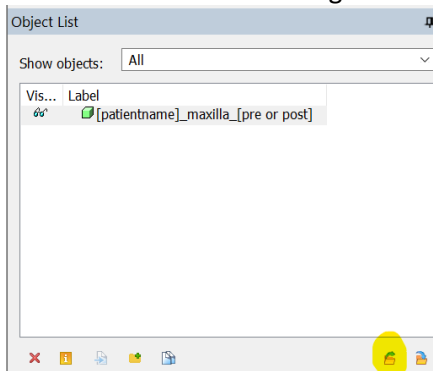

Figure 8: How to export a file in ProPlan

Aligning the intra oral teeth scan on the post op model in ProPlan

- Step 1: Open your .sppc file in ProPlan and go to Orthognathics.
- Step 2: In Select Maxilla, Select your post-operative model of your skull with a maxilla attached and in Select Maxillary Cast, select the teeth model from the intraoral scan that is also used in your planning. Press Next and press Next again when asked to add alignment points.
- Step 3: Align your teeth model to fit the CT scan of the patient by using the Rotate and Translate option as shown in Figure 9. Press next after aligning the intra oral scan correctly.
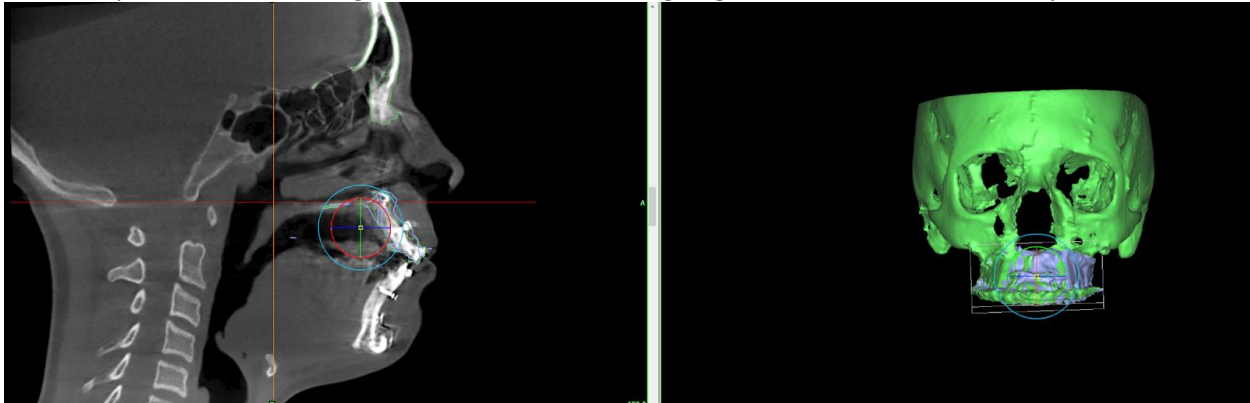

Figure 9: Aligning the maxillary cast in ProPlan

- Step 4: Translate, Rotate and Resize a block to remove the old teeth from the post operative scan as can be seen in Figure 10. Press next. ProPlan will create your post op scan with your superimposed teeth from the intraoral scan.
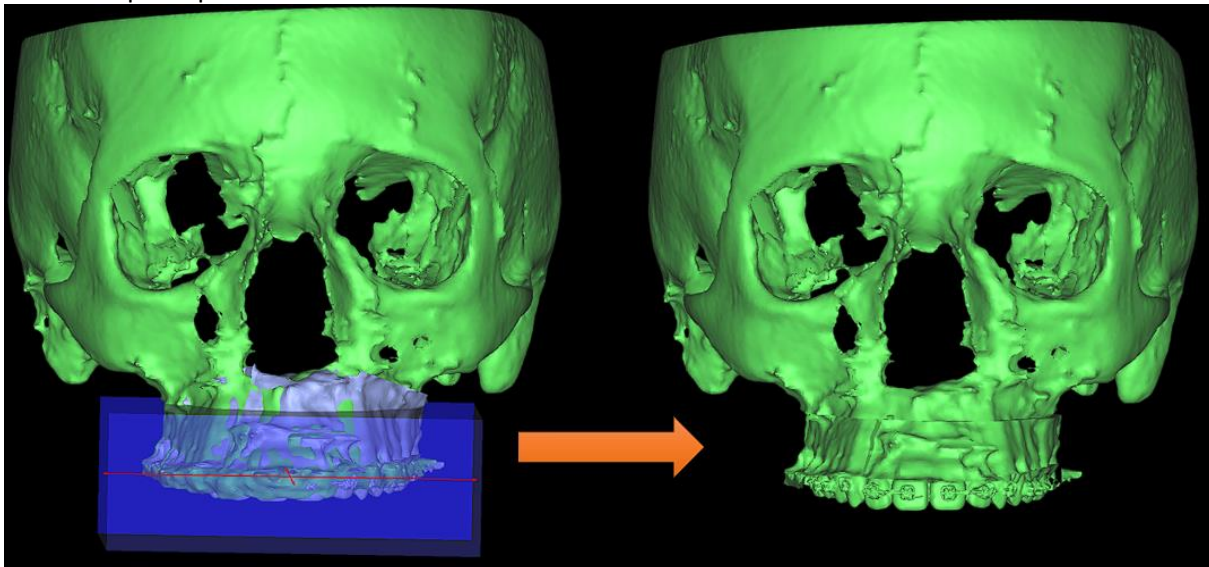

Figure 10: removing the CBCT maxilla in ProPlan

- Step 5: Press Finish and export your new STL file to your desired location.

Note that you'll have to repeat these steps for each separate maxillary segment to properly superimpose the teeth.

Merging the STL files of the planning model

- Step 1: Go to import images and open a DICOM or .sppc file in ProPlan (does not matter from which patient).
- Step 2: Go to Plan, Design tools.
- Step 3: In the bottom left corner, click on the import files icon and select the STL files that you'd like to be merged.
- Step 3: Go to General 3d operations, at Indicate: select Merge and select the files that you would like to merge as seen in Figure 11.
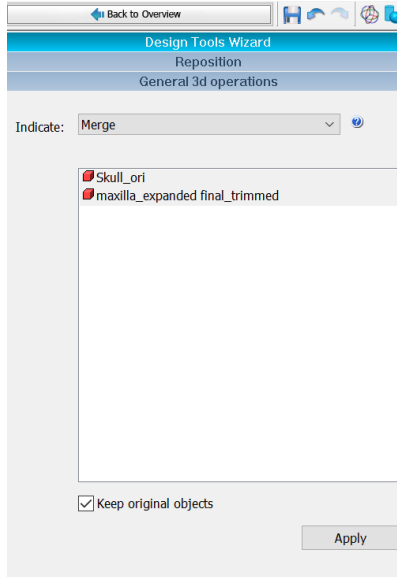

Figure 11: Selection of the files to be merged in ProPlan

- Step 4: Press Apply and go to the bottom left corner, click on the export files icon and select your folder.

Superimposition of the STL files

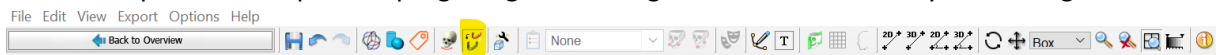- Step 1: At the top of the program go to the alignment tool marked in yellow in Figure 12.

Figure 12: Where to find the alignment tool in ProPlan

- Step 2: In the wizard, select the files that you'd like to superimpose and mark the areas on which you'd like them to be merged as shown in Figure 13. (Select the areas above the Le fort I osteotomy area as they have not changed after the operation and usually do not have a lot of scatter. Mark both models by making one invisible at the time in the bottom left corner.
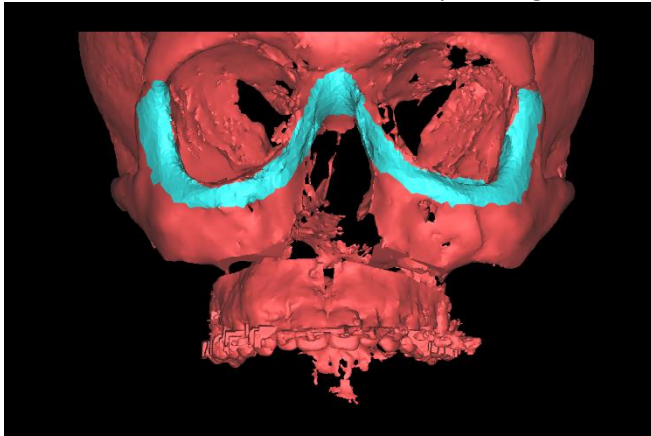

Figure 13: Surface based registration on one model in ProPlan

When they are close to each other you can make both visible and mark some overlapping areas to make the superimposition more accurate as seen in Figure 14.
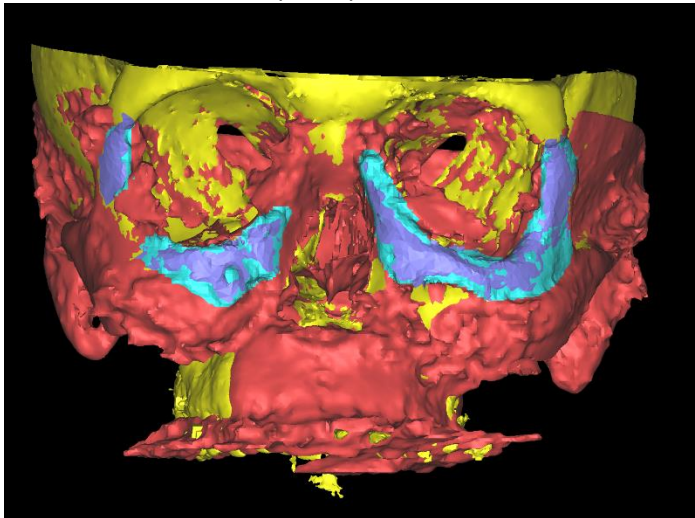

Figure 14: Surface based registration on both models in ProPlan

- Step 3: Export the superimposed STL files to the desired folder.

Using the OrthognathicDistanceCalculator in 3D Slicer

- Step 1: Make sure that Orthognathicdistancecalculator.py is saved in the same folder as the Slicer program location as seen in Figure 15.
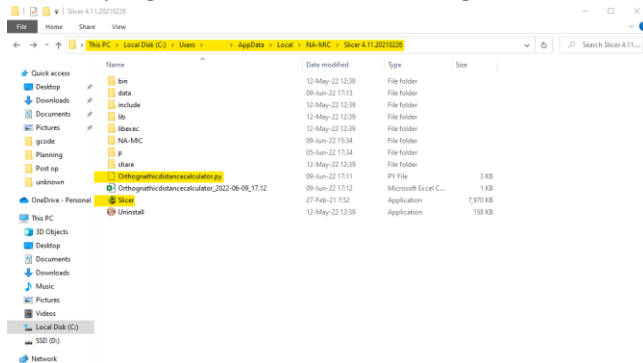

Figure 15: The file locations of the Python script

- Step 2: Open your planning and post operational STL models in Slicer.
- Step 3: Open the script in Notepad ++ or any other script viewer and adjust the parameters in the following line at the bottom of the script: find_delta_and_save('planning_model', 'postoperational_model', R=1.0, outfile=OUTFILE, jaw='maxilla')
  For the first adjustable parameter ('planning_model'), fill in the filename of your planning STL file.
  The second adjustable parameter ('postoperational_model') can be filled in with the filename of your post-operational vtk file.
  The third adjustable parameter (error rectification radius: R) can be changed in mm (R=0.5, R=2.0, etc). A too small radius will result in the markup node not reaching the apex and a too large R might result in the markup node changing its position to a different (longer) cusp. The optimal R value will be calculated in the validation methods.
  The outfile=OUTFILE bit can be ignored as it changes the name and filetype of the results file.
  The fourth adjustable parameter (jaw='maxilla') can be changed to jaw='maxilla' or jaw='mandible', depending on the jaw that you are researching. The z-axis position will change downwards at 'maxilla' and the z-axis position will change upwards at 'mandible'.
- Step 4: Go to the Markups module, press Point List (three red dots) and rename the markup node lists to F_plan and F_post as shown in Figure 16. Other names will not be accepted by the script.
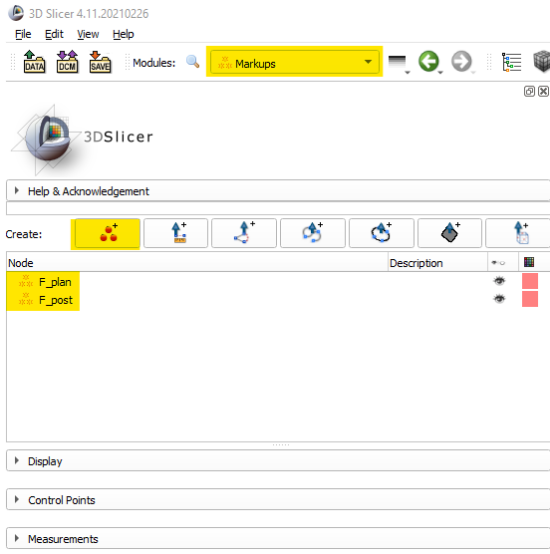
Figure 16: Creating the markup node folders in 3D Slicer

- Step 5: Press the F_plan markup node and place them on the apexes of the teeth on your planned model. Click on the F_post markup node and place them on the apexes of the teeth on your post operative model. The teeth should be selected in the following order: 16, 15, 14, 13, 12, 11, 21, 22, 23, 24, 25 and 26. The corresponding teeth are shown in Figure 17. Teeth numbers 17, 18, 27 and 28 are not analysed because not every person has these molars. The Data extension can be used to make models and markup nodes invisible to keep track of everything.
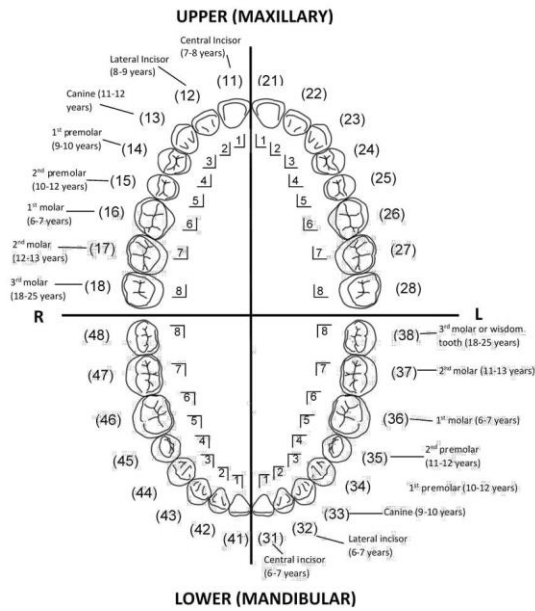
Figure 17: A full denture with the tooth numbering [19]

Make sure to use standard views (A, I, R and L) as shown in Figure 18. to make sure that you position your markup node as close to the apex of the tooth as possible as this will increase the accuracy of this method.
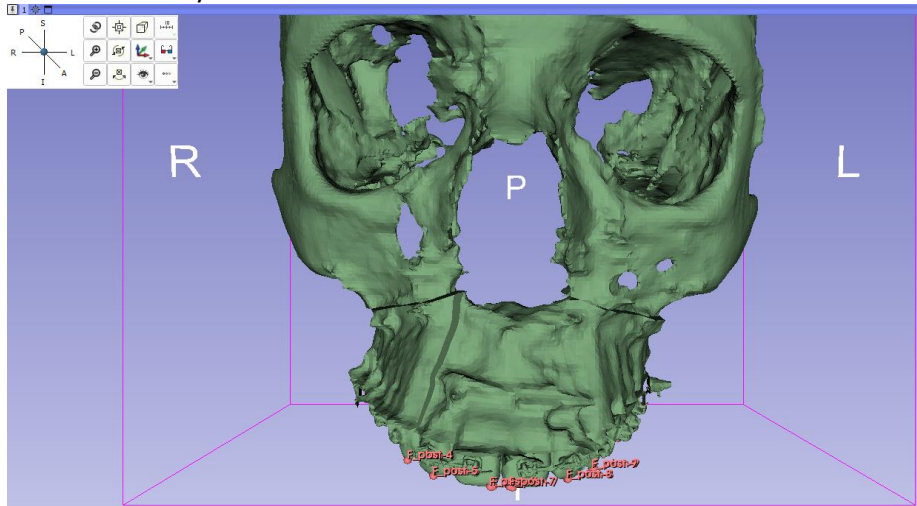
Figure 18: A 3D model with placed markup nodes and standard views selected in 3D Slicer

- Step 6: Open the python interactor and type the following line of code to run the script: exec(open('Orthognathicdistancecalculator.py', 'r').read()) Press Enter. You'll know that you've succeeded when Python interactor shows nothing on the next row and the found model nodes are placed on the model.
- Step 7: Obtain your automatically generated CSV data sheet from the same folder as where the Python script is located. It is named ODC_… with the date and time of creation behind it. CSV data files can be opened with excel to analyse the data.
- Step 8: Save your markup points to your folder to be able to look back at it.

Note that if the placed markup node and the found markup node are quite far apart, you could drag the placed markup node closer to the found markup node and run the script again to get closer to the apex of the tooth. The positions of the found markup nodes should always be checked to make sure that the found markup nodes are in the same positions on the planning and post operative model.

Validation method 1

Since this is a newly made and thus unknown research method, a proper validation method has to be made to validate the difference values. A simple model is shown in Figure 19 that replicates teeth displacements between planning models and post operational models was made with known lengths in the x, y and z direction. If the data obtained from the Python script has the exact same values as the lengths of the validation model, the research method is accurate.
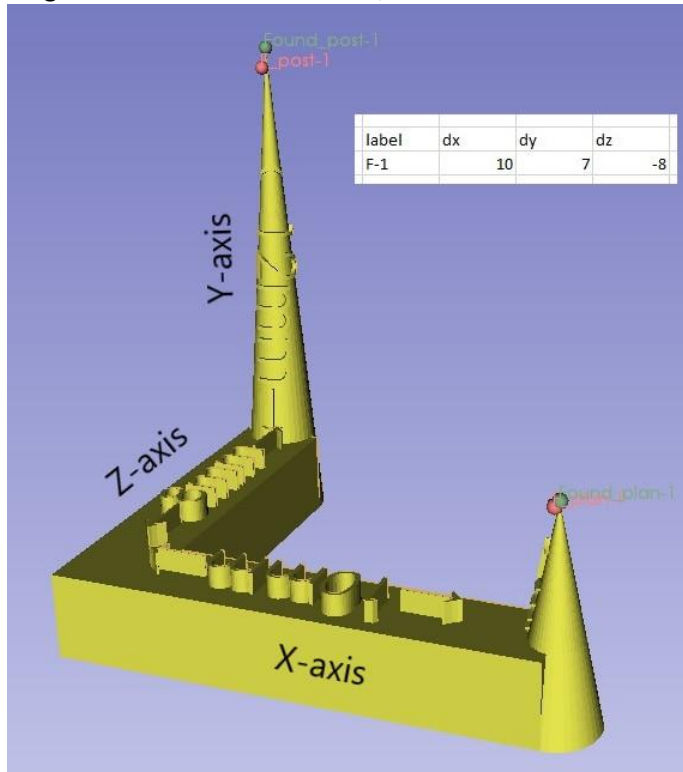
Figure 19: Displacement validation model in 3D Slicer

This model consisted of a small cone (mimics planning model) and a large cone (mimics the post operational model) attached to an L-shaped bracket. It can be seen that the found markups are placed higher than the placed markups. The mimicked planning model has a length of 5.0 mm on the Y-axis and zero displacement on the Y- and Z-axes. The mimicked post-op model has a length of 10.0mm on the X-axis, 8.0mm on the Z-axis and 12.0mm on the Y-axis. This means that the displacements should be: dx=10.0-0.0=10.0mm, dy=12.0-5.0=7.0mm and dz=8.0-0.0=8.0mm. As can be seen in Figure 19, the data from the generated CSV file has a dx of 10, a dy of 7 and a dz of -8. Even though the results do not show any decimals, the script calculates values more than six decimals. Excel deletes unnecessary zeros which means that the actual values from the script are: dx=10.00000, dy=7.00000 and dz=-8.000000. The negative value of dz has to do with the direction that the model was oriented in. It can be concluded that the OrthognathicDistanceCalculator is 100% accurate on this model if the user places the markup nodes within a radius of 1.0 mm of the apex of the tooth. This however might not be as accurate on an actual dental scan with lots of bumpy surfaces and model rotations.

Validation method 2
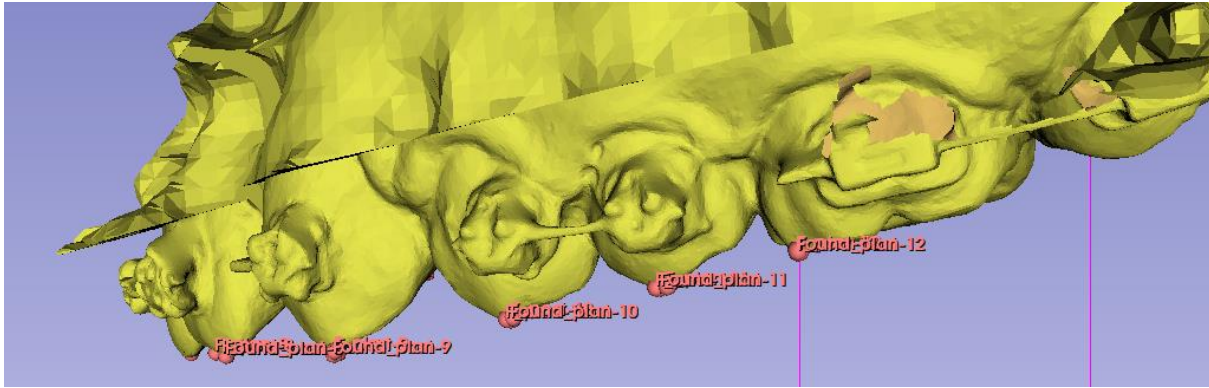
Figure 20: 3D model of maxilla as second displacement validation model in 3D Slicer

Now that it is confirmed that the OrthognathicDistanceCalculator can be used to precisely calculate a distance on the cone-shaped 3D model, a second validation method has to be done to analyse the accuracy of the OrthognathicDistanceCalculator on an actual dental scan as shown in Figure 20. This validation method analyses the difference of 12 different teeth in the x, y and z directions on two identical 3D models. No changes have been made to the coordinates of the 3D models, so in theory dx, dy and dz should all be zero.
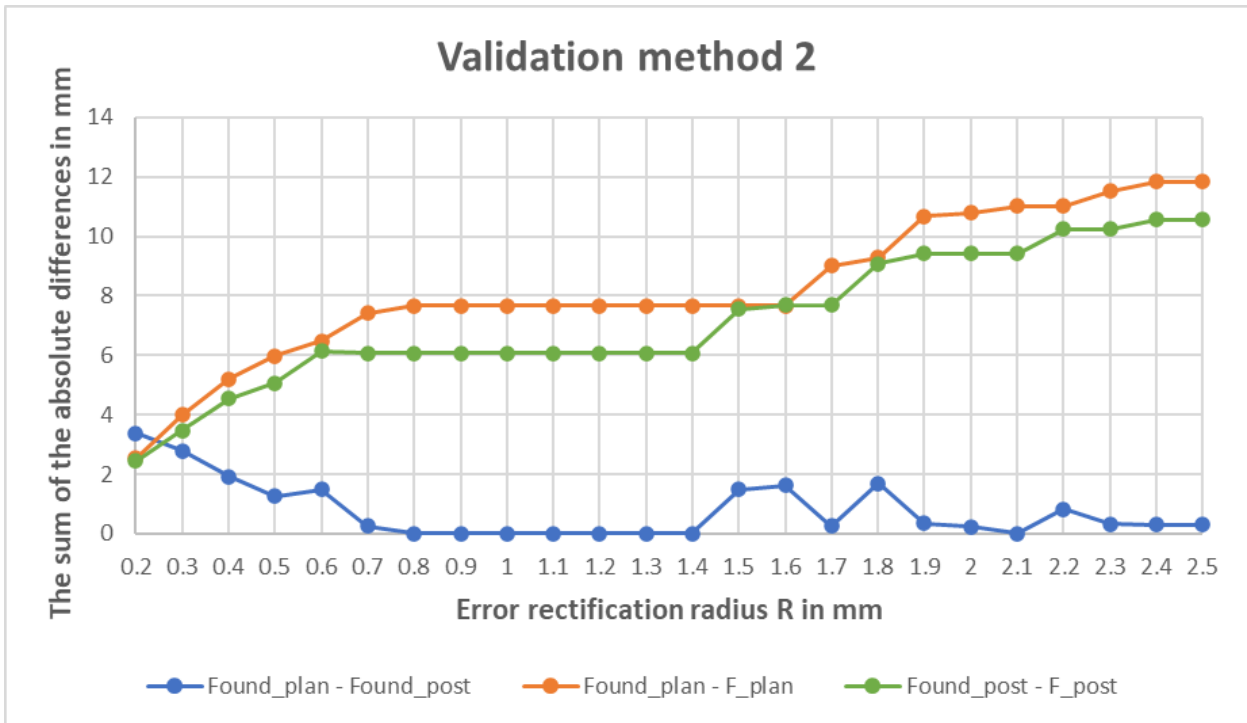
Figure 21: Calculated value differences at different error rectification radii

In this method the standard views are used during the placement of the markup nodes, which elucidates the position of the model compared to the z axis. The differences were measured at multiple error rectification radii, to find the optimal R. The differences between the placed and found markups were also taken into consideration.

As can be seen in Figure 21, the sum of the absolute differences is exactly zero (0.000000mm) when the R is between 0.8mm and 1.4mm. The differences between the placed markup nodes and the found markup nodes remains exactly the same throughout this range, which means that the apex of this tooth is found consistently within this range. From this data it can be concluded that the OrthognathicDistanceCalculator is 100% accurate within a range of 0.8 to 1.4 mm.

The difference values that are greater than zero from R = 0.2 to 0.7mm can be explained by the (majority of) the placed markups not located within 0.2 to 0.7mm of the apex of the tooth respectively. This range cannot be used as the apex is not found yet, which will make the method inconsistent. The difference values that are greater than zero from R = 1.5 to 2.5 mm can be explained by the (majority of) the placed markups having found a higher apex (on a different tooth or cusp) to climb up to. This range cannot be used as a different apex will be found than anticipated.

An error rectification radius of 1.0mm was chosen as a standard R, as it lies within the 100% accurate range and is a feasible range to work with. This means that the OrthognathicDistanceCalculator has an error of 0.000000mm (at least six decimal points) if the user places his markup nodes within 1.0mm from the apex of the tooth, if the z axis is taken into consideration. The error rectification radius of 1.0mm was also used to evaluate the patient cases.

The overall accuracy of this analysis method does not only rely on the OrthognathicDistanceCalculator, but also on the accuracy of the CBCT scanner, the superimposition of the intraoral scan on the 3D models and the surface based superimposition on the skulls of the 3D models. According to Brülmann et al. the visually identifiable resolution of a CBCT scan is about 1 line-pair per millimetre [20]. This means that an accuracy of 0.5 mm is present when placing a markup node. An intraoral scan has a visually identifiable resolution of about 10 line-pairs per millimetre. This means that an accuracy error of 0.05 mm is present when placing a markup node.

According to Holte et al. the average mean surface distance was found to be about 0.4mm (found in Supplementary Material 1) when using surface based matching [15].

The accuracy of the method is only as good as its worst component which means that the error of the results obtained from the OrthognathicDistanceCalculator is ±0.4mm.

Note that this technical information is often not used to calculate the accuracy of a method. Most analysis methods base the accuracy purely on the average distance of markup nodes placed by two individual researchers. This means that the accuracy of the OrthognathicDistanceCalculator depends on if the technical information is included in the calculations.

Results

A group of 6 patients that underwent a 2 or 3 segment bimaxillary osteotomy in the years 2020 to 2021 has been analysed to research the success rates of these surgeries. The preparation of the STL models was performed in ProPlan as described in the step-by-step plan documented in this research.

The OrthognathicDistanceCalculator was used to obtain the differences in the x, y and z direction after moving the markups to the apexes of the teeth. The markup nodes were placed on twelve teeth from tooth 16 to 26 with an error rectification radius of R=1.0mm. The placements of the found markup nodes were visually evaluated using multiple standard views to approximately be as close to the tooth-apex as possible on both the 3D planning model and the postoperative 3D model.

The patient data is fully anonymised to protect the privacy of the patients.

Data interpretation

As can be seen in the results, tooth position differences in the x, y and z direction were gathered from F-1 to F-12 or tooth 16 to 26 respectively. Two widenings are also analysed. W-1 is the widening at tooth 16 to 26 and W-2 is the widening at tooth 13 to 23 tooth. The values at dx, dy and dz are the position differences in the transverse axis, the anterior-posterior axis and the vertical height respectively for each tooth or widening. The vector value is the total displacement through space and is calculated by: $(dx^2 + dy^2 + dz^2)^{0.5}$. It is nice to know this vector for a better understanding of the total displacement, but it is not used in the analysis. The sign of the displacement value can be either positive or negative. This indicates the direction along the corresponding axis.

The values in the tables are colour coded by clinical relevance. Green: A maximum difference of -0.5mm to 0.5mm is strived for in 3D Lab Groningen at the UMCG. Light blue: A maximum difference between ±(0.5mm to 2.0mm) is considered to be clinically acceptable, but braces could be necessary to correct for the errors obtained in the surgery. A difference of <2.0mm is the accepted clinically significant first introduced by Proffit et al [7]. Red: Anything outside of this range is considered to be clinically significant and can be considered to be a failed segmentation.

The displacement of the segments along the x, y and z axis can be described with anatomical terms with the help of Table 2 below.

Axis \ sign	negative	positive
x	sinistral	dextral
y	anterior	posterior
z	inferior	superior
widening	wide	narrow

Table 2: Translation of value sign to anatomical terms

Patient 1

This patient has had a bimaxillary osteotomy done with a 3-segment Le Fort I osteotomy as can be seen in Figure 22. On this patient conventional fixation plates were used.

Figure 22: The OrthognathicDistanceCalculator analysis performed on Patient 1

label (tooth)	dx	dy	dz	vector
F-1 (16)	0.1401596069	0.8750762939	0.003044128418	0.8862350153
F-2 (15)	-0.04920959473	0.4852981567	-0.0007972717285	0.4877873725
F-3 (14)	-1.232498169	0.1720809937	-0.9698867798	1.577765499
F-4 (13)	-0.7606964111	-0.04861068726	-1.999340057	2.139715563
F-5 (12)	-0.7241592407	1.106647491	0.7486305237	1.519711465
F-6 (11)	-2.02519989	0.06555175781	0.04640960693	2.026791918
F-7 (21)	-1.198738098	-0.7591438293	-0.4228172302	1.480556244
F-8 (22)	-1.455886841	-0.9219856262	0.05978012085	1.724307876
F-9 (23)	-0.3805084229	-0.8031349182	-0.5858078003	1.064416805
F-10 (24)	-0.9179382324	-0.6058959961	-0.7307357788	1.320490566

F-11 (25)	-1.321365356	-0.4824905396	-0.4905662537	1.489784808
F-12 (26)	-1.930847168	-0.5057220459	-0.1745300293	2.003593348
Molaris (16-26)	2.071006775	1.38079834	0.1775741577	2.495436976
Cuspid (13-23)	-0.3801879883	0.754524231	-1.413532257	1.646791779
Avg Seg 1	-0.475561142	0.3709611893	-0.741744995	0.9560105864
Avg Seg 2	-1.350996017	-0.1272325517	0.1080007553	1.361265046
Avg Seg 3	-1.137664795	-0.599310875	-0.4954099655	1.378000633

Table 3: Data collection of Patient 1

In Table 3 it can be seen that segment 1 differs -0.48mm on average in the x direction, 0.37mm on average in the y direction and -0.74mm in the z direction. This means that segment 1 has a sinistral displacement of 0.48mm within the accepted clinical significance of 2.0mm, a posterior displacement of 0.37mm within the accepted clinical significance of 2.0mm and an inferior displacement of 0.74mm within the accepted clinical significance of 2.0mm [7].

It can be seen that segment 2 differs -1.35mm on average in the x direction, -0.13mm on average in the y direction and 0.11mm in the z direction. This means that segment 2 has a sinistral displacement of 1.35mm within the accepted clinical significance of 2.0mm, a posterior displacement of 0.13mm within the accepted clinical significance of 2.0mm and a superior displacement of 0.11mm within the accepted clinical significance of 2.0mm [7].

It can be seen that segment 3 differs -1.14mm on average in the x direction, -0.60mm on average in the y direction and -0.50mm in the z direction. This means that segment 3 has a sinistral displacement of 1.14mm within the accepted clinical significance of 2.0mm, a posterior displacement of 0.60mm within the accepted clinical significance of 2.0mm and a superior displacement of 0.50mm within the accepted clinical significance of 2.0mm [7].

The widening measured at the 16-26 molars was made 2.07mm too narrow which is just barely outside of the accepted clinical significance of 2.0mm. The widening measured at the 13-23 cuspids was made 0.38mm too wide which is within the accepted clinical significance of 2.0mm [7].

30

Patient 2

This patient has had a bimaxillary osteotomy done with a 3-segment Le Fort I osteotomy as can be seen in Figure 23. On this patient conventional fixation plates were used.
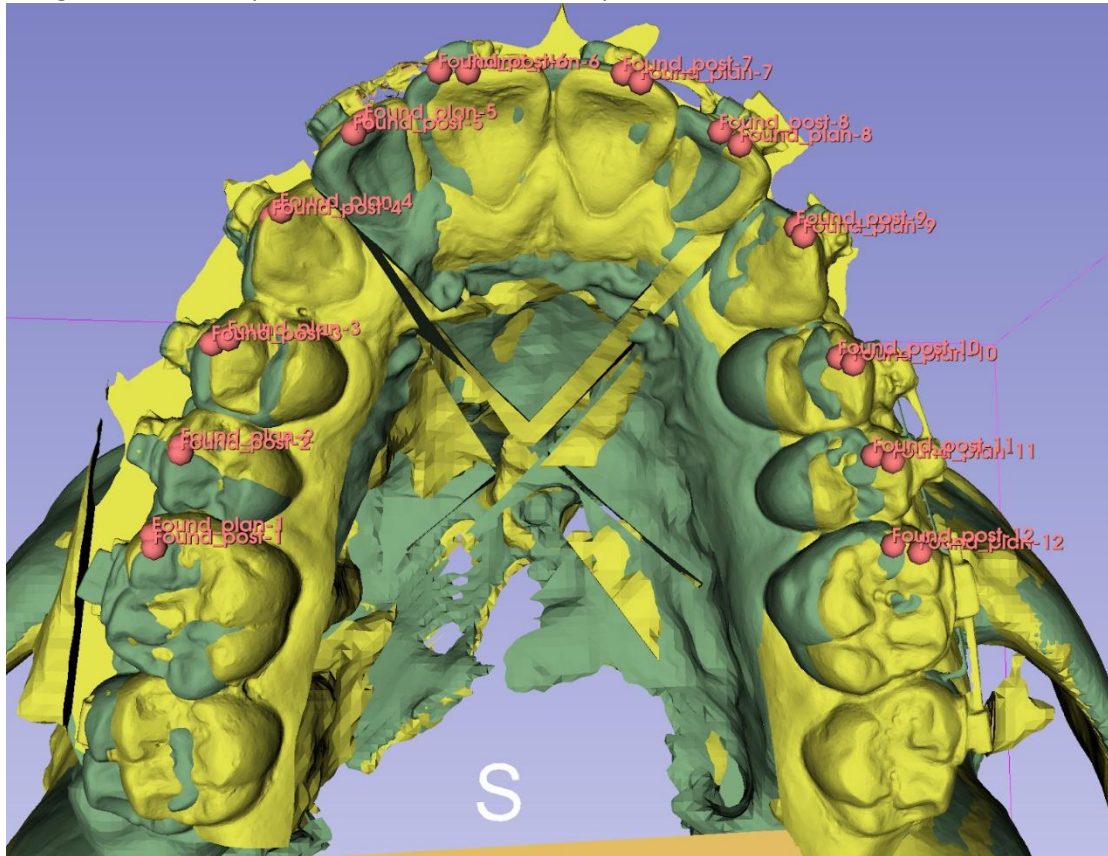

Figure 23: The OrthognathicDistanceCalculator analysis performed on Patient 2

label (tooth)	dx	dy	dz	vector
F-1 (16)	1.816040039	0.7893676758	-1.477607727	2.470713934
F-2 (15)	1.176879883	1.560680389	-1.491378784	2.458654147
F-3 (14)	1.76033783	1.080245972	-1.511238098	2.559211055
F-4 (13)	1.770133972	1.083667755	-1.532623291	2.580047332
F-5 (12)	2.532249451	0.9365959167	0.2224502563	2.709055797
F-6 (11)	2.250862122	0.9103317261	-0.05754089355	2.428661174
F-7 (21)	2.701568604	0.5396728516	-0.03942871094	2.75522673
F-8 (22)	2.647201538	0.8598594666	0.2169876099	2.791794747
F-9 (23)	1.04196167	2.873531342	-0.6111679077	3.11711288
F-10 (24)	0.7029266357	3.411460876	-0.2848052979	3.494751096
F-11 (25)	0.8717346191	2.993537903	-0.01100921631	3.117901799
F-12 (26)	0.7968139648	3.028717041	0.2546081543	3.142111507

Molaris (16-26)	1.019226074	-2.239349365	-1.732215881	3.008999705
Cuspid (13-23)	0.7281723022	-1.789863586	-0.9214553833	2.140777098
Avg Seg 1	1.630847931	1.128490448	-1.503211975	2.488534088
Avg Seg 2	2.532970429	0.8116149903	0.08561706543	2.66120055
Avg Seg 3	0.8533592224	3.076811791	-0.1630935669	3.197122498

Table 4: Data collection of Patient 2

In Table 4 it can be seen that segment 1 differs 1.63mm on average in the x direction, 1.12mm on average in the y direction and -1.52mm in the z direction. This means that segment 1 has a dextral displacement of 1.63mm within the accepted clinical significance of 2.0mm, a posterior displacement of 1.12mm within the accepted clinical significance of 2.0mm and an inferior displacement of 1.15mm within the accepted clinical significance of 2.0mm [7].

It can be seen that segment 2 differs 2.53mm on average in the x direction, 0.81mm on average in the y direction and 0.09mm in the z direction. This means that segment 2 has a dextral displacement of 2.53mm outside of the accepted clinical significance of 2.0mm, a posterior displacement of 0.81mm within the accepted clinical significance of 2.0mm and a superior displacement of 0.09mm within the accepted clinical significance of 2.0mm [7].

It can be seen that segment 3 differs 0.85mm on average in the x direction, 3.08mm on average in the y direction and -0.16mm in the z direction. This means that segment 3 has a dextral displacement of 0.85mm within the accepted clinical significance of 2.0mm, a posterior displacement of 3.08mm outside of the accepted clinical significance of 2.0mm and an inferior displacement of 0.16mm within the accepted clinical significance of 2.0mm [7].

The widening measured at the 16-26 molars was made 1.02mm too narrow which is within the accepted clinical significance of 2.0mm. The widening measured at the 13-23 cuspids was made 0.73mm too narrow which is within the accepted clinical significance of 2.0mm [7].

Patient 3

This patient has had a bimaxillary osteotomy done with a 2-segment Le Fort I osteotomy as can be seen in Figure 24. On this patient conventional fixation plates were used.
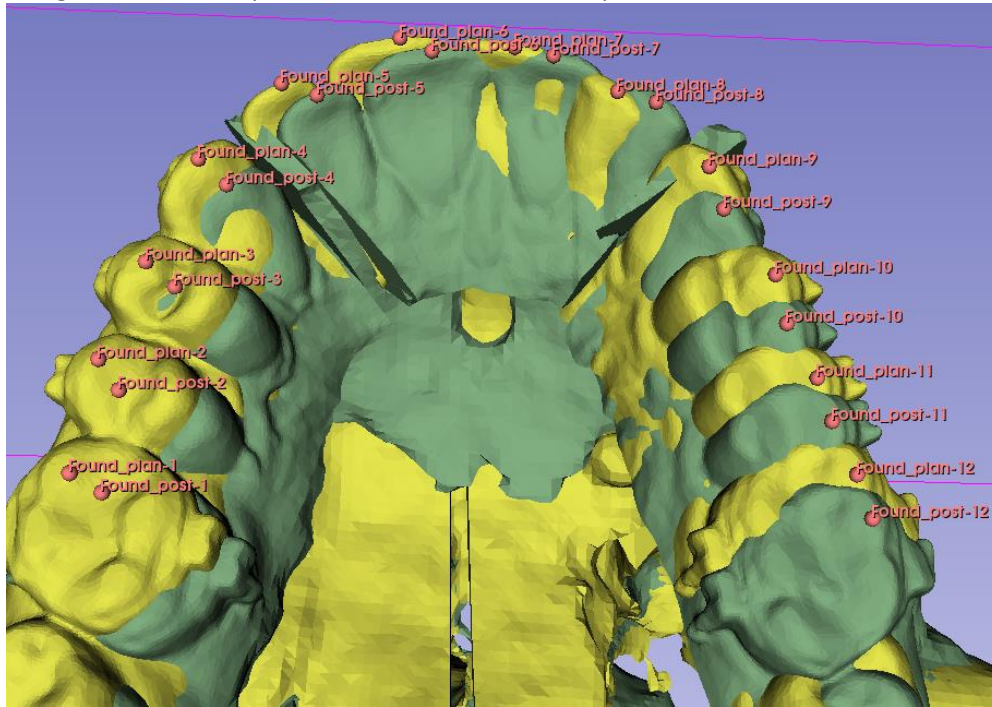

Figure 24: The OrthognathicDistanceCalculator analysis performed on Patient 3

label (tooth)	dx	dy	dz	vector
F-1 (16)	2.341293335	-0.1005630493	-0.3651275635	2.37172628
F-2 (15)	2.489013672	-0.2241249084	-0.6015853882	2.570471944
F-3 (14)	2.61933136	-0.1647262573	-0.8604431152	2.761954719
F-4 (13)	2.753128052	-0.1139411926	-1.12613678	2.97672315
F-5 (12)	2.851272583	0.003952026367	-1.320854187	3.14236006
F-6 (11)	2.681228638	0.2292861938	-1.421634674	3.043452696
F-7 (21)	4.045295715	-0.8657417297	-2.556510925	4.863093077
F-8 (22)	4.143417358	-1.018569946	-2.150588989	4.778119414
F-9 (23)	4.433517456	-1.17590332	-1.469055176	4.816321082
F-10 (24)	4.653274536	-1.358703613	-0.4890441895	4.872186741
F-11 (25)	4.834762573	-1.402751923	0.3970489502	5.04978118
F-12 (26)	5.049118042	-1.478889465	1.165313721	5.388753392

Molaris (16-26)	-2.707824707	1.378326416	-1.530441284	3.402109475
Cuspid (13-23)	-1.680389404	1.061962128	0.342918396	2.01719239
Avg Seg 1	2.622544607	-0.06168619791	-0.9492969513	2.789750903
Avg Seg 2	4.52656428	-1.216759999	-0.8504727681	4.763779278

Table 5: Data collection of Patient 3

In Table 5 it can be seen that segment 1 differs 2.62mm on average in the x direction, -0.06mm on average in the y direction and -0.95mm in the z direction. This means that segment 1 has a dextral displacement of 2.63mm outside of the accepted clinical significance of 2.0mm, an anterior displacement of 0.06mm within the accepted clinical significance of 2.0mm and a superior displacement of 0.95mm within the accepted clinical significance of 2.0mm [7].

It can be seen that segment 2 differs 4.53mm on average in the x direction, -1.22mm on average in the y direction and -0.85mm in the z direction. This means that segment 2 has a dextral displacement of 4.53mm outside of the accepted clinical significance of 2.0mm, a posterior displacement of 1.22mm within the accepted clinical significance of 2.0mm and an inferior displacement of 0.85mm within the accepted clinical significance of 2.0mm [7].

The widening measured at the 16-26 molars was made 2.71mm too wide which is outside of the accepted clinical significance of 2.0mm. The widening measured at the 13-23 cuspids was made 1.68mm too wide which is within the accepted clinical significance of 2.0mm [7].

34

Patient 4

This patient has had a bimaxillary osteotomy done with a 3-segment Le Fort I osteotomy as can be seen in Figure 25. On this patient conventional fixation plates were used.
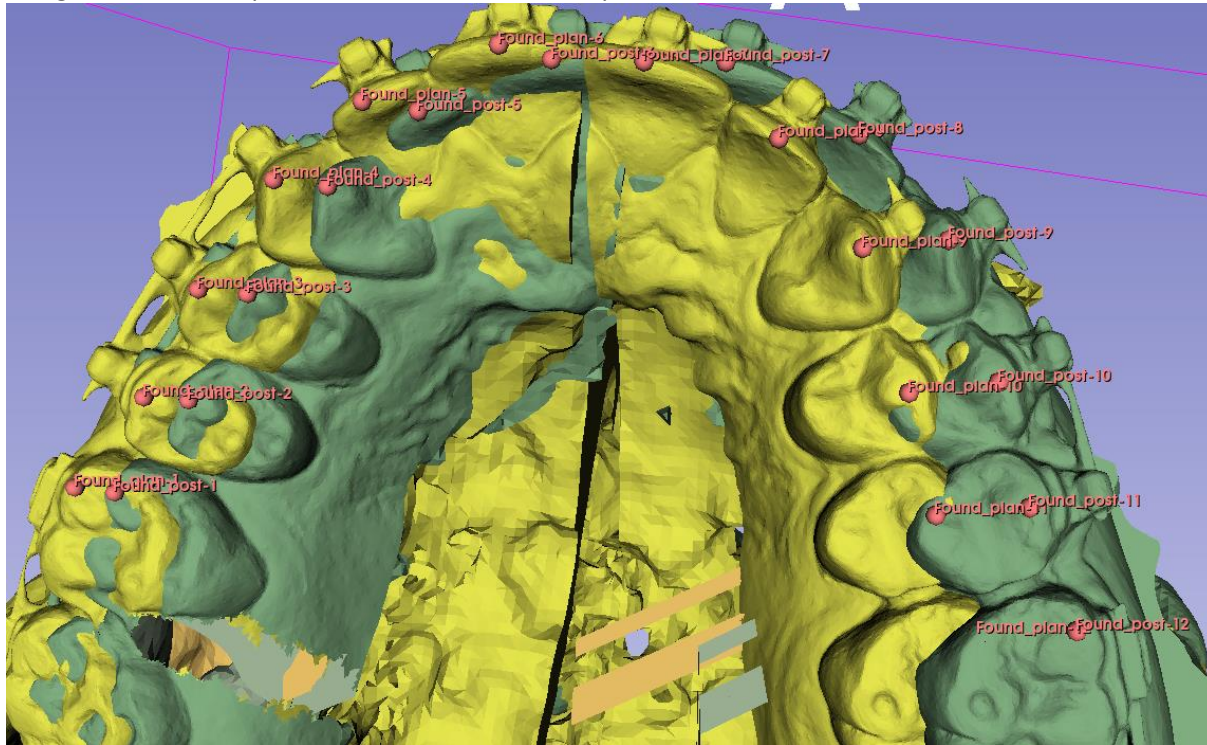

Figure 25: The OrthognathicDistanceCalculator analysis performed on Patient 4

label (tooth)	dx	dy	dz	vector
F-1 (16)	1.181526184	0.2161254883	-0.6577148438	1.36941709
F-2 (15)	0.9298400879	0.198600769	-0.501449585	1.07494025
F-3 (14)	0.6856079102	0.1258163452	-0.3528442383	0.7812726898
F-4 (13)	0.3663253784	0.04769134521	-0.1576843262	0.4016629109
F-5 (12)	1.170539856	-0.1946334839	-0.2946395874	1.222643952
F-6 (11)	1.415542603	0.6436233521	-0.3012237549	1.583902658
F-7 (21)	0.6056213379	1.22637558	-0.2609481812	1.392432484
F-8 (22)	0.5991134644	2.089752197	-0.2710037231	2.190763384
F-9 (23)	1.411270142	3.176761627	-0.684677124	3.542919786
F-10 (24)	0.6969909668	3.732837677	-1.010398865	3.929475715

F-11 (25)	0.1528167725	4.175113678	-1.258987427	4.363482157
F-12 (26)	0.01336669922	4.602592468	-1.636283875	4.884819445
Molaris (16-26)	1.168159485	-4.38646698	0.9785690308	4.643628592
Cuspid (13-23)	-1.044944763	-3.129070282	0.5269927979	3.340765151
Avg Seg 1	0.7908248901	0.1470584869	-0.4174232483	0.9062407923
Avg Seg 2	0.9477043153	0.9412794113	-0.2819538117	1.365155065
Avg Seg 3	0.5686111451	3.921826363	-1.147586823	4.125650999

Table 6: Data collection of Patient 4

In Table 6 it can be seen that segment 1 differs 0.79mm on average in the x direction, 0.15mm on average in the y direction and -0.42mm in the z direction. This means that segment 1 has a dextral displacement of 0.79mm within the accepted clinical significance of 2.0mm, a posterior displacement of 0.15mm within the accepted clinical significance of 2.0mm and an inferior displacement of 0.42mm within the accepted clinical significance of 2.0mm [7].

It can be seen that segment 2 differs 0.95mm on average in the x direction, 0.94mm on average in the y direction and -0.28mm in the z direction. This means that segment 2 has a dextral displacement of 0.95mm within the accepted clinical significance of 2.0mm, a posterior displacement of 0.94mm within the accepted clinical significance of 2.0mm and an inferior displacement of 0.28mm within the accepted clinical significance of 2.0mm [7].

It can be seen that segment 3 differs 0.57mm on average in the x direction, 3.92mm on average in the y direction and -1.15mm in the z direction. This means that segment 3 has a dextral displacement of 0.57mm within the accepted clinical significance of 2.0mm, a posterior displacement of 3.92mm outside of the accepted clinical significance of 2.0mm and an inferior displacement of 1.15mm within the accepted clinical significance of 2.0mm [7].

The widening measured at the 16-26 molars was made 1.17mm too narrow which is within the accepted clinical significance of 2.0mm. The widening measured at the 13-23 cuspids was made 1.04mm too wide which is within the accepted clinical significance of 2.0mm [7].

Patient 5

This patient has had a bimaxillary osteotomy done with a 2-segment Le Fort I osteotomy as can be seen in Figure 26. On this patient Createch fixation plates were used.
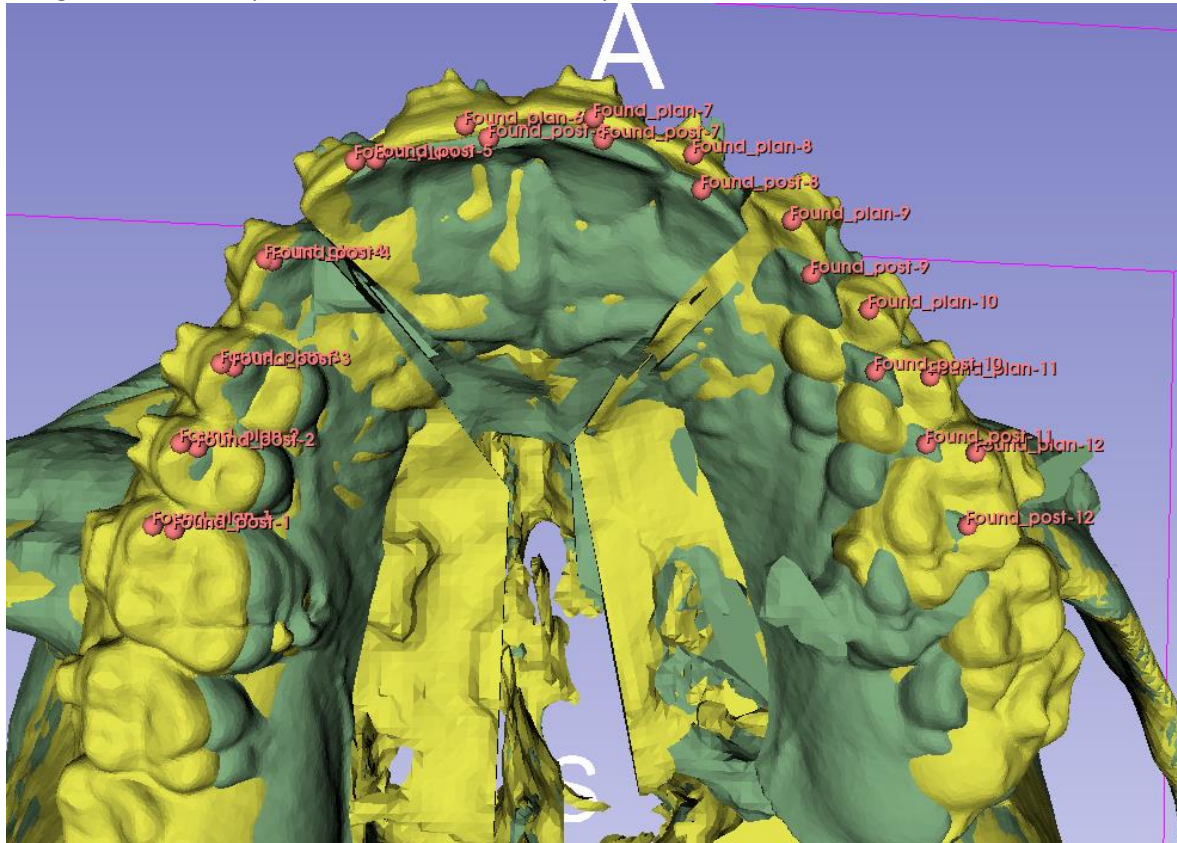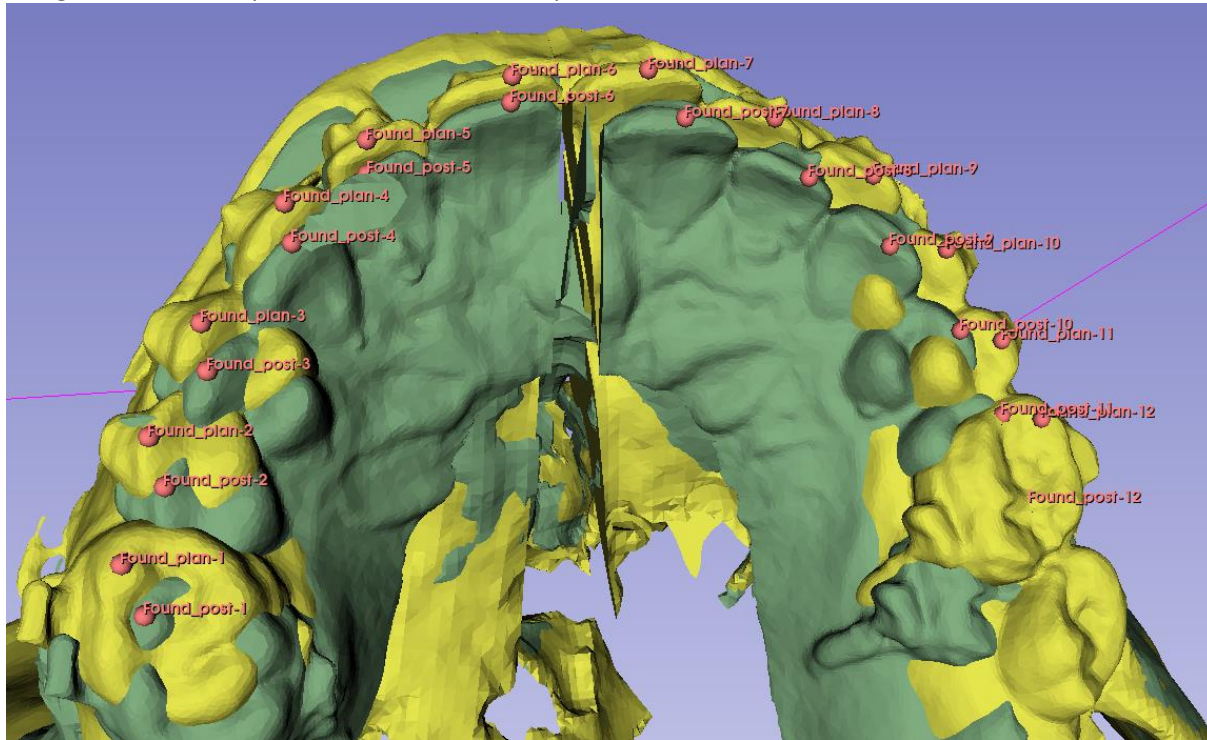

Figure 26: The OrthognathicDistanceCalculator analysis performed on Patient 5

label (tooth)	dx	dy	dz	vector
F-1 (16)	0.9513320923	2.722728729	-0.8408050537	3.004203325
F-2 (15)	0.6293106079	2.674331665	-0.5668411255	2.805243404
F-3 (14)	0.1477508545	2.63104248	-0.332824707	2.656122575
F-4 (13)	0.2312545776	2.36100769	0.006561279297	2.372315123
F-5 (12)	-0.1619644165	2.157089233	0.1588668823	2.168987118
F-6 (11)	-0.3338317871	1.809780121	0.3474578857	1.872825334
F-7 (21)	1.438026428	3.696941376	1.362365723	4.194202655
F-8 (22)	1.232086182	4.300193787	0.9528274536	4.573574436
F-9 (23)	0.1782836914	4.753551483	0.3265914917	4.768091733
F-10 (24)	0.1330871582	5.229816437	-0.327003479	5.241719511
F-11 (25)	-0.3748321533	4.614383698	-1.057098389	4.748735943
F-12 (26)	-0.9158172607	5.058162689	-1.817581177	5.452277724

Molaris (16-26)	1.867149353	-2.33543396	0.976776123	3.145566735
Cuspid (13-23)	0.05297088623	-2.392543793	-0.3200302124	2.414433899
Avg Seg 1	0.2439753215	2.39266332	-0.2045974732	2.413756791
Avg Seg 2	0.2818056743	4.608841578	-0.09331639612	4.618391829

Table 7: Data collection of Patient 5

In Table 7 it can be seen that segment 1 differs 0.24mm on average in the x direction, 2.39mm on average in the y direction and -0.20mm in the z direction. This means that segment 1 has a dextral displacement of 0.24mm within the accepted clinical significance of 2.0mm, a posterior displacement of 2.39mm outside of the accepted clinical significance of 2.0mm and an inferior displacement of 0.20mm within the accepted clinical significance of 2.0mm [7].

It can be seen that segment 2 differs 0.28mm on average in the x direction, 4.61mm on average in the y direction and -0.09mm in the z direction. This means that segment 2 has a dextral displacement of 0.28mm within the accepted clinical significance of 2.0mm, a posterior displacement of 4.61mm outside of the accepted clinical significance of 2.0mm and an inferior displacement of 0.09mm within the accepted clinical significance of 2.0mm [7].

The widening measured at the 16-26 molars was made 1.87mm too narrow which is within the accepted clinical significance of 2.0mm. The widening measured at the 13-23 cuspids was made 0.05mm too wide which is within the accepted clinical significance of 2.0mm [7].

Patient 6

This patient has had a bimaxillary osteotomy done with a 3-segment Le Fort I osteotomy as can be seen in Figure 27. On this patient conventional fixation plates were used.
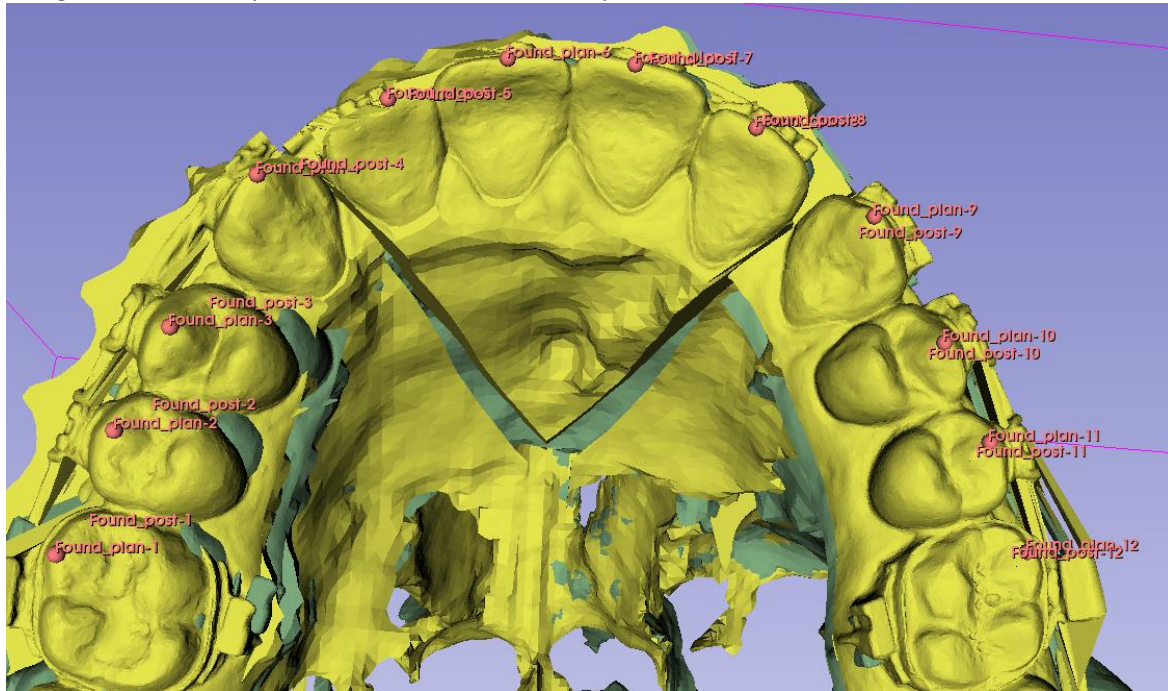

Figure 27: The OrthognathicDistanceCalculator analysis performed on Patient 6

label (tooth)	dx	dy	dz	vector
F-1 (16)	1.108467102	-2.109169006	-1.738571167	2.949563174
F-2 (15)	1.394432068	-2.011734009	-2.411445618	3.436071082
F-3 (14)	1.372543335	-2.37928772	-3.000289917	4.067754276
F-4 (13)	1.730636597	-2.334938049	-3.888641357	4.854747195
F-5 (12)	0.8382873535	-1.82598877	-3.533149719	4.064493525
F-6 (11)	0.8178253174	-1.849014282	-3.462753296	4.009782096
F-7 (21)	1.076057434	-1.956924438	-3.421562195	4.085895338
F-8 (22)	0.8384017944	-1.929836273	-3.370285034	3.97316081
F-9 (23)	-0.2621917725	0.0546836853	-3.50630188	3.516516416
F-10 (24)	-0.2199401855	0.0876083374	-3.157936096	3.166797956
F-11 (25)	-0.04208374023	0.259021759	-2.886573792	2.898477457
F-12 (26)	-0.1858978271	-0.02903366089	-2.588920593	2.5957486
Molaris (16-26)	1.294364929	-2.080135345	0.8503494263	2.5933449

Cuspid (13-23)	1.992828369	-2.389621735	-0.3823394775	3.134938663
Avg Seg 1	1.401519776	-2.208782196	-2.759737015	3.802515596
Avg Seg 2	0.8926429748	-1.890440941	-3.446937561	4.0313716
Avg Seg 3	-0.1775283813	0.0930700302	-3.03493309	3.041545203

Table 8: Data collection of Patient 6

In Table 8 it can be seen that segment 1 differs 1.40mm on average in the x direction, -2.21mm on average in the y direction and -2.76mm in the z direction. This means that segment 1 has a dextral displacement of 1.40mm within the accepted clinical significance of 2.0mm, an anterior displacement of 2.21mm outside of the accepted clinical significance of 2.0mm and an inferior displacement of 2.76mm outside of the accepted clinical significance of 2.0mm [7].

It can be seen that segment 2 differs 0.89mm on average in the x direction, -1.89mm on average in the y direction and -3.45mm in the z direction. This means that segment 2 has a dextral displacement of 0.89mm within the accepted clinical significance of 2.0mm, an anterior displacement of 1.89mm within the accepted clinical significance of 2.0mm and an inferior displacement of 3.45mm outside of the accepted clinical significance of 2.0mm [7].

It can be seen that segment 3 differs -0.18mm on average in the x direction, 0.09mm on average in the y direction and -3.03mm in the z direction. This means that segment 3 has a sinistral displacement of 0.18mm within the accepted clinical significance of 2.0mm, a posterior displacement of 0.09mm within the accepted clinical significance of 2.0mm and an inferior displacement of 3.03mm outside of the accepted clinical significance of 2.0mm [7].

The widening measured at the 16-26 molars was made 1.29mm too narrow which is within the accepted clinical significance of 2.0mm. The widening measured at the 13-23 cuspids was made 0.89mm too narrow which is within the accepted clinical significance of 2.0mm [7].

Results on the surgical success

After looking at all of the results, the surgical success of patients can be divided in two groups: Failure and success.

Firstly, only the placement of the segments has been evaluated. The patient would be categorised as a success if the average of all the segment displacements in the x, y and z direction stays within the clinically accepted significance of 2.0 mm [7]. Only one patient had all of the segments placed successfully. As can be seen in Figure 28, the success rate of the segment placement in this patient group was only 16.7%.

Secondly, only the widening of the segments has been evaluated. The patient would be categorised as a success if the deviation of the both widenings in the x direction (which is the direction in which a widening takes place) stays within the clinically accepted significance of 2.0 mm [7]. In this case, 5 patients had all widenings done correctly. Technically, one of these widenings was out of the clinically accepted range by 0.07mm, but as this difference is so small it is accepted in the success category. As can be seen in Figure 29, the success rate of the widenings in this patient group was 83.3%.

Lastly, both the widening and the placement of the segments has been evaluated. The patient would be categorised as a success only if both the widenings and the displacement stayed within the clinically accepted significance of 2.0 mm [7]. Only one patient had all of the segments placed successfully. Technically, the surgery on this patient is a failure as this patient had one widening out of the clinically accepted range by 0.07mm. This difference is so small that it is still accepted in the success category. As can be seen in Figure 30, the success rate of the segment placement in this patient group was only 16.7%.

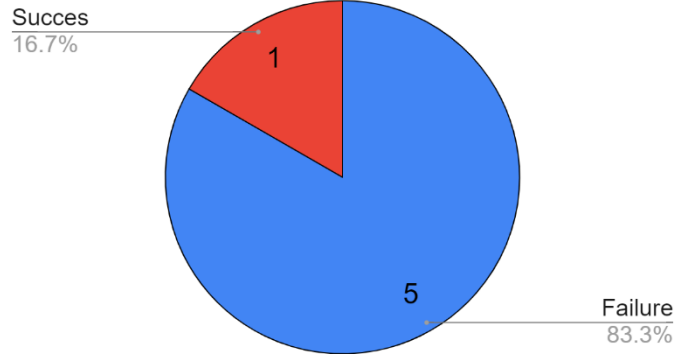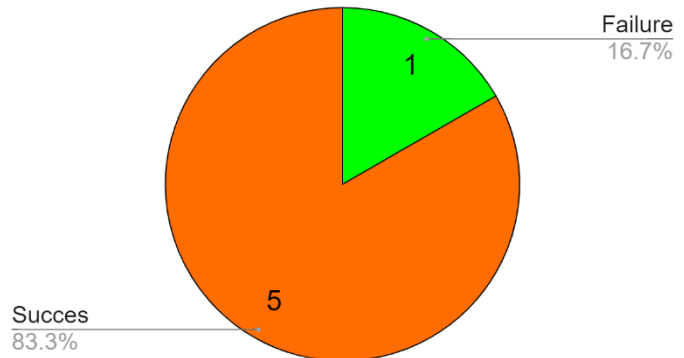Patients that had all segments placed correctly

Succes
16.7%

Failure
83.3%

Figure 28: A pie chart of the success rate of the segment placement

Patients that had all widenings done correctly

Failure
16.7%

Succes
83.3%

Figure 29: A pie chart of the success rate of the widenings

Patients that had all segments and widenings done correctly
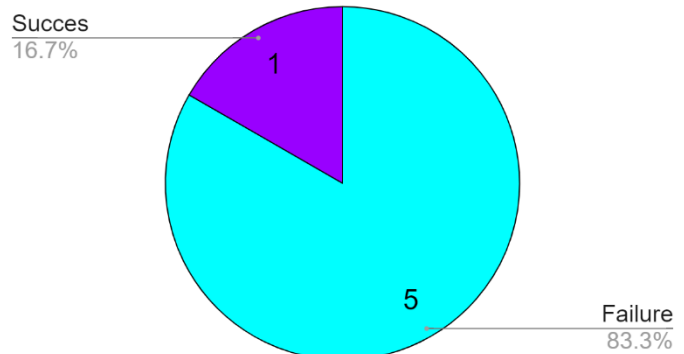

Succes
16.7%

Failure
83.3%

Figure 30: A pie chart of the success rate the segment placement and widenings

Results on the type of displacements

When evaluating the surgery, it is not only important to know how many surgeries were a success or a failure, it is also important to know what kind of displacement is made. Maybe a surgeon has the habit to place segments a little bit more dextral than he or she is supposed to. The amount of segments were counted for each type of displacement and categorised on clinical significance as can be seen in Table 9.

Amount of displacements within the specified range				
Axis	Displacement	-0.5mm to 0.5mm	±(0.5mm to 2.0mm)	<-2.0mm and >2.0mm
dx	sinistral	1	2	0
	dextral	2	7	3
dy	anterior	1	1	1
	posterior	4	5	4
dz	inferior	5	4	3
	superior	3	1	0
widening	wide	2	2	1
	narrow	0	7*	0

Table 9: the amount of segments that were displaced in a certain way

*One of the segments is technically outside of the clinically accepted range of 2.0mm [7], but as it is only 0.03 mm too much, it is still acceptable.

As shown in Table 9, there are more segments placed dextral than sinistral. There are also more segments placed dextral that are not clinically accepted.

There are more segments placed posterior than anterior. There are also more segments placed posterior that are not clinically accepted.

There are more segments placed inferior than superior. There are also more segments placed inferior that are not clinically accepted.

There are more segments placed too narrow than too narrow. In this case, there is one segment placed too wide that is not clinically accepted, while none are placed significantly too narrow.

Conclusion

The OrthognathicDistanceCalculator has shown to be a really accurate method to analyse the differences between a 3D planning and a post operational 3D model. All of the requirements and wishes have been implemented in this analysis method. Apart from being free and open source, it is easy to use and quicker than 2D cephalometry in ProPlan. It has a lot of potential to be used in larger case studies and could be even more useful as a lot of implementations could be added to the code.

A proper conclusion about the accuracy of segmented bimaxillary osteotomies cannot be made as no statistical analysis was done. However, the results do imply that this surgical procedure is rather unsuccessful as only one out of five patients had no clinically significant deviations of over 2 mm in relation to the 3D planning [7]. It also seems that the overall displacements are done more towards dextral, posterior and inferior. The widenings do not seem to be significantly too narrow or wide. The surgeons should try to move segments a little bit more sinistral, anterior and superior.

Discussion

Quite a few additions and improvements could be added to the OrthognathicDistanceCalculator to upgrade the accuracy and abilities of the program:

The accuracy OrthognathicDistanceCalculator could be improved by calculating the occlusal plane derived from the markup points and using the axis perpendicular to that plane instead of using the z axis. This could result in better apex locating.

The script could be automated a bit more by using teeth names instead of the names of the markup nodes. This would simplify and quicken the research process.

The OrthognathicDistanceCalculator should automatically recognise the STL files that are opened in 3D Slicer so that the user does not have to manually change that in the script.

A downloadable extension should be made that can be used directly in 3D Slicer so that the user does not have to manually adapt a python script. This widget should allow the user to change all the parameters that at the moment, have to be changed in the script like: The axis in which the markup node selects the highest coordinate, the type of jaw that is being researched.

The average displacement of each segment was calculated in excel. This could be included in the script of the OrthognathicDistanceCalculator in the future.

If the first twelve markup nodes could be relocated based on the lowest z coordinate and the 13th to 24th teeth could be relocated based on the highest z coordinate, an analysis method can be made that analyses both the maxilla and mandible in one go. This would also allow the user to make conclusions about the occlusion and the midline.

The OrthognathicDistanceCalculator is more accurate when the markup points are placed closer to the apex of the teeth. This means that more experience will result in more accurate results, which should be taken into account when doing an analysis.

As the mandible is not assessed, no conclusions could be made on the success of the occlusion. This could be implemented in future studies.

The case analysis was lacking in quite a few aspects:

Only a limited number of patients that fit the requirements to be included in this research, could be obtained within the limited amount of time this internship offered. There were more patients that had a segmented bimaxillary osteotomy done, but some had no intraoral scans available and some patient cases had no post operational scans available yet. The documentation of patients data was not saved well, which made it difficult to know if the bimaxillary osteotomy included a segmented Le Fort I osteotomy or not.

The limited number of patients and the limited amount of time is why a proper statistical analysis could not be done to make a proper conclusion about the overall accuracy of segmented bimaxillary osteotomies.

The small number of cases is also the reason that no conclusions could be made about the differences between Createch versus conventional and 2-segmented versus 3-segmented Le Fort I osteotomies.

As the mandible has not been researched, no conclusions could be made about the correction of the malocclusion.

An error of 0.00mm was used to calculate the results. The errors of the CBCT scan and the superimposition methods were not included in the results, because it is almost never included in other research papers. Including it would give the OrthognathicDistanceCalculator an unfair disadvantage compared to other analysis methods.

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Afterword

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