3D Assessment of the skeletal stability of the surgery-first approach for orthognathic correction of maxillary deficiency

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ABSTRACT

Introduction

Stability is one of the important criteria for determining the success of orthognathic surgery. Stability is defined as the maintenance of the skeleton and associated dental structures in the intended postoperative position over the long-term. The stability following surgery-first and orthodontic-first approach might be affected by the quality of occlusion, a fact which is not yet confirmed. Skeletal, dental and surgical factors can affect the post-operative stability (Jackson & Golden, 2016). These factors include degree of incisor inclination, overjet, overbite, depth of the curve of Spee, mandibular and maxillary plane angles, occlusion, as well as rotation of maxilla-mandibular complex, condylar position, alterations of masticatory muscle, the magnitude of jaw movement and method of fixation (Jackson & Golden, 2016; Peiro-Guijarro et al, 2016)

One of the main objectives of orthognathic surgery is skeletal stability, which can be categorized into short and long-term stability. Short-term stability can be defined as physiological adaptation, directly related to the post-surgical healing and orthodontic treatment. The long-term stability is influenced by surgical or patient-related factors and orthodontic treatment. The pre-operative orthodontic alignments maximize the optimal surgical repositioning of the jaws, while the postoperative orthodontic treatment ensures refinement of occlusion and retention (Proffit et al, 2007).

In the surgery-first approach, orthodontic dental alignment and decompensation are deferred until after surgery, therefore, the surgical occlusion is different from the final occlusion and expected to be unstable due to premature occlusal contacts. The unstable occlusion may hinder the long-term skeletal stability, leading to skeletal relapse (Nagasaka et al, 2009; Soverina et al, 2019).

Nadjmi et al. (2010) stated that a stable dental occlusion is one of the key goals in orthognathic surgery planning, since it defines the postoperative position of the maxilla and mandible (Nadjmi et al, 2010).

Meanwhile, the quality of postoperative occlusion and its influence on skeletal stability has not been fully understood. There are no consistent evidence or criteria to define the post-operative occlusion. Some studies have reported no statistically significant differences in postoperative stability between surgery-first and conventional approach (Choi et al, 2015; Choi et al, 2016; Park et al, 2016), while others stated that surgery-first was less stable than conventional approach due to lower quality of post-operative occlusion (Kim et al, 2014b; Ko et al, 2013).

Aims

The aim of this project was the 3D assessment of the skeletal stability in skeletal class III patients who underwent Le Fort I osteotomy by surgery-first approach. The second aim of the study was to assess the relationship between immediate post-operative occlusion and skeletal stability.

Methodology

The study was carried out on the pre- and post-operative CBCT images of 25 patients who received their orthognathic surgery treatment at Glasgow dental hospital and school, Glasgow, UK. Skeletal class III patients who underwent Le Fort I maxillary osteotomy by surgery-first approach and had complete CBCT records were included. Ethical approval was obtained from the NHS Greater Glasgow & Clyde (R & D reference: GN20OD634, REC reference: 21/NE/0019). Patients were selected from the Glasgow Dental School database from 2012-2022.

All patients were diagnosed with maxillary retrognathism, which required orthognathic surgical correction. Patients who had previous facial surgery, cleft lip and palate cases, or history of dentofacial trauma were excluded. The CBCT scans taken within one week prior to surgery (T0), at 1 week (T1) and 6 months following surgery (T2) were used for the analysis. The pre- and post-operative CBCT DICOM images of each patient were segmented at HU=276 to generate the STL files. Total of 3 STL files were generated for each patient. The 3D STL models were assessed with VRMesh software (Virtual Grid, Seattle City, U.S.A), to measure the surgical and skeletal changes. The anterior cranial base, zygomatic arches, and forehead unaffected by surgery, were used for the registration of postoperative (T1, T2) 3D models to the preoperative (T0) 3D model using Surface-based registration (SBR). The maxillary right and left greater palatine foramen and incisive foramen were selected to measure 3D surgical movement (T0-T1) and skeletal changes (T1-T2).The translation and rotation of the coordinates of these 3 landmarks were reported in six degrees of freedom along x, y, z axis; left/right (L/R), anterior/posterior (A/P) and superior/inferior (S/I) and pitch, roll and yaw. The dental study models taken at one day before surgery, were scanned using 3Shape intra-oral scanner (TRIOS3, 3shape A/S, Copenhagen, Denmark) and imported to IPS Case Designer® software (KLS Martin, Tuttlingen, Germany) for replacement of the defective dentition of postoperative CBCT scans (T1). The occlusal colour map representing the distances between the maxillary and mandibular dentition was generated within the VRMesh software (Virtual Grid, Seattle City, U.S.A). The inter-occlusal distance of -0.5 to 0.5mm was defined for visualisation of the occlusal contacts. The anterior region from the right canine to left canine and posterior regions extending from the Premolars to 2nd molars of the right and the left sides were defined. The distribution of occlusal contacts was divided to three regions, two regions, and the one region group. The overjet, overbite, and number of teeth in occlusal contacts were recorded.

The statistical significance of mean surgical movements (T0-T1) and skeletal relapse (T1-T2) were measured with Paired t-test or Wilcoxon signed test for normal and non-normal data, respectively. Pearson's or Spearman's correlation analysis was applied for assessment of the relationship between skeletal relapse at 6-month following surgery and the quality of the occlusion immediately following surgery. The correlation between magnitude of surgical movements and the stability at 6 months was measured. Probabilities of 0.05 or less were accepted as significant.

Results

The result showed no statistically significant difference between the repeated measurements of skeletal changes (T0-T1) and relapse (T1-T2). The maxilla was positioned in forward direction by (6.79 $\pm$ 2.3 mm), (1.28 $\pm$ 1.09 mm) in vertical direction and (0.71 $\pm$ 0.79 mm) medio-lateral movement. The absolute mean relapse of maxilla was 0.72 $\pm$ 0.43 mm backward, 0.57 $\pm$ 0.43 mm vertical and 0.30 $\pm$ 0.33 mm in medio-lateral direction. Between T0-T1, there was a significant difference in overjet (mean = 6.94 $\pm$ 2.42, *P:* <0.001), overbite (mean = 2.56 $\pm$ 2.58, *P:* <0.001) and the category of the occlusal contact (mean = 0.53 $\pm$ 1.27, *P:* 0.041). The Spearman correlation coefficient showed a weak correlation between the magnitude of maxillary advancement and the relapse at T2. There was a weak correlation between the Roll, Yaw, and Pitch of the surgical movements and the detected relapse at T2. A weak negative correlation (r: -0.434, *P*: 0.030) between number of the teeth in contact and the relapse of the maxillary roll was detected.

Conclusion

Le Fort I maxillary advancement is reasonably stable, the measured relapse ranged between 1 mm and 1 degree, which is clinically insignificant. There was a weak correlation (r:0.204) between relapse at 6 months and the magnitude of maxillary surgical advancement. There was no strong correlation between the quality of immediate post-operative occlusion and the relapse at 6 months following surgery.

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AUTHOR'S DECLARATION

I declare that, except where explicit reference is made to the contribution of others, this thesis is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

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LIST OF ABBREVIATIONS

2D - Two dimensional

3D – Three dimensional

CBCT - Cone Beam Computed Tomography

CT - Computerized Tomography

MRI - Magnetic Resonance Imaging

HU - Hounsfield Unit

PPA - Partial Procrustes Analysis

LBR – Landmark Based Registration

SBR - Surface Based Registration

VBR - Voxel Based Registration

ICP - Iterative Closest Point

DICOM - Digital Imaging Communications in Medicine

STL – Standard Tessellation Language

ICC - Interclass Correlation Coefficient

SFA - Surgery First Approach

OFA - Orthodontic First Approach

COA - Conventional Orthognathic Approach

RMS - Root mean square

BSSO - Bilateral Sagittal Split Osteotomy

AOB – Anterior open bite

ANS – Anterior nasal spine
PNS – Posterior nasal spine
SNA – Sella Nasion angle
SNB - Sella, nasion, B point
ANB - A point, nasion, B point
OB - Overbite
OJ - Overjet
IVRO - Intraoral Vertical Ramus Osteotomy
RCT – Randomised control trials
PAR - Peer Assessment Rating
ABO - American Board of Orthodontics
DI - Discrepancy Index
IMPA - Incisor Mandibular Plane Angle
IOTN - Index of Orthodontic Treatment Need
IOFTN - Index of Orthognathic Functional Treatment Need
ICON - Index of complexity, outcome, and need
MDT - Multidisciplinary Team
ES - Effect size
FH - Frankfort horizontal
IF - Incisive foramen
RGP - Right Greater palatine foramen
LGP - Left Greater palatine foramen

ME - Measurement error
AI - Artificial Intelligence
DL - Deep Learning
CNN - Convolutional Neural Networks
ASM - Active shape model
MSCT - Multi-slice computed tomography
RAP - Rapid acceleratory phenomenon
MPO - Minimal Preoperative Orthodontic treatment
TAD - Temporary Anchorage Devices

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1.1 3D IMAGE ANALYSIS

Traditionally, cephalometric radiographs were used to quantify and determine craniofacial growth changes as well as for orthodontic diagnosis and treatment planning. However, two dimensional (2D) cephalometric radiographs have inherent limitations which include the magnification, distortion, and the technical difficulty in parasagittal landmarks' identification.

Recently, the innovations in three-dimensional (3D) imaging technology allow a more accurate capturing of patient's face for the comprehensive diagnosis of the dento-facial deformities and treatment planning. The 3D imaging has improved the evaluations of facial changes and treatment outcomes in orthognathic surgery (Ponce-Garcia et al, 2018).

The 3D morphology of the skin of the face has been successfully captured using laser scanners and Stereophotogrammetry, or by methods that penetrate through the surface which includes CBCT, CT scans and MRI. The matrix of a 2D image slice is composed of several squares called pixels of a standardized height, width, and a value of grayscale level (Yitschaky et al, 2011). The grayscale represents the X-ray beam attenuation of the tissue. When combining multiple slices to generate 3D images, the thickness of the slice creates an additional volume element known as voxel. Voxels are volumetric units with x, y, and z dimensions. Each individual voxel has a Hounsfield Unit (HU). A HU represent the x-ray attenuation coefficient of the captured tissue in relation to the attenuation of an equal volume of water. The HU of water is zero, it is used as the reference material due to its uniform density and its abundance in the human body. The range of HU values varies from -1000 for air to +4000 for metals (Grauer et al, 2009).

The 3D modelling is a mathematical rendering of the 3D images acquired from multi-range scanners, CT, and MRI. It is utilized for the diagnosis, simulation, and treatment planning in the medical field. The 3D models segmented from these images are usually rendered in 3D polygonal mesh form. A mesh is a set of points "vertices", and it contains information about how these vertices are linked. They represent the details of objects' surface topography. Various algorithms have been applied for building-up a polygonal surface mesh from a scanned image. The most used 3D model construction algorithm is the Marching Cubes algorithm, developed by Lorensen and Cline in 1987 (Newman & Yi, 2006; Yemez & Schmitt, 2004).

The Marching cubes algorithm utilizes the divide-and-conquer approach to locate the surface in a cube (voxel) created from eight pixels, four from each two adjacent slices. The algorithm determines the polygon(s) needed to represent the surface that intersects one cube, then moves to the next cube. Each cube has 8 vertices with an assigned value. If the value at each vertex exceeds or equals the value of the surface being constructed, then the vertex is then inside or on the surface. Vertices below the assigned value are outside the surface. The algorithm calculates an index for the cube by comparing the eight density values at the cube vertices with that of the representing surface. The generated index tells which surface intersects with the representing surface. The algorithm uses a table of edge intersections to describe how a surface cuts through each cube in a 3D data set. Finally, each vertex of the generated polygons is placed on the appropriate position along the cube's edge by linearly interpolating the two values that are connected by that edge to create a triangle which is the base unit of the surface mesh that describes the shape of the 3D surface (Lorensen, 2020). Once the 3D surface mesh of the model is generated, it can be utilized for visualizing the 3D captured skeletal and soft tissue surfaces for analysis and assessment of the changes or treatment outcomes. In order to assess these changes over the time, sequential images are captured and superimposed on anatomically stable structure (Weissheimer et al, 2015).

1.1.1 3D Image superimposition

Superimposing tracings of serial lateral cephalograms has been utilized to monitor craniofacial growth and monitor the changes of orthodontic treatments and orthognathic surgery. The 2D cephalometric superimposition process requires a reference that is visible and stable during the observation period. Several studies have reported the anterior cranial base as reference for the superimposition of a sequence of cephalography since there is little or no growth of this region after age 7 to 8 years (Arat et al, 2010; Lenza et al, 2015). The cranial base remains morphologically stable and unaffected by surgery; therefore, it is considered as the most reliable reference base for image superimposition, however, nowadays superimposition of CBCT scans allows a 3D visualization of craniofacial changes. Similarly, 3D models constructed of the CBCT scans can be superimposed by registering the images on the anterior cranial base. The superimposition method should be able to register precisely and aid understanding of the changes as a result of growth and/or treatment relative to the structure of reference. Three main approaches of superimpositions have been applied widely. These are landmarks-based registration, surface-based registration, and volume (voxel) based registration (Arat et al, 2010; Haner et al, 2020; Weissheimer et al, 2015).

The landmarks-based registration (LBR)

Once the homologous landmarks on two images are identified, the translation and rotation of one image, bring the corresponding landmarks into their best fit relying on centroid match **(Figure 1)**. The Centroid is the geometric centre of an object that its surface points are on an average distance to this central point (Rohlf, 1999). The scaling is avoided to preserve the facial geometry without the effect of the size; therefore, it is called Partial Procrustes Analysis (PPA). This method is less precise when a small number of landmarks are selected. Additionally, the method suffers from the errors associated with the manual landmarking and increased risk of observer dependent errors (Hajeer et al, 2004).

The surface-based registration (SBR)

The registration is implemented by Partial Procrustes Analysis which involve translation and rotation to approximate the two 3D surface models. To maximise the superimposition, an Iterative closest point (ICP) algorithm is applied. The algorithm searches for corresponding points between the two 3D models, until the square root distance between the two surface models is minimized to achieve the maximum superimposition. The surface-based analysis is carried out by calculating the mean and maximum values of the linear distances (Euclidean distance) between the surfaces. The morphological differences between the superimposed structures are represented by different colours through a colour coded map (Almukhtar et al, 2014). **(Figure 1)**

The voxel-based Registration (VBR)

Cevidanes et al. (2005) introduced voxel-based registration for fully automated 3D superimposition of CBCT images in dentofacial area. The registration algorithm is based on maximizing mutual information. The algorithm utilizes the greyscale difference to align the two images, achieving the least total greyscale density. Utilizing the cranial base as region of reference, the two 3D images are automatically superimposed with an iterative translation and rotation of the DICOM image volume. **(Figure 1)** Following the superimposition, the two superimposed images are segmented and export as 3D surface model in STL format. The Euclidean distances between the two images are assessed by a 3D colour coded map (Cevidanes et al, 2005).

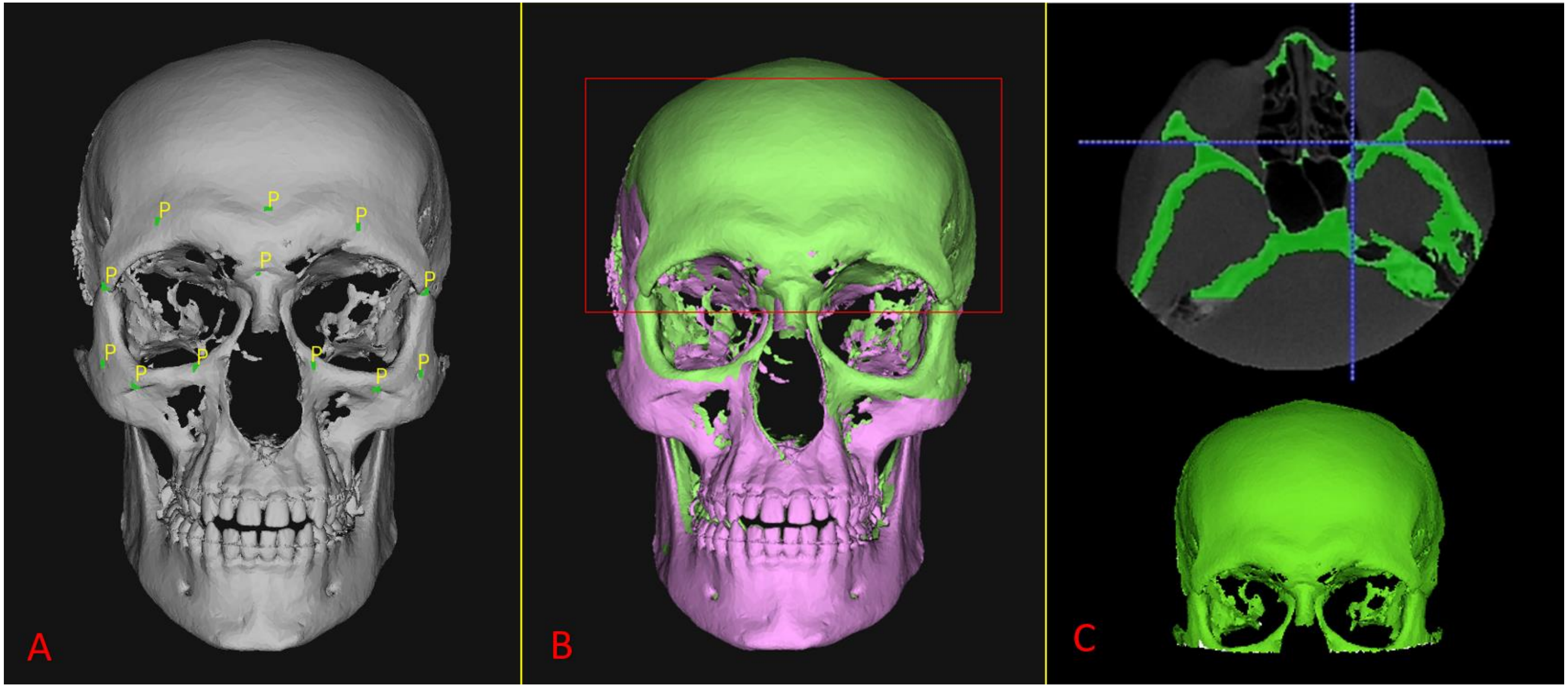

Figure 1. The three registration methods: A: Landmark based registration. B: Surface based registration. C: Voxel based registration

1.1.2 Comparison between methods of 3D image superimposition

The accuracy and reliability of the above three different methods of superimpositions were assessed in study by Ghoneima et al. (2017). The pre- and post- treatment CBCT images of 20 patients who underwent orthodontic treatment were superimposed on anterior cranial base as reference. The reliability and accuracy of the superimpositions were assessed by selecting 11 landmarks on maxillo-mandibular complex. The three superimposition methods showed an overall high degree of reliability with ICCs over 0.90, with ICC being statistically higher in landmark-based superimposition compared to the other two methods. The results showed that the surface-based superimposition was highly reliable, However, it was a technique-sensitive method. The landmark-based superimposition method was reliable but less accurate than the other two methods, surface- based and voxel-based superimposition methods using the anterior cranial base as a reference structure were accurate and reliable in detecting changes in landmark positions. The study reported that accuracy and reliability of the superimposition methods are directly dependent on the precision of identification of the anatomic structures that are used for registration (Ghoneima et al, 2017).

Ponce-Garcia et al., (2020) Compared landmark-based registration and voxel-based registration methods by 2 software: CMFreg (Craniomaxillofacial registration) Slicer and Dolphin software. The CBCTs of 36 patients (11-14 years) at before (T1) and after (T2) orthodontic treatment were used. The intra-rater reliability with the voxel-based registration and landmark-based registration were calculated for CMFreg Slicer and Dolphin software. The voxel-based registrations using CMFreg Slicer and Dolphin software showed similar mean differences between T1 and T2. On the other hand, the landmark-based registration showed mean differences as high as twice the mean differences obtained with the voxel- based registration. The Intra class correlations (ICC) were the lowest when comparing the landmark-based method with voxel- based method. Moderate to excellent agreement was observed when comparing the voxel-based methods against each other (CMFreg Slicer versus Dolphin software). The results showed that landmark-based registration generated the highest measurement error (Ponce-Garcia et al, 2020).

Han et al. (2021) evaluated the accuracy and reliability of voxel-based and surface-based registrations using the CBCT of mandible of 27 adult orthodontic patients. The pre- and post-orthodontic CBCT scans of mandible were superimposed using the mandibular body, from symphysis to the first molar, as the reference. To evaluate the accuracy the absolute mean distance between the seven areas including chin, bilateral mental foramen, bilateral gonion region, and bilateral ramus region of the mandible were measured. The absolute mean distance between the voxel- and surface-based registration methods showed no significant differences. The ICC results for the inter-observer reliability (ICC:0.91) showed both methods had high reliability, with surface-based registration (ICC 0.918–0.990) being slightly lower than voxel-based registration (ICC 0.984–0.996). The study reported that the two methods for CBCT mandibular superimposition using the body as reference, are accurate and reliable (Han et al, 2021).

The review of the literature showed that the voxel-based superimposition method is the most efficient, reliable and accurate since it does not depend on the accuracy of landmark identification, the precision of the 3D surface models or the accuracy of segmentation (Almukhtar et al, 2014; Koerich et al, 2016; Nada et al, 2011; Weissheimer et al, 2015).

The study by Weissheimer et al. (2015) tested the validity of voxel-based registration on On-Demand3D software (Cyber med, Seoul, Korea). The CBCT of 18 orthodontics patients were superimposed on anterior cranial base to measure the pre- and post-treatment differences. The precision of the On-Demand3D voxel-based superimpositions was verified by quantification of the surface distances using colour coded map. It was reported that the superimposition error was less than 0.5 mm (Weissheimer et al, 2015).

Similarly, Nada et al. (2011) tested the accuracy and reproducibility of CBCT superimposition on the anterior cranial base and the zygomatic arches using voxel-based registration. Sixteen pairs of 3D CBCT models were constructed from pre and post treatment CBCT scans of patients who underwent combined orthognathic surgery and orthodontic treatment. Each pair of CBCTs were registered on the anterior cranial base and on the left zygomatic arch using voxel-based superimposition in Maxilim Software (Medicim Medical Image Computing, Belgium). Following the superimposition, the mean absolute distances between the 2 models were calculated at 4 regions: anterior cranial base, forehead, left and right zygomatic arches. The resulted mean differences were ranged between 0.12 to 0.19 mm at the 4 regions. The study reported that voxel-based registration on both anterior cranial base and zygomatic arch could be considered as an accurate and reproducible method for CBCT superimposition (Nada et al, 2011).

Koerich et al. (2016) assessed the accuracy and reliability of the 3D regional voxel-based superimposition of CBCT scans of 14 non-growing patients underwent orthodontic treatment compared to CBCT of 2 dry skulls as gold standard. The cropped pre- and post-treatment mandibular and maxillary CBCTs were superimposed using On-Demand 3D software. The smallest distance between the two surfaces was reported as the root mean square (RMS). An RMS value smaller than 0.25 mm (the voxel size) was used as a parameter to assess the accuracy of superimposition. The results showed that ICC was excellent (≥0.980) for all measured areas, ensuring the reproducibility of the measurements. The RMS of dry skulls were < 0.25mm, while 68% of the patients had RMS smaller than 0.25mm, which could be due to the regional superimposition. The study concluded that voxel-based superimposition appears to represent the gold standard when the cranial base is used as the reference and will probably also represent the gold standard for regional superimposition in the future (Koerich et al, 2016).

In comparing the voxel-based registration with surface-based registration Almukhtar et al.,2014 performed the superimpositions of pre-operative and 6 months post-operative CBCT images of 31 patients who underwent orthognathic surgery. Voxel based registration was performed on Maxilim software (Medicim-Medical Image Computing, Belgium) and surface-based registration was performed on VRMesh software (Virtual Grid, Bellevue City, WA). The accuracy of the superimposition was reported by mean value of the absolute distance between the two 3D images. The results showed no significant difference between the two superimposition methods (P<0.05), However, high variability in the mean distances between the corresponding surfaces was reported for surface-based registration of soft tissue. The study highlighted that voxel-based registration allows easy assessment of the inner surfaces, since the superimposed structures can be viewed in the multiplanar slices (axial, sagittal and coronal) (Almukhtar et al, 2014).

1.1.3 Commercially available software packages

Over the past 10 years, studies have reported on advantages of cone-beam computed tomography (CBCT) over spiral multi-slice CT. CBCT scans, with a significantly lower radiation dose, provide similar imaging quality and the facility to zoom on a specific anatomic area with the higher resolution. The CBCT also overcomes some inherent flaws of 2D imaging, such as patient's head position, image magnification and distortions (Evangelista et al, 2010; Liang et al, 2010). The CBCT scans are broadly used to assess facial asymmetries, skeletal treatment outcomes and for surgical planning. They facilitate the assessment of the maxillofacial structures in variable thickness of the axial, coronal and sagittal slices (Kapila et al, 2011).

In the past decade, several commercial software programs have been developed to facilitate image analysis. The software allows users to approximate and register CBCT scans or the surface models and perform 3D analysis and quantification of changes at different time-points.

The most commonly used ones are open-source software, ITK-Snap and 3DSlicer, which allow users to segment volumetric models, approximate and register CBCT scans or surface models, and allow 3D analysis (Weissheimer et al, 2015).
Some of the commercial software available are *Dolphin* Imaging (Dolphin Imaging and Management Solutions, Chatsworth, CA, USA), It has the facility of a semi-automatic landmark-based registration process that allows the user to manually adjust the position of CBCT images and visualize the changes between the two images. The *In Vivo* Dental (Anatomage, San Jose, CA, USA) and Maxilim Software (Medicim NV, Mechelen, Belgium) allows voxel-based registration. The 3dMDvultus (3dMD, Atlanta, Georgia, USA) software uses a surface-based registration process where users manually select the stable anatomic regions to be registered when superimposing images taken at different time points. The OnDemand3D (Cyber med, Seoul, Korea) software has the functionality of voxel-based superimposition (10-15 seconds) and has a user-friendly interface (Choi & Mah, 2010; Weissheimer et al, 2015).

The literature shows that superimposition of CBCTs utilizing available software has been reliable for both adult and growing patients. These software are user-friendly, does not require extensive training of the operators and facilitate superimpositions in a few seconds or minutes (Gupta et al, 2015).

1.2 STABILITY FOLLOWING ORTHOGNATHIC SURGERY

The combined orthognathic surgery and orthodontic treatment is the conventional approach for correction of dentofacial deformities with a satisfactory outcome. However, masticatory muscle activity, preoperative and postoperative orthodontics, surgical complications, inefficient fixation of bone segments, and the extent of the surgical movement can lead to bone instability and relapse (VanSickels & Richardson, 1996). Stability has been evaluated primarily with the analysis of the 2D images including lateral and frontal cephalograms. The changes in landmark locations were registered in 2D as x, y coordinates. However, errors in landmark selection, magnification, distortion and the technical difficulty in tracing are the main challenges associated with 2D cephalometric analysis (Proffit et al, 1996).

The first hierarchy of stability of the orthognathic surgical procedures was based on the percentage of patients who experienced changes following conventional orthognathic surgery was published by Proffit et.al. (2007) (Proffit et al, 1996; Proffit et al, 2007). The study assessed the stability of orthognathic surgery by superimposition of lateral cephalometric radiographs taken before surgery, at 1 year and 5 years post-operatively. The changes of <2mm, 2° were reported as clinically insignificant and considered highly stable. Changes between 2–4 mm, 2°-4° were potentially clinically significant. The changes of >4 mm, 4° classified as beyond the range of orthodontic compensation and falls into problematic group. The study highlighted the importance to differentiate post-surgical stability (changes in the first post-surgical year) which relate directly to the surgical healing, post-operative orthodontics, and short-term physiologic adaptation, from long-term adaptation and possible post-operative growth in younger group of patients. The result showed that during the first post-surgical year maxillary superior impaction and mandible advancement were in highly stable category. Maxillary advancements were stable in 80% of the patients while isolated mandibular setback, downward movement of the maxilla and maxillary expansion fall into problematic category.

The study concluded that long term clinically satisfactory results can be obtained and maintained in majority of orthognathic surgical procedures, however, the differences among various directions of movement, skeletal pattern and different surgical approach may affected the results. Furthermore, their presented results were based on the evaluation of the patients who underwent conventional orthodontic-first approach (OFA) orthognathic surgery, and no clear methodological criteria or statistical analysis were provided.

The overview of systematic reviews by Haas et al. (2019) aimed to provide a hierarchy of stability in orthognathic surgery with the aid of the highest level of scientific evidence. The systematic search was conducted in the PubMed, Embase, and Cochrane databases and included eight systematic reviews and seven meta-analyses. The included studies evaluated the stability by the percentage of skeletal relapse. The percentage relapse was categorized as ‘highly unstable’ (relapse between 75-100%), ‘unstable’ (relapse between 50-74.9%), ‘stable’ (relapse between 25-49.9%), or ‘highly stable’ (relapse between 0-24.9%). The result showed that stability was evaluated by superimposition of cephalometric radiographs. When evaluating the stability in sagittal plane, maxillary advancements were highly stable (relapse < 0% to 19.7% and 0% to 18.06% for segmental osteotomy) while maxillary setback were unstable with relapse rate between 44.57% to 55.7%. Mandibular advancements were highly stable with relapse rate between 4.14% to 12.06%, while mandibular setback was classified as stable with relapse rate 26.65% to 45%.

In vertical plane, the maxillary impactions were in stable category with relapse rate of 19.7% to 49.45%. The maxillary downward movements were unstable with 73.1% relapse rate. Bilateral sagittal split osteotomy for clockwise rotation of the mandible and posterior maxillary expansion were considered highly unstable. The hierarchy of stability proposed in their review was the combined result of the experience of several surgeons, different methods of fixations and 2D analysis of stability of orthodontic-first approach (OFA). The review suggested there is a need to improve the level of scientific evidence of primary studies by conducting well-designed clinical trials and three-dimensional analysis of pre and post-operative CBCT scans (Haas et al, 2019).

1.2.1 Surgery-first versus Orthodontic-first approach

Conventionally, orthognathic surgery involves pre-surgical orthodontic preparation, followed by surgical correction of skeletal discrepancy and post-surgery orthodontic treatment. The pre-surgical orthodontic treatment provides a stable occlusion during surgery, however, most patients experience deterioration of their facial profile prior to surgery due to orthodontic dental decompensation (Hernández-Alfaro & Guijarro-Martínez, 2014).

Recently, the surgery-first approach (SFA) which eliminates the pre-surgical orthodontics was proposed. The SFA commences with correction of jaw discrepancy followed by post-surgery orthodontic treatment **(Figure 2).** The surgery-first approach (SFA) results in early improvement in facial profile and reduction of total treatment duration compared with orthodontic-first (conventional) approach (Hernández-Alfaro et al, 2011; Hernández-Alfaro et al, 2014).

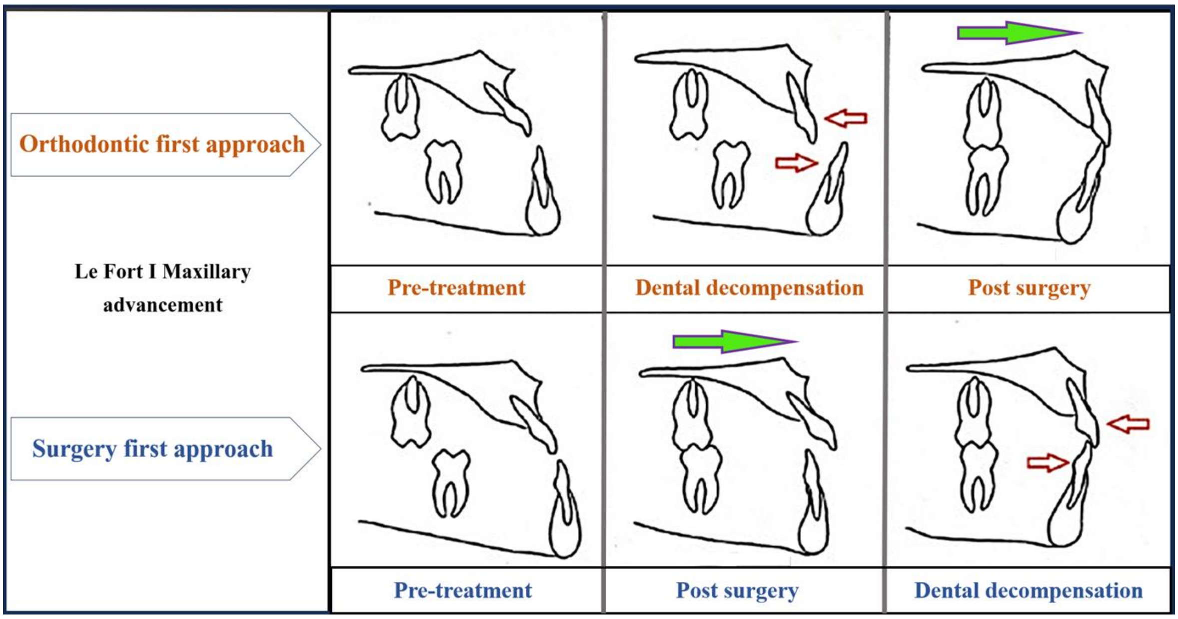

Figure 2. Illustration of Le Fort I maxillary advancement in Orthodontic-first approach and Surgery-first approach.

In 1977, Epker and Fish suggested that for the skeletal surgical repositioning of the jawbones, the surgery should be performed prior to orthodontic treatment. The surgery can be done first if the skeletal segments could be surgically repositioned and the post-operative orthodontic tooth movement to be accomplished safely and easily. In their case report of 2 patients with anterior open bite and skeletal class II pattern, the surgery was performed before orthodontic treatment and cephalometric radiographs were used for evaluation of the results. The authors mentioned several advantages of the surgery-first approach, including: early improvement in patient's facial profile, improvement in swallowing and speech, accelerated orthodontic tooth movement following surgery, restoration of the normal functional and anatomic relationships of the jaw bones and surrounding soft tissues, and stability of results equal to traditional orthodontic-first approach (Epker & Fish, 1977).

Nagasaka et al. (2009) recommended that orthognathic surgery should commence and be followed by regular postoperative dental alignments. The concept implied that most of the orthodontic treatment is performed postoperatively. The author reported that surgery-first approach has the advantage of rapid tooth movement following surgery owing to the increased bone turnover rate known as regional acceleratory phenomenon. In addition, SFA can eliminate the potential side effects of preoperative orthodontic decompensation that result in worsening of the facial profile and malocclusion. Meanwhile the shortened total treatment time would have a positive impact on patients' satisfaction with the treatment (Nagasaka et al, 2009).

Alfaro et al. (2011), published the first report of bimaxillary cases treated with surgery-first approach. The case report included a class II + AOB patient who was treated with segmented Le Fort I maxillary osteotomy with posterior impaction, plus bilateral sagittal split osteotomies (BSSO) advancement. The second case was a skeletal class III patient who underwent Le Fort I maxillary advancement and BSSO setback. The optimal esthetic and functional results combined with significant reduction in total treatment time, resulted in high patient satisfaction. The study reported that SFA may offer a reasonable, cost-effective method to treat skeletal malocclusions in selected cases, and has the potential to become a standard approach for orthognathic surgery in the future (Hernandez-Alfaro et al, 2011).

The study by Alfaro et al. (2014) assessed the patients' satisfaction and orthodontists' satisfaction at 12 months follow-up for group of 45 surgery-first approach patients. The study reported the mean duration of total orthodontic treatment was 37.8 weeks (range from 24 to 52 weeks). The orthodontists' satisfaction of the overall treatment outcome (VAS average, 9.7) was similar to the patients' satisfaction (VAS average, 9.4). The conventional orthodontic-first approach (OFA) involves longer orthodontic phase (15 to 24 months) preoperatively which worsens the facial profile and may result in lower patient satisfaction. On the other hand, the orthodontic management of SFA can be technically demanding mainly due to patient's baseline occlusion which cannot serve as a guide for the treatment planning. Furthermore, the study reported that the mean surgical time was 84 minutes for a bimaxillary procedure, and 1 hour for Le Fort I surgeries (including maxillary segmentation) which was similar to conventional approach (Hernández-Alfaro et al, 2014).

1.2.2 Stability of surgery-first approach

Baek et al. (2010) assessed the stability of 11 cases of skeletal Class III patients who underwent bimaxillary surgery (Le Fort I osteotomy posterior impaction of the maxilla and BSSO setback of the mandible) by the surgery-first approach. Sixteen angular and linear measurements were used to evaluate skeletal stability. Lateral cephalograms taken at initial examination (T0), immediately after surgery (T1), and after debonding (T2) were utilized. The result showed forward relapse of mandible from T1 to T2 was statistically significant ($P<0.05$) while there were no changes in maxilla. The study emphasized that the SFA requires accurate postoperative orthodontic prediction at the very beginning of the treatment. This is crucial in maximizing arch coordination and dental alignment. The study reported the surgical wafer was removed 4 weeks following surgery, because unstable occlusion may hamper the stability of ideally positioned maxilla and mandible. They noted the improved patient cooperation and shortened treatment time. There was no report on the magnitude of relapse or the surgical movement. The use of wafer in post-operative phase could have impacted on the stability. Furthermore, point A and pogonion landmarks are subjected to remodelling, which affect the accuracy of the measurements (Baek et al, 2010).

Ko et al. (2013), assessed the stability of bimaxillary surgery in 45 class III patients who underwent surgery-first approach. Seven linear and 6 angular parameters were measured on serial cephalometric radiographs taken at the initial examination, 1 week postoperatively, and after orthodontic debonding (12.22 months after surgery). Relapse was defined as horizontal forward movement at the innermost point of the contour of the mandible (B point). The sample was divided to two groups: group 1 ($N=15$), less stable, relapse >2.5 mm and group 2 ($N=18$), highly stable, relapse <1 mm. The result of remaining 33 patients showed the mean of sagittal relapse at the B point was 3.19 mm (23.22%) in group 1 and 0.37 mm (3.33%) in group 2. The mean vertical relapse at the B point was 2.387 mm in group 1 and 1.039 mm in group 2. The difference between groups was significant ($P < .05$). The study concluded that patients in group 2 (mean surgical setback: 11.02 mm, relapse: 0.37 mm) showed better stability compared with patients in group 1 (mean surgical setback: 15.09 mm, relapse: 3.19 mm).

Furthermore, the regression model indicated that only overbite was significantly associated with mandibular relapse. A 1-mm greater initial overbite in patients with class III malocclusion contributed to 0.449 mm of mandibular sagittal skeletal relapse at the B point. The result of the study was limited to 2D measurements at B point which is subjected to remodeling during post-operative orthodontic treatment. The study didn't comment on the drop out of 12 patients and skeletal changes of maxilla (Ko et al, 2013).

The retrospective study by Kim-J et al. (2014) included 37 class III mandibular prognathism cases who were treated by surgery-first bimaxillary surgery including Le Fort I osteotomy and intraoral vertical ramus osteotomy (IVRO). The lateral cephalograms obtained preoperatively (T0), 2 days postoperatively (T1), 6 months postoperatively (T2), and 12 months postoperatively (T3), were used to measure horizontal distances from A point and from ANS to the Y-axis in the maxilla, and from pogonion (Pog) to the Y-axis in the mandible. The vertical distances were calculated from A point, ANS, and Menton to the X-axis. The results showed no significant relapse of the maxilla and mandible in the horizontal direction, but mandibular vertical relapse was significant at all time intervals, particularly during the first 6 months postoperatively. At 6-month mandible has relapsed by 0.6 (2.3) mm anteriorly and 2.9 (1.4) mm superiorly. The study reported that most of postoperative skeletal and dental changes being occurred within 6 months postoperatively. However, the result of the study was based on 2D linear measurements of landmarks that are subjected to remodelling or may be removed during surgery including the ANS in maxillary advancement. The clinical significance of relapse rate was not reported. The relationship between the quality of the immediate postoperative occlusion and skeletal stability was not investigated (Kim et al, 2014b).

The study by Lo et al. (2019), included 42 skeletal class III patients who underwent bimaxillary surgery by surgery-first approach, reported no relationship between skeletal stability and the occlusion. The hand-articulated dental casts were scanned, and an occlusal map of maxillary dentition were generated to assess the occlusal contacts.

The anterior nasal spine (ANS), posterior nasal spine (PNS), point A, point B, and pogonion (Pog) were digitized on the CBCT to assess the skeletal stability at before treatment (T0), 1 week after surgery (T1), and at orthodontic debonding (T2). The results showed during T1 to T2, there was posterior movement of ANS and point A ($P < 0.001$) and point B and Pog showed upward and forward movements ($P < 0.01$). The study concluded that the post-surgical stability was not related to initial overjet, overbite or the number and location of occlusal contacts, however, the occlusal map was generated from the planned occlusion, not the actual post-operative occlusion. There was no report on the magnitude of movements of the osteotomy segments which may have contributed to the skeletal stability/relapse. Furthermore, the selected landmarks for the assessment of skeletal changes are subjected to remodelling or may be reduced by the surgery which is the case for the ANS in maxillary advancement. The impact of the maxillary position on mandibular relapse was not considered in the analysis and the interpretation of the results (Lo et al, 2019).

1.2.3 Stability of Surgery-first vs Orthodontic-first approach for orthognathic correction of dentofacial deformity

Stability is one of the important criteria for determining the success of orthognathic surgery. Stability is defined as the maintenance of the skeleton and associated dental structures in the intended postoperative position over the long-term. Skeletal, dental and surgical factors can affect the post-operative stability (Jackson & Golden, 2016). These factors include degree of incisor inclination, overjet, overbite, depth of the curve of Spee, mandibular and maxillary plane angles, occlusion stability, as well as rotation of maxilla-mandibular complex, condylar position, alterations of masticatory muscle, the magnitude of jaw movement and method of fixation (Jackson & Golden, 2016; Peiro-Guijarro et al, 2016).

One of the main objectives of orthognathic surgery is skeletal stability, which can be categorized into short- and long-term targets. Short-term stability can be defined as physiological adaptation, directly related to the post-surgical healing and orthodontic treatment. The long-term stability is influenced by surgical or patient-related factors and orthodontic treatment. The pre-operative orthodontic alignments maximize optimal surgical repositioning of the jaw, while the postoperative orthodontic treatment ensures refinement of occlusion and retention (Proffit et al, 2007).

In the surgery-first approach, orthodontic dental alignment and decompensation are deferred until after surgery, therefore, the surgical occlusion is different from the final occlusion and expected to be unstable due to premature occlusal contacts. The unstable occlusion may hinder the long-term skeletal stability, leading to skeletal relapse (Nagasaka et al, 2009; Soverina et al, 2019). Nadjmi et al., (2010) stated that a stable dental occlusion is one of the key goals in orthognathic surgery planning, since it defines the postoperative position of the mandible and maxilla (Nadjmi et al, 2010).

The quality of postoperative occlusion and its influence on skeletal stability has not been fully investigated. There are no consistent evidence or criteria to define the quality of post-operative occlusion. Some studies have reported no statistically significant differences in postoperative stability between surgery-first and conventional approach,(Choi et al, 2015; Choi et al, 2016; Park et al, 2016) while other studies stated that surgery-first approach was less stable than conventional approach (Kim et al, 2014b; Ko et al, 2013).

The systematic review by Peiróguijarro et al. (2016) included 11 studies published from 2000 to 2015 who assessed the treatment duration, patient satisfaction, orthodontist satisfaction, and stability following orthodontic-first and surgery-first approach. Total of 295 patients, of which 239 were corrected by bi-maxillary surgery, 45 patients underwent bilateral sagittal split osteotomy, and 11 patients who had undergone an isolated Le Fort I osteotomy were included. The systematic review included 5 case-control studies, 3 cohorts and 3 case series. Most of the studies were based on Asian population (91%). Class III was the most prevalent (84.7%) skeletal pattern. Only 5 studies reported on stability outcomes. In the vertical plane, mandibular stability was reported to be worse in the surgery-first group. Patients with a relapse rate above 3 mm comprised 39.1% of the surgery-first group versus only 15.8% of the orthodontic-first group.

Meanwhile, relapse below 1.5 mm was more common in the orthodontic-first group than in the surgery-first group. The review revealed that the greatest vertical relapse could be due to the occlusal instability during postsurgical bone healing, when a transient increased vertical dimension secondary to premature occlusal contacts is present. However, final splint was left in place as a means of occlusal stabilization for 2 to 6 weeks in 4 studies. The substantial reporting biases, the heterogeneity and low evidence levels among retrieved articles and the wide variety of outcome variables make it difficult to draw a robust conclusion. Despite the heterogeneity of publications, a shorter treatment time, improved post-operative orthodontic efficiency and early improvement of the facial profile was the most reported advantages of a surgery-first approach (Peiro-Guijarro et al, 2016).

Soverina et al. (2019) included 14 studies between 2010-2017 in a systematic review to assess the horizontal and vertical mandibular and maxillary stability following SFA and OFA with a minimum of 1 year of follow-up. A total of 560 skeletal class III patients treated with the SFA (n = 339) and the OFA (n = 221) were included in the review. A total of 394 patients had bimaxillary osteotomy and 166 were treated by bilateral sagittal split osteotomy (BSSO)/intraoral vertical ramus osteotomy (IVRO) of the mandible. The stability was assessed by measuring the horizontal and vertical distances from skeletal landmarks (point A, point B, pogonion (Pog), menton) to the reference planes. At the last time point (6 or 12 months after surgery, depending on the individual study) the results showed Pog and point B moved forward in both groups, with a greater movement in SFA (>1mm). The Pog and point B moved upward in 8 studies with the difference between SFA and OFA being always greater than 1 mm.

Eight articles evaluated horizontal, and 6 studies evaluated vertical maxillary relapse at point A, which was always <1 mm. The studies reported a forward, and upward movement of the mandible due to counterclockwise mandibular rotation around the condylar head. The review has some limitations including the different parameters that were considered to define stability, variation in time points and reference planes and the use of lateral cephalograms for the analysis of the outcomes. Furthermore, the heterogeneity among study's methodology including minimum pre-operative orthodontic treatment in SFA patients, post-operative 2-6 weeks use of occlusal wafer and effects of maxilla on mandibular relapse are potential sources of bias and impact negatively on the interpretation of the results (Soverina et al, 2019).

Liao et al. (2010) reported on stability of thirty-three adult patients who had skeletal class III open bite that was corrected by Le Fort I posterior impaction and bilateral sagittal split osteotomy. Thirteen patients were treated with orthodontic-first approach, and 20 underwent surgery-first approach. The lateral cephalometric radiographs were obtained before treatment, 1 month before surgery, 1 week after surgery, and at orthodontic debonding were used to assess the surgical movements and the stability of the results.

They reported the superior movement of point B and pogonion ($p < 0.05$) in surgery-first group. Both groups showed similar stability in the horizontal and vertical directions. The study reported that the mandible continued to move upward approximately 1 to 1.5 mm more after surgery, thus increasing the overbite and reducing the anterior face height in surgery-first group. The study has some limitations including 2D landmark selections (ANS, PNS, Point A, Point B, Pog), two orthodontists have been involved in treatment of the patients and segmental maxillary osteotomy was performed for some of the patients. These factors are potential sources of bias and confounding factors in assessing the orthognathic stability (Liao et al, 2010).

In the study by Mah et al., (2017), horizontal and vertical movement of the point B and pogonion (Pog) of 40 skeletal class III patients (20 SFA, 20 OFA) who underwent BSSO set-back surgery was measured. Pre-surgery (T0), 2-4 weeks after surgery (T1), and post-surgery (T2, after 1 year or at debonding) lateral cephalometric radiographs were used. Reporting no significant difference in the mean setback (T0 –T1); the horizontal anterior movement of point B (3.49 ± 1.71 mm) and Pog (4.11 ± 1.93 mm) was greater in SFA group between T1 to T2. Results revealed that the SFA group showed inferior and superior movements of point B and Pog at T0, T1, and T2. Greater horizontal and vertical relapses due to the counterclockwise rotation of the mandible and unstable occlusion was reported as the main drawback of surgery-first approach, however, there was no report on the occlusal characteristics including overbite, crowding, curve of Spee and overjet that might affect the stability of occlusion in surgery-first group. The results were limited to 2D analysis of mandible stability based on 2 landmarks which are subjected to remodeling. The study didn’t report on use of wafer in post-operative phase and its influence on mandibular relapse (Mah et al, 2017).

Kim-CS et al. (2014) reported on relapse of 61 patients with mandibular prognathism who underwent bilateral sagittal split ramus osteotomy (BSSO). Skeletal changes and stability were evaluated by lateral cephalograms taken 1 month before surgery (T1), 2 to 3 days after surgery (T2), and at the time of debonding (T3; 6 to 22 months) for 23 SFA and 38 OFA patients. The result showed relapse at point B was more evident in the SFA group than in the OFA group (P=.043). At T3 to T2, the mean anterior-inferior movement of point B was greater in SFA (2.4 mm) than in OFA approach (1.6 mm). Relapse greater than 3 mm at the point B was present more dominantly in SFA (39.1%; n = 8 of 23) than in the OFA group (15.8%; n = 6 of 38). A relapse less than 1.5 mm was found in 30.4% (n = 7 of 23) of the SFA patients and 57.9% (n = 22 of 38) of the OFA group. The vertical relapse at the point B was significantly correlated with vertical movement by surgery (P<0.05).

The study reported that having similar presurgical angular and linear measurements and surgical movement for both groups, the mandibular setback surgery by SFA approach produced greater anterior relapse than OFA orthognathic surgery. This might be due to the post-surgical occlusal instability in SFA group that would lead to skeletal instability. The results were based on 2D analysis of point B, which is subjected to remodelling. Furthermore, confounding variables such as mandibular autorotation after the removal of the surgical wafer (interocclusal wafer left for 4 to 6 weeks following surgery for occlusal stabilization) or postoperative orthodontic correction of occlusal interference might affect the relapse pattern. The relationship between occlusal characteristics and relapse was not investigated (Kim et al, 2014a).

In comparison of 15 SFA patients with 11 OFA skeletal class III patient who underwent mandibular setback surgery, the greater forward, and upward movements of mandible in SFA patients were reported by Kim et al. (2013). Lateral cephalograms were taken during the initial examination (T0), at 4 weeks after surgery (T1), and immediately after debonding (T2) were used to evaluate the surgical changes (T1 vs T0) and relapse rates (T2 vs T1). Although the two groups showed similar occlusal and cephalometric characteristic prior to surgery, the SFA had greater amount of setback (T1). During T2-T1, the forward movement of 3.41 vs 1.30 mm for pogonion, 4.08 vs 1.51 mm for menton and upward movement of 2.69 vs 0.93 mm for pogonion and 2.20 vs 0.96 for menton were reported.

The study reported that due to occlusal interferences, establishing a stable occlusion to allow predictable skeletal movements in SFA patients is difficult. Patients in SFA group underwent 6 months period of orthodontic levelling and alignment, which is a risk of bias in interpreting the results. Due to the small sample size and the choice of pogonion and menton which are subjected to remodelling drawing a robust conclusion is not possible (Kim et al, 2013).

The study by Akamatsu et al. (2016) included 38 skeletal class III patients who underwent sagittal split ramus osteotomy (SSRO) and measured the horizontal and vertical changes at Pogonion (Pog) and Point B at T0: 2 weeks before surgery, T1: 2 weeks after surgery, and T2: 1 year after surgery for OFA / debonding for SFA. The results showed no significant difference between two groups in the amount of surgical movement (T0-T1). SFA (n: 14) had greater vertical movements at point B than OFA group (n: 24) during T1 –T2. The mean vertical relapse at the point B was (0.87 ± 1.01) mm and Pog was (1.59 ± 2.91) mm in the downward direction in the SFA group, and (0.45 ± 1.95) mm at point B and (0.14 ± 1.30) mm at Pog in the upward direction in the OFA group, showing significant difference between the two groups. However, at T1-T2 no significant difference was reported for horizontal movements and overbite, overjet, lower incisor-occlusal plane angle, and interincisal angle between the two groups. The study reported the minimum preoperative orthodontic treatment was performed for SFA group that might reduce the postoperative horizontal relapse by improving the stability of occlusion. Multiple factors including occlusal wafer being left for 14 days following surgery, five orthodontists being involved in orthodontic treatment and pre-operative orthodontic adjustment of SFA group are source of bias. The results are based on 2D linear measurements of point B and pogonion which are subjected to remodelling (Akamatsu et al, 2016).

Park et al. (2015) compared the relapse rate in 19 SFA and 19 OFA class III patients who underwent bimaxillary surgery (one-piece Le Fort I osteotomy and bilateral sagittal split ramus osteotomy). Total of 8 landmarks including point A, ANS, PNS, pogonion and Point B were selected on lateral cephalometric taken at before treatment (T0), at 1 month before surgery (T1), immediately after surgery (T2), and at debonding (T3, at least 6 months after surgery). The result showed at T2, T3, and T2–T3 there were no significant differences in the amounts of posterior impaction of the maxilla (4.5 mm vs 3.8 mm) and mandibular setback (2.7 mm vs 1.8 mm). During T1–T2 OFA group showed more forward movement of the maxilla than SFA group (1.2 mm vs 0.1 mm). The relapse rate in SFA group (11 of 19 [57.9%]) was higher than OFA group (5 of 19 [26.3%]). However, SFA patients have received preoperative orthodontic treatment of <3 months and wore a surgical wafer for comparatively longer period than OFA patients after surgery. Furthermore, relapse rate was measured as vertical movement of point B during (T2–T3) / (T0–T2), where the T0 is before start of orthodontic treatment for both groups. These two factors are high source of bias that affect the results of the study. The study reported possible factors for ‘‘high relapse’’ rate in SFA cases, include occlusal prematurity and instability, transverse arch width discrepancy, vertical discrepancy, and occlusal plane discrepancy. The results suggested that SFA might be an effective alternative to OFA if the cause of high relapse can be controlled (Park et al, 2015).

The study by Ko et al. (2011) reported similar postoperative stability (relapse <2mm) between SFA (relapse rate 50.0%) and OFA (relapse rate 54.3%) after Bimaxillary surgery in 53 patients with skeletal Class III malocclusion. The skeletal and dental changes before treatment (T1), before surgery (T2), 1 month after surgery (T3), and at completion of treatment (T4) were measured by 9 angular and linear measurements on lateral cephalometric images. For sagittal relapse between 2 and 4 mm at pogonion (Pog-x, T4 - T3), the OFA group had a greater ratio (37.1%) than the SFA group (22.2%). In contrast, the SFA group had a greater ratio (27.8%) than the OFA group (8.6%) for relapse larger than 4 mm. The 2D cephalometric analysis, combination of extraction and non-extraction and Le fort I segmental osteotomy, orthodontic treatments being performed by 2 orthodontists and impartial sample size existed between the 2 groups (SFA: 18, OFA: 35) are potential sources of bias in the study (Ko et al, 2011).

The study by Ann et al. (2016) compared 12 SFA with 12 OFA skeletal Class III patients, who underwent bimaxillary orthognathic surgery. By generating lateral cephalograms from CBCT scans, the changes at ANS, PNS, Point A, Point B, pogonion and 2 mental foramens were evaluated at before surgery (T0), 1 month after surgery (T1), and 1 year after surgery (T2). During (T1–T2), all mandibular landmarks (point B, pogonion, and both mental foramen) showed forward movement, and these changes did not differ significantly between the two groups. Along the vertical plane, the pogonion and both mental foramens showed greater upward movement in the SFA group than in the OFA group (Pog: 0.1 mm vs 1.6 mm). At 1 year following the surgery the two groups showed no significant differences in n SNA, SNB, ANB, overjet and overbite. The study didn't comment on correlation between overjet, overbite, and the skeletal relapse. Significant clinical relapse rate was not defined by the study. Landmarks that are subjected to remodelling and maxillary movements could be a confounding factor when interpreting mandibular relapse. Furthermore, the patients underwent Lefort I and intraoral vertical ramus osteotomy (IVRO), which is reported to have lower stability than Bilateral sagittal split mandibular osteotomy, due to reduced bone contact (Ann et al, 2016).

Four systematic reviews were carried out by Yang et al. (2017), Wei et al. (2018), Barone et al. (2021) and Mulier et al. (2021) to compare the stability between SFA and OFA. The pooled data from 6 studies showed no significant difference in mandibular relapse between the SFA and OFA groups. The pooled data from 4 studies showed no difference in maxillary relapse. Only two studies reported on overjet and overbite. The overjet was smaller in the OFA group, but the difference was not statistically significant (Yang et al, 2017). On the other hand, Wei et al. (2018), showed statistically and clinically significant difference between SFA and OFA. The pooled measurement showed SFA had lower postoperative stability (mean: 1.50 mm, $P < .00001$). The review reported mandible tends to rotate counterclockwise in the SFA group more than the OFA group, which indicates an unfavourable postoperative stability in the SFA group (Wei et al, 2018). Likewise, Barone et al. (2021) showed the horizontal mandibular relapse after surgery, was higher in SFA group, but neither statistical significance nor clinical relevance were determined (Barone et al, 2021). The systematic reviews highlighted the considerable heterogeneity exists across studies, with several differences in data sources, methods of surgery and fixation and different length of follow-up. The results were limited to 2D cephalometric analysis. The importance of well-designed 3D studies with a long-term follow-up were highlighted for clarification of the findings.

Yang et al. (2017) performed a systematic review and meta-analysis including 10 studies published from 2010 to 2016, who compared the treatment duration, postoperative stability, surgical movement, and postoperative occlusion between surgery-first approach (SFA) and conventional orthognathic approach (COA). Total of 513 class III patients (SFA, n = 238; COA, n = 275) were corrected with bi-maxillary surgery in 8 studies and bilateral sagittal split osteotomy in 2 studies. The horizontal movements of the maxilla and mandible at point A, point B or pogonion before and after surgery as well as overjet and overbite were measured on lateral cephalograms. The pooled data from 6 studies showed no significant difference in mandibular relapse between the SFA and COA groups. The pooled data from 4 studies showed no difference in maxillary relapse. Only two studies reported on overjet and overbite. The overjet was smaller in the COA group, but the difference was not statistically significant.

The post-operative overbite was significantly smaller in the COA group (*P*=0.007). However, the review has some limitations; studies with small sample sizes, the 2D cephalometric analysis, limited number of skeletal landmarks that are subjected to bone remodelling and heterogeneity of surgical methods tend to increase the risk of bias. Furthermore, post-operative surgical wafer being left for 2-4 weeks, effects of maxillary movements on mandibular relapse and pre-operative levelling and removal of occlusal interferences in SFA groups were reported in some of the studies that could have affected the results (Yang et al, 2017).

Wei et al. (2018) performed a systematic review included 12 studies who compared postoperative horizontal and vertical changes of pogonion, Point A, Point B, ANS, PNS, SNA and SNB between SFA and OFA groups. A total of 498 patients (229 SFA, 269 OFA) were included in studies published between 2010 and 2017. Majority of studies (8 out of 12) were conducted in South Korea. The Bimaxillary surgery was performed in 7 studies, BSSO in 4 studies and 1 study reported the Le Fort I osteotomy with intraoral vertical ramus osteotomy (IVRO). The SFA Patients in 6 studies received minimum preoperative orthodontic treatment of less than 6 months. The results showed the postoperative stability of pogonion (horizontally), point B (both horizontally and vertically) and changes of SNB were different between the SFA and OFA group.

The differences have been both statistically and clinically significant. The pooled measurement showed SFA had lower postoperative stability (mean: 1.50 mm, P < .00001). The review reported mandible tends to rotate counterclockwise in the SFA group more than the OFA group, which indicates an unfavourable postoperative stability in the SFA group. The results of the review showed wide range of differences across studies. Different sample size, surgery and fixation methods, pre-operative orthodontics, and methods of 2D cephalometric analysis were recorded. The review suggested further studies with unified method of operation and fixation and 3D analysis of stability are required (Wei et al, 2018).

The systematic review by Barone et al. (2021) reviewed the systematic reviews published between 2014 to 2020 to evaluate any difference between surgery-first approach (SFA) and conventional orthognathic approach (COA) in terms of skeletal stability, treatment time, complications, and quality of life. The two investigators included 10 studies after applying inclusion and exclusion criteria. The review reported skeletal class III was the most common dentoskeletal malocclusion followed by the bimaxillary surgery being the most frequent treatment performed (>70%). Maxilla-mandibular stability was reported both horizontally; by modifications of the B point, A point, and pogonion and vertically by the rotation of the jaws.

The result showed that most of the included studies (8 out of 10) had a low and critically low methodological quality. In comparison between SFA and COA, the difference of the forward movement at B-point and/or pogonion was determined to be <1mm with a greater anterior relapse in the SFA. On the vertical plane, a mandibular upward relapse was reported by most of the reviews. Although four studies reported about maxillary movement after surgery, with two found no significant difference between SFA and COA and others reported greater maxillary relapse, but no consistent data or clear measurements were recorded. The horizontal mandibular relapse after surgery, was higher in SFA groups than in the COA, but neither statistical significance nor clinical relevance were determined.

The review reported that considerable heterogeneity exists across studies, with several differences in data sources, methods of surgery and fixation, length of follow-up, and cephalometric analysis. Lateral cephalograms were used for the analysis of skeletal outcomes, However, a significant variability emerged in the choice of reference points, planes and angles that have defined the skeletal relapse. The review suggested that well-designed 3D studies with a long-term follow-up are required to clarify the findings (Barone et al, 2021).

The systematic review by Mulier et al. (2021) aimed to evaluate the long-term dental stability after orthognathic surgery in patients with the minimum of 5 years follow-up. Searching the literature up to December 2019, Two Randomized controlled trials (RCTs) and nine retrospective studies with a follow-up period of 5 to 15 years were selected. A dental or skeletal relapse of ≥2 mm at postoperative follow-up was considered clinically significant. Reported dental outcomes including overjet (OJ), overbite (OB) and upper and lower incisor positions were measured on lateral cephalograms obtained at different follow-up times. Only 3 articles assessed OJ in skeletal class II patients. Clinically significant increased OJ between 2 and 4 mm, was reported for 8% of skeletal class II patients treated by bimaxillary surgery and 20% who underwent mandibular advancement. Only 1 study reported on OJ in skeletal class III patients.

The results showed 2% of the patients had > 4mm OJ relapse after bimaxillary surgery. The review showed OJ tended to increase in skeletal class II and decrease in skeletal class III patients over the time, independent of the type of osteotomy or direction of movement. The long-term changes in OB for skeletal class II and III patients were reported in eight studies, by two studies showed a clinically significant increase in OB for skeletal class II patients at long-term follow-up. The quality of evidence was limited to retrospective design and small sample size, variability of methods of assessment, and serious to moderate overall risk of bias associated with the reviewed articles. None of the included studies compared immediate and long-term postoperative dental outcomes utilizing 3D imaging (Mulier et al, 2021).

Valls-Ontañón et al. (2023) compared the stability of the SFA and OFA of 56 patients (29 SFA, 27 OFA) who underwent bimaxillary surgery. Linear and angular measurement of posterior nasal spine (PNS), point A, point B, Upper incisor, Lower incisor, SNA, SNB and pogonion were calculated on CBCTs taken preoperatively (T0), 1 month after surgery (T1), and at 1 year after surgery (T2). There were 3 class I, 17 Class II (30.4%) and 36 Class III (64.3%) patients. The results showed PNS and point A measurements had a greater change in vertical direction in the OFA at T0-T1 and T1-T2. The SNA angle showed a greater increase at T0-T1 and a greater relapse at 1 year in OFA group. The higher SNA angle relapse in the OFA group was only happening in Class III patients (P = 0.013).

The study concluded that there is not enough statistical evidence to demonstrate differences in stability between the two groups. However, the mean effect size was set at (ES = 0.2) which is very small to detect significant difference, and no clinical significance level was defined for the skeletal relapse by the study. The combination of class I, II, and III and the different direction of maxilla-mandibular movements are source of heterogeneity in the study. Furthermore, some of the landmarks used to assess the stability are subjected to remodelling and alteration by surgery (Valls-Ontanon et al, 2023).

The literature is conflicting and controversial. Factors including post-operative unstable occlusion, and faster tooth movement during post-operative orthodontic treatment may contribute to the relapse of SFA. However, the unstable post-operative occlusion was reported as the main concern of surgery-first approach by multiple studies (Baek et al, 2010; Choi et al, 2015; Mah et al, 2017). Furthermore, there is no universal terminology agreed regarding the assessment of occlusal quality. There were no clear criteria to explain the relationship between skeletal relapse and occlusion.

Almost all the studies were based on the 2D cephalometric analysis, by assessing different skeletal and dental landmarks. The 2D cephalometry is subjected to magnification, distortion, and the technical difficulty in landmark registration. The relationship between skeletal stability and occlusion, was evaluated by linear and angular measurements at different skeletal landmarks, including ANS, point A, point B and pogonion. These points are subjected to remodelling due to orthodontic teeth movements or alterations by surgery.

Different terminologies such as number of occlusal contacts, maximum occlusal interdigitation or ideal occlusion were utilized to define occlusion. The outcome measures of occlusal and skeletal stability need further refinements. **Table 1** shows the summary of studies who measured the overjet and overbite at 1week or 1 month following surgery as well as at debonding. The results show heterogeneity among studies. The inclusion of bimaxillary cases, with post-operative counterclockwise rotation of mandible, have impacted the overjet and overbite measurements. Furthermore, the relationship between the skeletal stability and the immediate post-operative occlusion was not studied.

Three-dimensional imaging is required to assess the skeletal relapse and occlusion of surgery-first and conventional orthognathic surgery. It would be important to consider a relatively strict sample selection criteria for the accurate and objective evaluation of the postsurgical stability and relapse. The criteria including patients with similar skeletal-dental pattern, identical surgical methods, and direction of the surgical movement of the maxillo-mandibular complex should be considered.

Study	DFD	Surgery	Patients, n		Overjet at 1wk /1m			Overjet at debonding			Overbite at 1wk /1m			Overbite at debonding		
			SFA	**OFA**	**SFA**	**OFA**	***P* value**	**SFA**	**OFA**	***P* value**	**SFA**	**OFA**	***P* value**	**SFA**	**OFA**	***P* value**
Park et al. 2014	Class III	LF1 + BSSO	24	36	9.25	3.27	**0.00**	3.14	2.91	0.31	2.09	1.29	**0.04**	2.15	1.60	**0.01**
Joh et al. 2013	Class III	LF1 + BSSO	16	16	5.20	4.19	**0.02**	3.46	2.82	**0.009**	2.63	3.04	0.22	2.78	2.49	0.31
Liao et al. 2010	Class III	LF1 + BSSO	20	13	-	-	-	3.0	2.2	**0.02**	-	-	-	2.6	2.0	**0.06**
Ann et al. 2016	Class III	LF1 + IVRO	12	12	4.83	2.63	**<0.05**	2.99	2.70	>0.05	0.21	1.49	**<0.01**	1.59	1.90	>0.05
Akamatsu et al. 2016	Class III	LF1 + BSSO	14	24	-	-	-	3.25	3.38	0.73	-	-	-	1.60	1.65	0.91
Park et al. 2015	Class III	LF1 + BSSO	19	19	3.15	3.68	0.21	2.53	3.29	0.98	1.46	1.40	0.75	2.57	2.12	0.32
Zhou et al. 2016	Class III	LF1 + BSSO	20	20	4.49	3.89	>0.05	3.26	3.8	>0.05	0.91	0.84	>0.05	1.79	2.08	>0.05

Table 1. Reported Overjet and Overbite measurements of skeletal class III patients following Orthognathic surgery.

1.3 DENTAL OCCLUSION

The maxillary and mandibular arches come into contact in a static or a dynamic way. Static occlusal relationship usually occurs in maximum intercuspation, whereas dynamic occlusion happens during mandibular protrusion and lateral eccentric movements. Occlusal contacts are defined as the touching of opposing teeth on elevation of the mandible, increasing on maximum intercuspation. Location of occlusal contacts in this position is one of the key factors that maintain an accurate alignment of the arches (Davis et al, 2005; Ehrlich & Taicher, 1981).

The masticatory performance is influenced by the bite force, the number of occlusal contacts and occlusal contact areas. The presence of occlusal interference or premature contact during maximum intercuspation or jaw movement is referred to as traumatic occlusal interference. If present, even within a few micrometres, it will lead to a forced bite, which is associated with uneven masticatory muscle activity, and may result in temporomandibular joint dysfunction, facial, head and neck pain, hearing impairment, or tinnitus (Sharma et al, 2013).

The stable occlusion is defined both in terms of structure and function. Structural durability is expressed by lack of tooth and skeletal relapse, while the function is assured primarily by good intercuspation, with many proper occlusal contacts (Dincer et al, 2003).

1.4 OCCLUSAL INDICES

The Occlusal indices have been utilized to determine the need, complexity, and outcome of orthodontic treatment. More recently studies have reported the assessment of the occlusion in combined orthodontic/orthognathic patients by the occlusal indices.

The Peer Assessment Rating (PAR) index is applied to assess the outcome of orthodontic treatment in terms of alignment and occlusion. The index is composed of 5 components, including: Anomalies of the upper and lower anterior teeth (crowding, spacing and impacted teeth), Buccal occlusion, Overjet, Overbite and Centreline. The sum of the scores of the 5 components, represent the degree to which a case deviates from normal alignment and occlusion. The higher the score the greater the deviation from normal. The difference between the pre- and post-treatment scores shows the degree of improvement as a result of orthodontic intervention (Richmond et al, 1992).

The concerns regarding the weightings of PAR index, especially those assigned to overjet and overbite have been reported. The high weighting of overjet may influence the sensitivity of the index in any malocclusion where overjet is increased. For example, reduction of an increased overjet by retro-clining the upper incisors will score 'Greatly improved' according to the PAR nomogram, while the aesthetic and functional benefit of such treatment may be questioned. On the other hand, the weighting for overbite is low. The correction of a complete and traumatic overbite produces only a small reduction, failing to represent correction of function and appearance (Hamdan & Rock, 1999).

The American Board of Orthodontics (ABO) has developed the Discrepancy Index (DI) to provide an objective evaluation of complexity of the orthodontic treatment. The DI is composed of measurements of overjet, overbite, anterior and lateral open bite, crowding, occlusion, lingual and buccal posterior cross bite, ANB angle, IMPA and SN-Go-Gn angle. The DI is utilized to assess the overall case acceptability and completeness. However, the DI needs cephalometric measurements, the limitations of which have been reported widely (Cangialosi et al, 2004).

The need for orthodontic treatment mostly assessed by the Index of Orthodontic Treatment Need (IOTN). The IOTN is composed of two separate components to record the dental health (DHC) and the dental aesthetics (AC). There are five grades, grade 1 representing little or no need for treatment and grade 5 representing great need for treatment. Although widely used, the IOTN has some limitations when applied for orthognathic patients. The aesthetic component is comprised of class I and class II division 1 incisor relationships. The class II division 2 or class III incisor relationships are not considered. Some features like excessive upper labial segment show at rest are not included in the IOTN, while this might be amenable to treatment with combined orthodontic and orthognathic treatment (Brook & Shaw, 1989).

The Index of Orthognathic Functional Treatment Need (IOFTN) was developed with modifications and additions to IOTN to reflect the functional indications for treatment involving orthognathic patients. The IOFTN is applied for prioritization of severe malocclusions that are not amenable to orthodontic treatment alone, and therefore it is not utilized to assess orthodontic outcomes or occlusal quality (Ireland et al, 2014).

The Index of complexity, outcome, and need (ICON) was developed to provide a more unified case assessment using one set of occlusal traits. The ICON calculates a pretreatment score of five components (the Aesthetic Component, maxillary and mandibular crowding/spacing, cross bites, anterior open bite/overbite, and buccal segment anterior posterior relationship). It is composed of a 5-point grading of treatment complexity (simple, mild, moderate, difficult, and very difficult) (Daniels & Richmond, 2000).

Few studies have assessed the treatment outcome by use of the index in combined orthodontics/orthognathic surgery patients. Templeton et al. 2006 assessed the correlation between PAR and ICON scores with subjective opinion of panel of 5 orthodontists. The study models of 30 patients who underwent conventional orthognathic surgery were scored using the PAR and ICON indices. The pre-treatment, post-treatment, and treatment improvement scores were recorded. The correlation between subjective and objective score of both outcome and improvement were calculated. Both PAR (r:0.72, 0.68) and ICON (r:0.66, 0.69) showed a very good correlation with subjective opinion for treatment outcome and treatment improvement. The details of occlusion, skeletal deformity of the patients and the type of orthognathic surgery was not reported (Templeton et al, 2006).

The study by Ponduri et al. (2011) found that the PAR index was a valid tool in assessing the outcome of orthodontic/orthognathic treatment by comparing a group of 20 orthognathic patients with a group of 20 orthodontic-only cases. The overall mean percentage reduction in the PAR scores was similar (77% vs 74%) for both groups. However, the results are limited to conventional orthognathic approach and does not address the features of immediate post-operative occlusion of surgery-first approach (Ponduri et al, 2011).

In the study by Cartwright et al. (2016), the absolute and percentage PAR score reductions of pre- and post-treatment dental study casts of 73 skeletal class III and II patients were generated by a single calibrated clinician. There was an average mean reduction of 83.7% in PAR score and a mean post-treatment score of 5.86 within the sample, which represented a greatly improved occlusion. However, the outcome was only evaluated in terms of static occlusion of 27 (36.9%) single jaw and 46 (63.1%) bimaxillary cases who underwent conventional orthognathic surgery (Cartwright et al, 2016).

Recently the study by Anwar et al. (2022) compared the PAR score between the 20 SFA and 23 OFA skeletal class III patients who underwent Lefort I maxillary advancement. The results showed the median pre-treatment PAR score was 45.0 for the OFA group, and 44.0 for the SFA group, while the median post-treatment PAR scores were 5.0 for the OFA group, and 4.0 for the SFA group. The percentage PAR reductions were 90% for the SFA group and 88% for the OFA group, which showed no statistically significant difference between the two groups and all cases were ‘greatly improved’ using the PAR Index (Anwar et al, 2022). The composition of patient groups differed from those in other studies, which included class I, II, and III malocclusions, as well as single jaw and bimaxillary. Although the study brings new insights in comparing the occlusion between SFA and OFA at the end of the treatment, the limitation associated with PAR index still exists.

To the date, there is no study that assessed the immediate post-operative occlusion of orthognathic patients by the occlusion criteria specific to these patients. Although different studies have compared the indices and reported on reliability and validity of them, the main reason of the development of an index was for orthodontic assessment. Therefore, the certain criteria and characteristics specific to occlusion of orthognathic patients have not been fully assessed.

1.5 OCCLUSAL INDICATORS

The occlusal indicators have been utilized to assess the occlusal contacts are categorized into two types: the qualitative and quantitative indicators. The qualitative methods are articulating papers, shim-stock foil, occlusal wax, plastic strips, and elastomeric impression material. They have been utilized to mark the number and location of occlusal contacts; however, these methods have not proved to be accurate in reproducing occlusal contacts. The sensitivity and reliability of these techniques for occlusal analysis depend on the thickness, strength, and elasticity of the recording materials, as well as the oral environment and clinician's technique (DeLong et al, 2007; Forrester et al, 2011).

The quantitative methods, including Photo-occlusion, Dental Prescale and T-scan, measure the occlusal contacts generated by occlusal forces (Forrester et al, 2011). Maness et al. (1987) developed the T-scan (Tekscan Inc., Boston, MA, USA) as a computerized occlusal analysis system. The T-scan technology has been developed over the last 30 years, including a T-scan II for Windows (1995), T-scan III with turbo recording (2004) **(Figure 3)**, and the newly updated T-scan v10 (2018) system **(Figure 4)**. The T-scan is advantageous as it can represent the occlusal contact area at different bite force levels in real time using the intraoral sensor. The thickness of the sensor film is 100 µm. The sensor is composed of conduction lines, which create a grid with small pressure-sensitive areas called sensels. When force is applied on the sensor film, the voltage drops in the sensels and these changes are digitalized and shown by the T-scan software (Cerna et al, 2015).

The placement of the sensor between the teeth and instructing the patient to bite at maximum intercuspation, allows the recording of contact area. The T-scan software generates a dynamic report showing an occlusal image during maximum intercuspation (Aras et al, 2009).

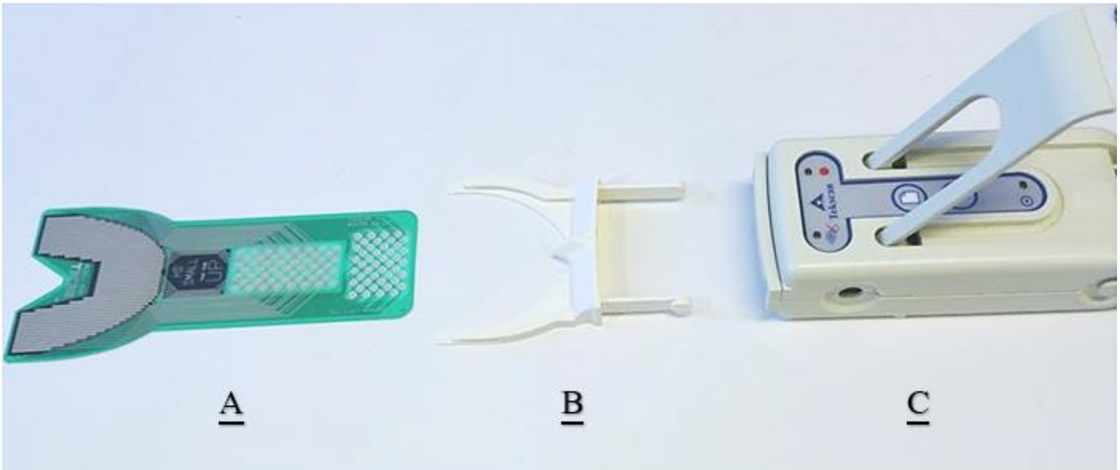

Figure 3. T-scan III device, A: The Sensor, B: The sensor support, C: Recording handle

Figure 4. T-scan v10 (Tekscan Inc., Boston, MA, USA)

The analysis of occlusal contacts has been reported by Zhao et al., 2023 who compared occlusal contact number and area between T-scan (Dental Prescale II) and intraoral scanner (Trios 3 Shape). Twenty-two dental students were asked to bite with the maximum force into the sensor foil and articulating paper respectively and held for at least 3 seconds. There was no significant difference between the occlusal contact number obtained from the two methods (37.75 vs 38.47) (Zhao et al, 2023).

The study by Ayuso-Montero et al. (2020) reported that T-Scan is more reliable when the patients apply maximum occlusal force rather than moderate occlusal force. Furthermore, the sensor film does not always show uniform sensitivity and requires adjustment before each recording to eliminate the potential differences from individual bite forces (Ayuso-Montero et al, 2020). The sensitivity of the T-scan sensors has been found to decrease when the sensors are used more than once (Garcia et al, 1997).

The Prescale system (Fuji Film Co., Japan) was developed in Japan in early 1990s, and consists of a horseshoe-shaped pressure sensitive film in which a pressure between 5Mpa and 150Mpa is applied **(Figure 5).** The pressure will result in the destruction of micro capsules within the film and mixing of red colour with a developing solution in the film. The colour becomes darker as the applied pressure increases, and the difference in the colour density is analysed by the scanner (Choi et al, 2010).

However, the scanner can only distinguish between eight shades and the occlusal contacts are not recorded simultaneously when the force is applied. Furthermore, the thickness of the plastic sheet or the sensors, which interfere with the normal occlusion, as well as the need to apply occlusal force, are the main limitations of these methods (Garcia et al, 1997; Saracoglu & Ozpinar, 2002).

<u>Figure 5. The Pre-scale system. A: Horse-shoe shaped pressure sensitive film. B: The recorded occlusal force on the left and right sides showing the quantity and the percentage of bite force</u>

1.6 DIGITAL OCCLUSION (STUDY MODELS)

The occlusal contacts have been assessed through digital study models. The 3D imaging technology allows the digitization of the dental occlusion by scanning the natural dentition or dental casts. Currently, there are 3 methods of producing digital orthodontic study models: 1. Direct Intra-oral laser scanning of the dental arches, 2. Laser scanning of impressions or plaster models, 3. Cone-beam computed tomography (CBCT) of orthodontic impressions or plaster models **(Figure 6).** The reproducibility, validity, and reliability of employing 3D digital study models have been evaluated and deemed satisfactory (Dalstra & Melsen, 2009; Fourie et al, 2011).

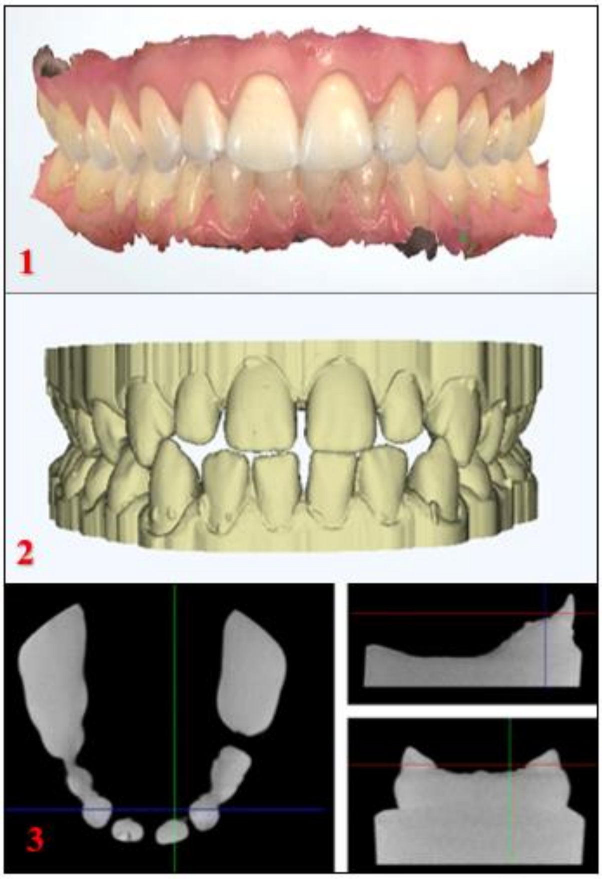

Figure 6. The 3 methods of producing digital study models; 1: Intra-oral laser scanned models. 2: Laser scanned plaster casts model, 3: CBCT scans of plaster casts in axial, sagittal, and coronal direction.

Intra-Oral scanners have been shown to enhance clinical diagnosis of dental conditions, facilitate treatment planning, and capture digital impressions for the fabrication of indirect restorations. The intra-oral scanner allows multiple scanning of the study models easily and quickly, with resulting data that can be fused with other virtual diagnostic records like CBCT and facial scans (Pieper, 2009; Zimmermann et al, 2015).

The study by Al-Rayes et al. (2014) evaluated the applicability of using 3D digital models to assess the occlusal contact area of 4 groups (class I, class II division 1, class II division 2 and class III) occlusions. Each group consisted of 30 orthodontic patients. The two digital software packages (Rapid form XOR 3, and O3DM) generated an occlusal map that showed the area of tooth contacts. The result showed the contact area for the Class I group was the largest while the Class III group was the smallest. There was a high correlation (r = 0.942) between the 2 software packages. The study concluded that using 3D digital models to measure occlusal contact using opposing points that lie in very close proximity, is a valid and reliable method of occlusal contact assessment (Al-Rayes & Hajeer, 2014).

In studies by Lee et al. (2015) and Jang et al. (2012) the occlusal contact areas were quantified using 3D digital models, which were generated through surface scanning of the study casts. Their studies aimed to measure differences in occlusal contact areas between class II and class I molar relationships at completion of orthodontic treatment. The same software package (Rapid-form XOR3) was utilized in two studies which automatically calculated the intersecting contact area in mm^2. The software quantified the occlusal contact areas of the 2 molars and premolars on each side. The studies reported that class I cases exhibited a larger contact area than class II cases at end of treatment (Jang et al, 2012; Lee et al, 2015).

Lee et al. (2018) compared the occlusal contact areas calculated by the Prescale method with the virtual occlusion derived from scanning of dental casts. Twenty-four sets of class I models and 20 sets of class II models were divided into a Molar, Premolar, and Anterior region. The percentages (%) of the total occlusal contact areas obtained from the occlusal maps were compared. The Prescale and the scanner showed similar contact areas in the molar and premolar regions. The anterior segments showed the highest amount of deviation and a statistically significant difference ($P < 0.05$) due to overestimation of the occlusal contact area obtained from the scanned dental models. However, the differences in occlusal forces and the thickness of the sensors associated with Prescale may have affected the results. The results demonstrated that scanning dental casts has high level of reproducibility of the actual occlusion (Lee et al, 2018).

However, the details of the methods used for the quantitative analysis of occlusal surface area have not been reported in previous studies. Reviewing the literature reveals a paucity of research evaluating occlusal contacts using 3D digital dental models. Furthermore, the possible relationships between occlusal contacts as well as overjet and overbite with skeletal stability of orthognathic patients have not yet been evaluated (Nilsson et al, 2016).

1.6.1 Digital measurement accuracy and threshold levels

Several studies have reported that lack of post-surgical occlusal interdigitation is a risk factor for skeletal relapse with the surgery-first approach. However, occlusal factors related to skeletal stability have not been quantified objectively (Han et al, 2016; Rhee et al, 2015).

Studies that look at occlusal contact distribution and contact area, have utilized a dental occlusal map. The different 3D intraoral scanners allow the scanning of plaster models and the generation of occlusal map. The colour-coded occlusal map shows the distances between the maxillary and mandibular dentition, with a specific colour assigned to regions where occlusal contact is present. The inter-occlusal distance or threshold levels are preset to represent the occlusal contacts.

In the study by Al-Rayes et al. (2014), utilizing the O3DM™ software (threshold 0.00 -1.5mm), the areas between 0 to 0.4 mm were defined as areas of occlusal contacts. However, the authors did not report on the threshold levels for the Rapid-form™ XOR3 software (Al-Rayes & Hajeer, 2014). Similarly, the studies by Jang et al. (2012) and Lee et al. (2015) did not report on threshold levels of the Rapid-form XOR3 software (Jang et al, 2012; Lee et al, 2015).

In the study by Lee et al. (2018) the models were scanned by Trios® 3D intraoral scanner (3 shape dental systems) and occlusal analysis was carried out by using Ortho-Analyzer software in the form of an occlusal map (threshold 0.00 – 3.00mm). The occlusal contact area, was defined as interocclusal distances between 0.00 to 0.098 mm (Lee et al, 2018).

Baan et al. (2021) compared the accuracy of the virtual occlusion with the occlusion achieved by conventional plaster models in orthognathic patients. The occlusogram indicating occlusal contact areas between -2 to 2 mm were utilised to assess the occlusal contacts (Baan et al, 2021b). The studies by Nadjmi et al., 2010 and Bowman et al 2023 assessed the virtual occlusion, utilizing a distance heatmap with a threshold range of -1.0 mm to 1.0 mm to assess the occlusal contacts (Bowman et al, 2023; Nadjmi et al, 2010).

Digital impressions are divided into direct and indirect methods. The direct method is obtained by scanning the occlusion of the patient intra-orally, while the indirect method involves scanning plaster casts or impressions. Most studies have evaluated the reproducibility and accuracy of the digital models by comparing the measurements obtained from virtual models with those taken from plaster models (Lippold et al, 2015; Sousa et al, 2012).

Table 2 shows the software programs that have been utilized in literature, to compare measurements made from digital and plaster models.

Software program	**Number of the times utilized in studies**
Ortho Analyzer (3Shape Denmark)	8
Digi model (Ortho proof USA)	4
O3DM (Ortho lab Poland)	3
Rapid form (INUS Korea)	3

Table 2.Software's utilised in different studies for assessment of occlusion.

The Digi model software uses its own individual file format, and therefor does not support the universal file format of digital models (STL) (Felter et al, 2018).

The O3DM and Ortho Analyzer software can perform basic measurements such as overbite, overjet, tooth size, space analysis, Bolton analysis, and arch length. The programs can show views of the digital cast in different planes; maps of occlusal contacts; free measurements from point to point, point to plane, or plane to plane; and measure tooth movements in different planes (Westerlund et al, 2015).

Santoro et al. (2003) measured overjet, overbite, and tooth width on 76 sets of dental casts using Ortho-CAD software and manual measurements. The study showed that the digital measurements were smaller for tooth width and overbite by 0.16 to 0.49 mm respectively, but not at a clinically significant level. In fact, earlier studies have shown that the intra-operator error for repeat clinical measurements on plaster casts, averages 0.2 mm (Santoro et al, 2003).

The study by Verma et al. (2019) included 132 study models scanned by Maestro 3D Dental model scanner (AGE Solutions Sr. l, Pontedera, Pisa, Italy). The mesiodistal width, transverse dimensions, arch length, overjet, and overbite were measured manually and digitally. The range of the difference of the means (0.013–0.32 on pre-treatment and 0.017–0.37 on posttreatment models) was statistically significant but not clinically significant. The digital measurement values were generally lower than the manual values for most of the variables (Verma et al, 2019).

Zhang et al. (2016) compared the measurements on dental cast with those derived from direct intraoral scans. The tooth dimensions in all three planes of space were recorded on 20 plaster models using a digital calliper and on the digital models using Rapid-form software. The differences between the two sets of measurements were between 0.1mm to 0.2 mm and were not clinically significant (Zhang et al, 2016).

The systematic review by Rossini et al. (2016) included 35 articles which compared measurements obtained from virtual dental models with those obtained from plaster models. The mean difference in the mesiodistal and vertical tooth dimensions, overjet, overbite, occlusal indices, and transverse measurements between digital and plaster models ranged from 0.01 to 0.5 mm. The review reported that differences in the impression procedures and model reconstruction processes may have contributed to some inconsistencies, However, the mean discrepancy between measurements on digital and plaster models were considered clinically insignificant (Rossini et al, 2016).

2 CHAPTER TWO: MATERIALS AND METHODS

SECTION A

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2.1 SECTION A: AIMS

The **Primary** aim of the study was the 3D assessment of the skeletal stability following the surgery-first approach for the correction of maxillary retrognathism with Le fort I osteotomy. The **Secondary** aim was the evaluation of the relationship between the quality of postoperative occlusion and the skeletal stability.

Hypotheses to be tested:

This study tested the following two hypotheses:

1.The skeletal relapse of the Le Fort I maxillary advancement at 6 months following surgery is within 1mm.

2. There is No statistically significant correlation between the quality of the immediate postoperative occlusion and the measured skeletal stability at 6 months following surgery.

2.1.1 Sample

This retrospective study was based on the analysis of the cone beam CT “CBCT” scans of a cohort of patients who according to the surgery-first approach had undergone Le Fort I maxillary advancement for the correction of maxillary retrognathism. The patients were assessed at the MDT Dentofacial planning clinic at the University of Glasgow Dental Hospital and School. Ethical approval was obtained from the NHS Greater Glasgow & Clyde (R & D reference: GN20OD634, REC reference: 21/NE/0019).

Patients were selected from the Glasgow Dental School database from 2012-2022. All patients were diagnosed with maxillary retrognathism, all required orthognathic surgical correction and had undergone Le Fort I maxillary advancement. The surgical procedure was carried out by the same surgeon, and all followed the same surgical protocol.

The study was carried out on 3D digital models of the face which was extracted from the preoperative CBCT scans taken within one month prior to surgery (T0) and at 1 week postoperatively at (T1) and at 6 months follow up interval (T2).

2.1.1.1 Sample Size and Power of the study

The sample size calculation was based on previous studies which investigated the relapse following surgery-first approach and orthodontic-first approach **(Table 3)**. The sample size of previous studies varied from 11 to 61 patients. Almost all the studies were based on 2D radiographic analysis of various orthognathic surgical procedures which included bimaxillary and bilateral sagittal split osteotomy (BSSO). The mean and standard deviation of skeletal changes of maxilla were reported in four of these studies.

The sample size was calculated using the G*Power software (latest ver. 3.1.9.7; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) (Kang, 2021). Based on the standard deviation of 1.28, the G power software calculated the effect size (ES: 0.8) and sample size as per: $P<0.05$ (α error), Confidence Interval 95%, and power of 90%. A sample size of 20 subjects was required to detect a 1mm or more of changes in skeletal stability. **(Figure 7)**

Author	Type of Surgery	Sample size	measurement
Baek et al. 2010	Bi-maxillary surgery	11 SFA	Maxilla & Mandible
Liao et al. 2010	Bi-maxillary surgery	20 SFA, 13 OFA	Maxilla & Mandible
Ko et al. 2011	Bi-maxillary surgery	18 SFA, 35 OFA	Mandible
Ko et al. 2013	Bi-maxillary surgery	33 SFA	Mandible
Park et al. 2015	Bi-maxillary surgery	19 SFA, 19 OFA	Maxilla & Mandible
Kim.J et al. 2014	Bi-maxillary surgery	37 SFA	Mandible
Ann et al. 2016	Bi-maxillary surgery	12 SFA, 12 OFA	Maxilla & Mandible
Kim.C et al.2014	BSSO set-back surgery	23 SFA, 38 OFA	Mandible
Mah et al. 2017	BSSO set-back surgery	20 SFA, 20 OFA	Mandible
Kim et al. 2013	BSSO set-back surgery	15 SFA. 11 OFA	Mandible
Akamatsu et al. 2016	BSSO set-back surgery	14 SFA, 24 OFA	Mandible

Table 3. Reported Sample size of previous studies.

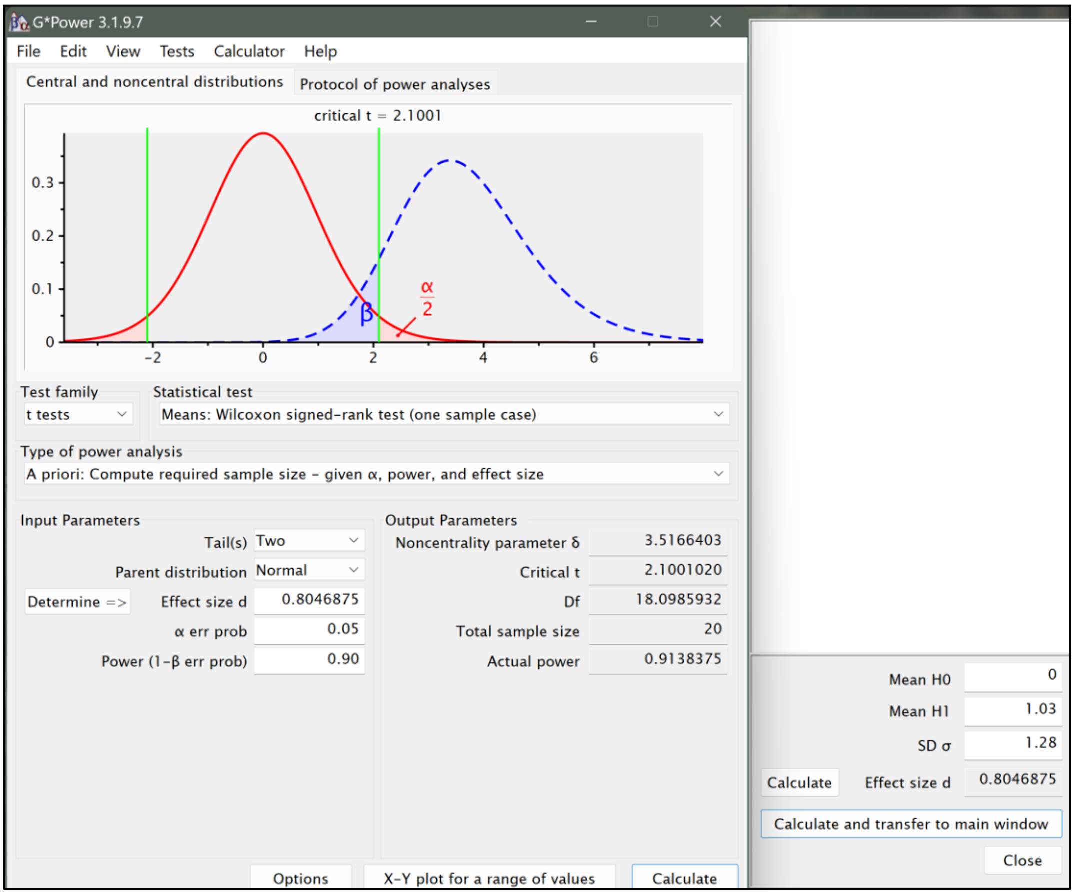

Figure 7. The G*Power software for sample size calculation.

2.1.1.2 Inclusion Criteria

The following inclusion criteria were considered in the study:

- Patients who underwent Le-fort I maxillary osteotomy with or without genioplasty followed the surgery-first approach between 2012 to 2022 at Glasgow dental hospital & school.
- Patients aged 17 years and older with no further anticipated growth.
- Availability of preoperative, immediate post-operative and the 6 months postoperative CBCT scans. The pre-operative scans must have been taken within one month before surgery and the postoperative scans taken within 1 week (T1) and at 6 months (T2) following surgery.
- The availability of the preoperative physical models of the dental occlusion.

2.1.1.3 Exclusion Criteria

The following exclusion criteria were considered in the study:

- Patients who had undergone segmental maxillary osteotomy, bimaxillary surgery and mandibular osteotomy.
- Patients who had previous orthognathic surgery, trauma, or other facial aesthetic surgery.
- Cleft lip and palate patients.
- Inadequate CBCT scans or occlusion records

A total of 69 surgery first approach patients were identified. Twenty-five patients who had undergone Le Fort I maxillary advancement with or without genioplasty and had complete CBCT record were included. Incomplete CBCT records was the main reason for exclusion. **Table 4** shows the details of the classification of malocclusion and the surgical procedures undertaken for all the surgery-first approach patients.

Surgery First Approach (SFA) Patients List			
Surgical Procedure	**Class III**	**Class II**	**Class I + Asymmetry**
Lefort I Advancement + - Impaction	**37**		
Le Fort I Advancement + Genioplasty	**10**		
Bilateral Sagittal Split Osteotomy	**2**	**4**	**1**
Bilateral Sagittal Split Osteotomy + Genioplasty	**2**	**2**	
Bimaxillary surgery	**6**	**3**	**1**
Bimaxillary surgery + Genioplasty	**1**		
Total: 69	**58**	**9**	**2**

Table 4.Malocclusion and surgical classifications of SFA patients

2.1.2 The Scanning Protocol of the CBCT scans

A Standard protocol was followed for taking the pre-operative and post-operative CBCT scans. The radiology department at the Glasgow Dental Hospital and School captured all the cases using the I-CAT 3D Dental Imaging System (Xoran-Technolog, Imaging Sciences, Hatfield, UK) according to the following parameters: 120 kVp, 0.4 mm voxels size, 20+ SEC scan time, and 22cm field of view.

To avoid soft-tissue distortion, prior to CBCT scanning the chin support of the i-CAT scanner was removed. The patients were instructed to sit upright. The laser beam of the i-CAT scanner was projected into the patients face to help in adjusting the Frankfort horizontal (FH) plane parallel to the floor. The patient's head was secured to the headrest of the scanner using a securing band placed as high as possible around the forehead. Patients were instructed to lick their lips and saying "N" and biting their teeth together to achieve the reproducible centric occlusion with the lips in repose. The patients were asked to remain still, not to swallow during scanning. CBCT Images were stored in Digital Imaging and Communications in Medicine (DICOM) format.

There was a limited need to adjust to the technical parameters of the CBCT scans, as the radiography technicians standardised the method of CBCT scans for orthognathic surgery patients.

2.1.2.1 DICOM Image anonymization

The pre-operative, 1-week, and 6-months post-operative DICOM images were anonymized. The DICOM-Cleaner software was used to anonymise the CBCT images by removing any tagged information including the CHI numbers of the patient off the DICOM files. An EXCEL worksheet was designed which included patients' names and their corresponding CHI numbers. This was stored in NHS computer for retrieving information if required. Total of 75 anonymized CBCT images were stored for purpose of analysis.

2.2 ANALYSIS OF CBCT IMAGES FOR SKELETAL ASSESSMENT

Analysis of serial CBCT images to evaluate changes over time has followed the following three steps; the 3D model construction, 3D surface-based registration and the quantitative measurement.

2.2.1 3D model construction and image orientation

The pre- and post-operative CBCT DICOM files of each patient were imported into Maxilim software (Medicim-Medical Image Computing, Belgium). The hard tissue models of the DICOM files were segmented at HU=276 to generate the STL files **(Figure 8)**. Total of 3 STL files were generated for each patient. The Horizontal(axial) reference plane passing through left and right Orbitale and the left Porion landmarks was defined. The median (sagittal) reference plane was established as a line connecting the hard tissue Nasion and Sella. The vertical (coronal) plane was automatically generated perpendicular to the other two planes passing at the Sella point. Total of 75 generated STL files were oriented according to the same reference plane and were exported into the VRMesh software (Virtual Grid, Seattle City, U.S.A) for further analysis.

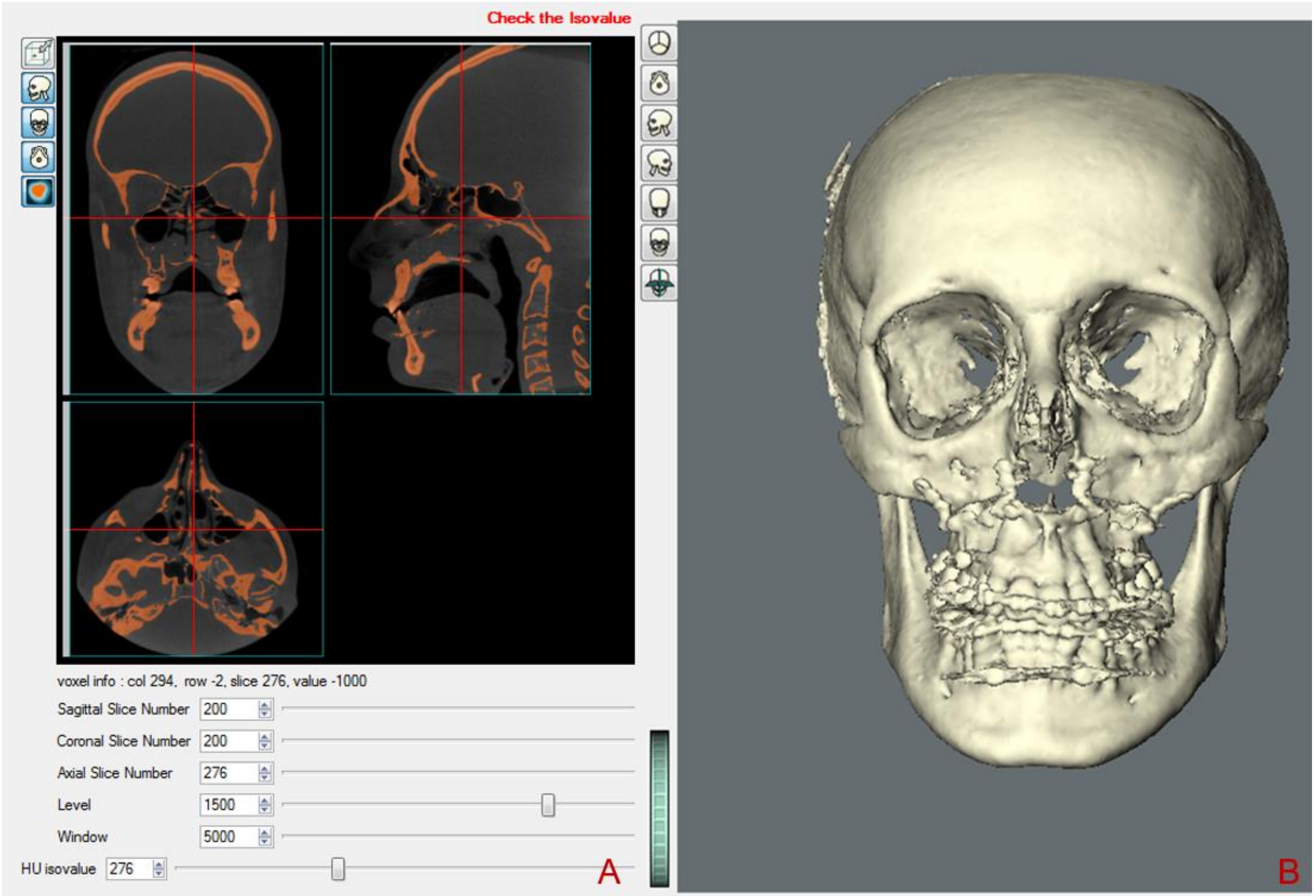

Figure 8. Segmented 3D models from the DICOM image using Maxilim software.

2.2.2 Surface based registration of the 3D skull models

The principals of surface-based registration were discussed in Section (1.1.1). In summary, the iterative closest point (ICP) method for the superimposition of two 3D surface models was applied. This was achieved by matching the corresponding closest points on the corresponding 3D surfaces to initiate the registration process.

For 2D cephalometric superimpositions, the American Board of Orthodontics suggests using the anterior cranial base to assess the total changes in the maxilla and the mandible. The same has been applied for the 3D CBCT superimpositions. The anterior cranial base was utilised to assess overall facial growth and treatment outcomes (Ghoneima et al, 2017).

VRMesh software (Virtual Grid, Seattle City, U.S.A), was used to measure the actual surgical movement and skeletal changes. The superimposition of the corresponding skull models was based on the stable regions that were unaffected by the surgery which included the anterior cranial base, zygomatic arches, and forehead. For this purpose, the preoperative and postoperative models were transformed such that the coordinates of the models were positioned with Nasion as mathematical centre of origin (0, 0, 0) **(Figure 9)**.

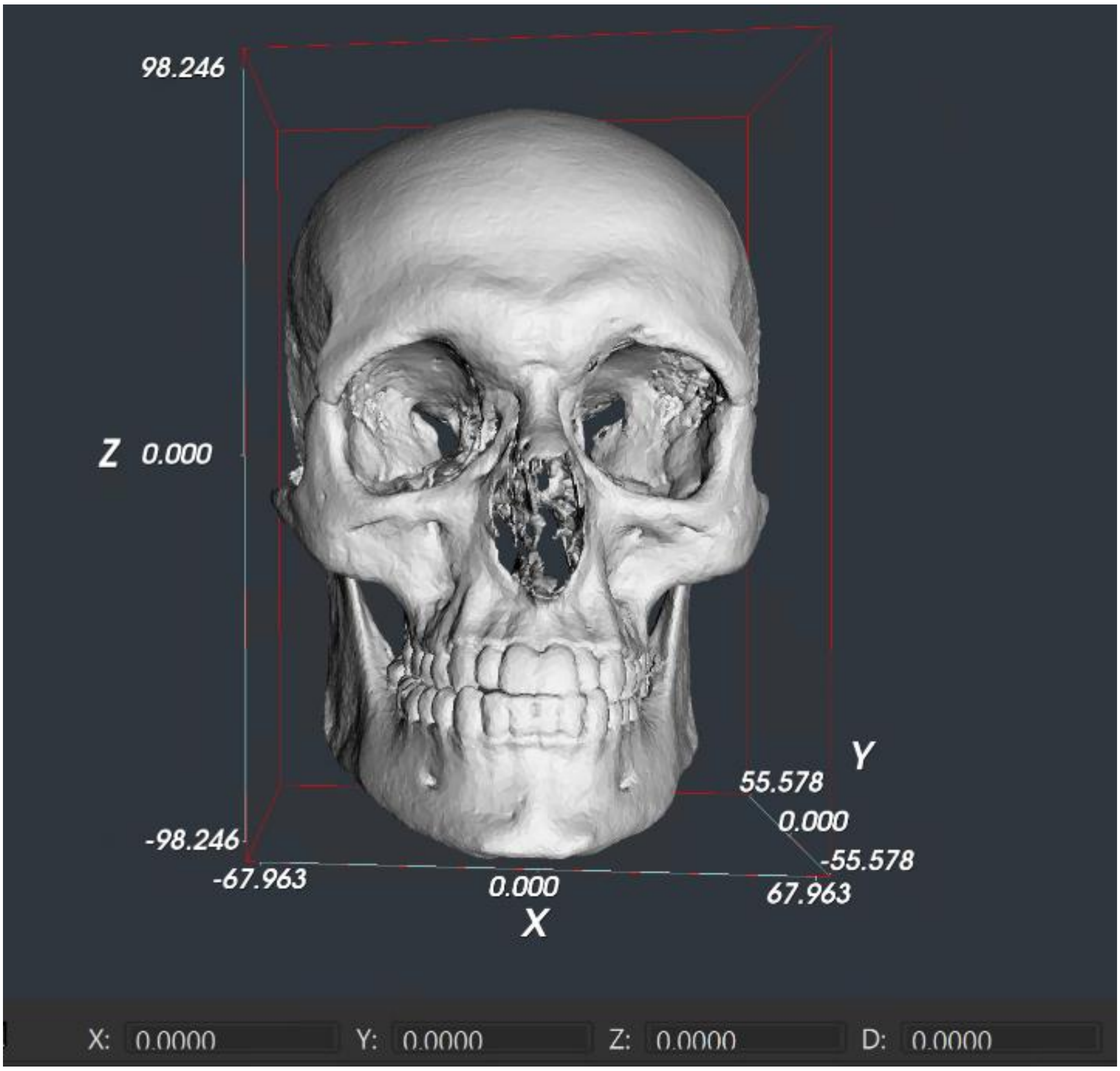

Figure 9.The 3D models with Nasion coordinates positioned at (0,0,0).

The first step of registration was carried out by approximating the pre-operative and postoperative corresponding 3D models. For this purpose, five landmarks were digitized on the preoperative model (Target), these were the left and right zygomatic-frontal sutures, nasion point and zygomatic arch. The corresponding landmarks were also digitized on the post-operative model (source). This has provided a set of close corresponding points to initiate the registration process. The post-operative models (source) were always registered by rotation and translation on to the preoperative model (target). The Partial Procrustes registration process allowed the translation and rotation of the corresponding surfaces “rigid registration” without scaling.

The second step was to improve the alignment of the post-operative model to the preoperative model. The (ICP) function within VRMesh was applied. The automatic iterations were set as 0.01 overlap distance in the selected region. The Analysis > Inspection function within VRMesh was applied to the registered “superimposed” models to visualize the distances between two superimposed models by Colour coded distance maps. The process was repeated for the 6-months post-operative 3D models as the source and the preoperative model as the Target. Each of the 1-week and 6 months postoperative 3D models of the skull were superimposed on the pre-operative model using surface-based registration. **Figure 10** shows the steps of surface-based registration with in VRMesh software.

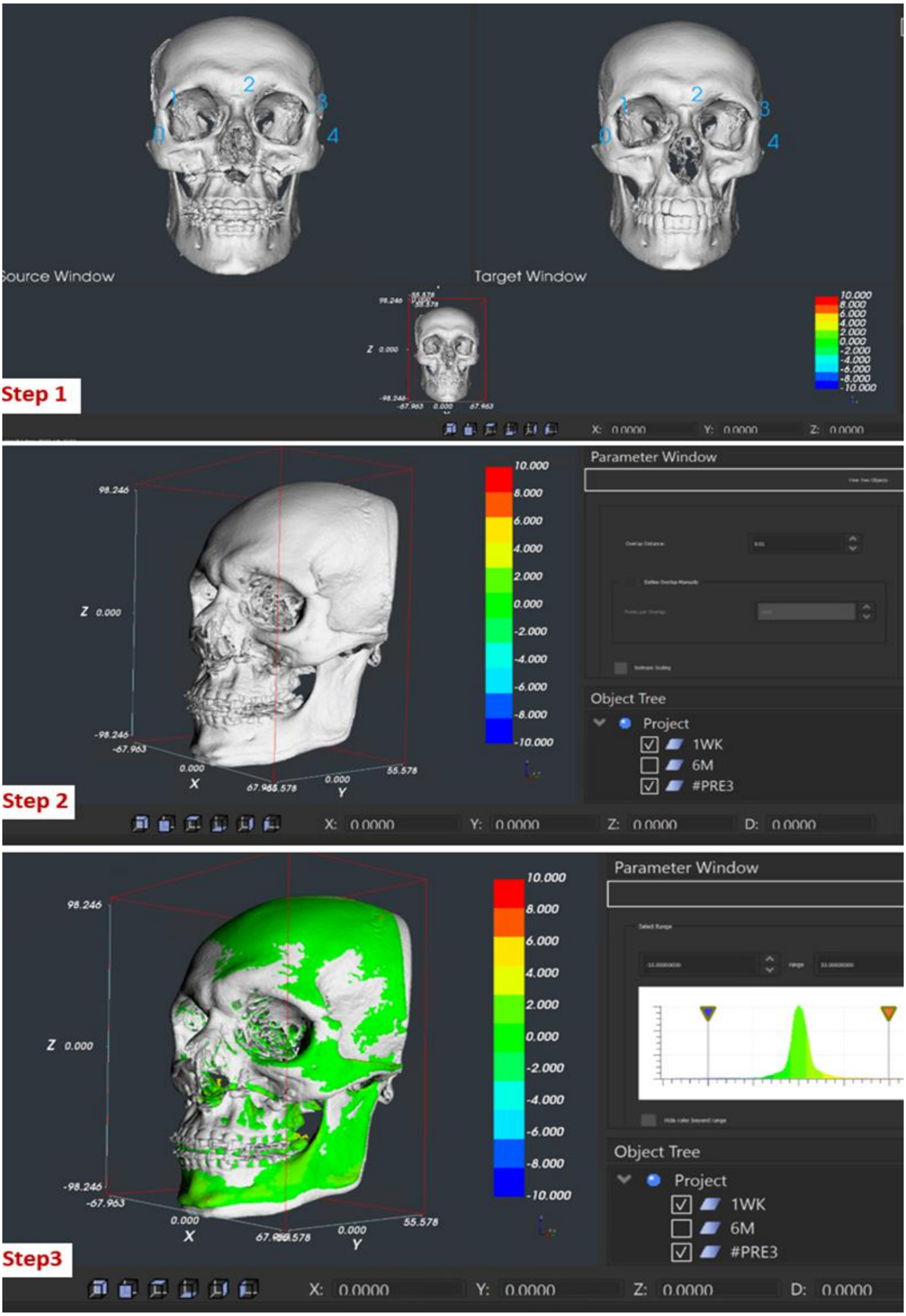

Figure 10. Visual representation of the steps of Surface based registration; Step 1: landmarks were identified on the preoperative (Target) and postoperative (Source) models. **Step 2:** The postoperative model was superimposed on the preoperative model on the anterior cranial base, forehead, and zygomatic arches. **Step3:** Colour coded distance maps to visualize the distances between two superimposed models.

2.2.3 Quantitative measurement of surgical movement (T0-T1) and skeletal relapse (T1-T2)

To measure the magnitude of surgical movement (T0-T1) and the relapse (T1-T2) in 6 degrees of freedom, the landmark selection was performed.

2.2.3.1 Landmark selection

The maxillary right and left greater palatine foramen and incisive foramen were selected to represent the maxillary plane **(Table 5).** The three landmarks which were digitised on the preoperative maxilla, were also digitized on the 1-week and 6 months post-operative models. The landmarks were labelled using the function "Scalar Label" of the VRMesh software. This allowed selection of the same landmark at the preoperative, 1 week and 6-month postoperative models **(Figure 11).** The three landmarks are stable internal reference points that are not affected by remodelling and are away from the surgical cuts and bony fixations, they provided the required details of the maxillary surgical changes which included linear movements and changes in the maxillary plane.

	Landmark	Definition
1	Incisive foramen (IF)	The most posterior point of the incisive canal
2	Greater palatine foramen/Right (GPR)	The most posterior point of the right greater palatine foramen
3	Greater palatine foramen/Left (GPL)	The most posterior point of the left greater palatine foramen

Table 5. The definition of selected landmarks

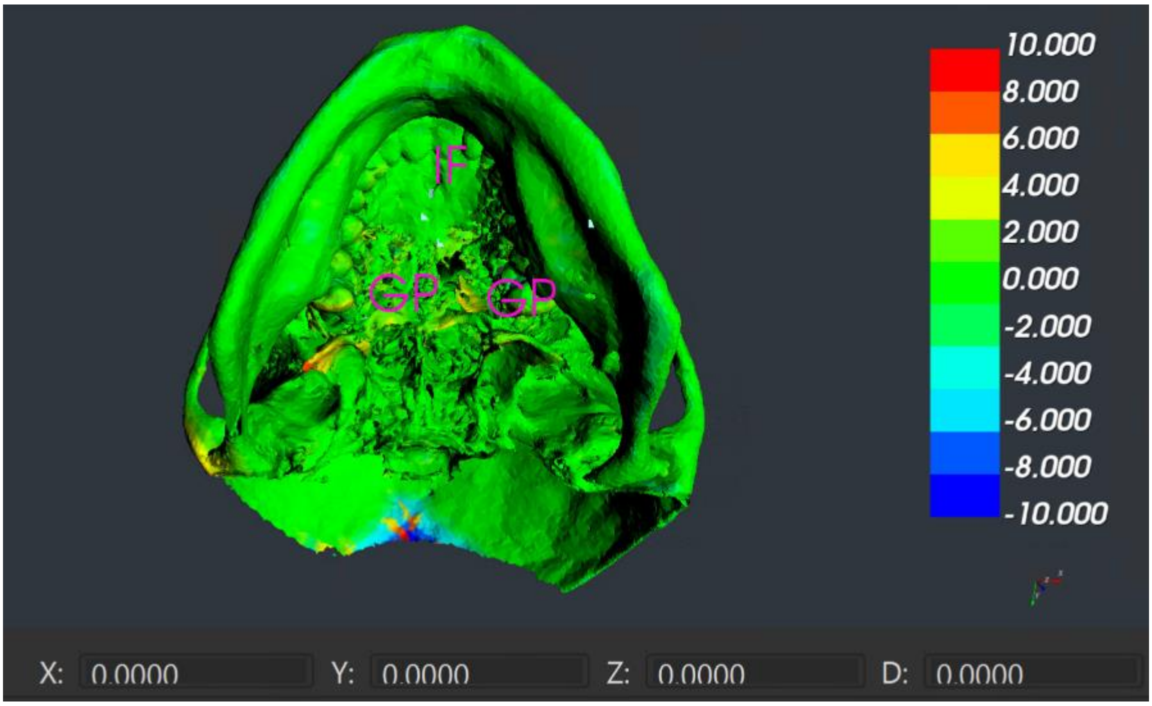

Figure 11. The 3 Landmarks digitized: Incisive foramen (IF) and 2 Greater palatine foramens (GP)

2.2.3.2 Calculation of the maxillary rotational and translational movements

The coordinates of the selected landmarks of the preoperative, 1 week and 6-month postoperative models were extracted. Two transformation matrices were developed which contained the information of the maxillary translations and rotations changes from the preoperative position to 1-week postoperative position (Surgical movement, T0-T1) and from 1-week postoperative position to the 6-month postoperative position (Relapse, T1-T2).

The positional changes from T0 to T1 and from T1 to T2 were measured in six degrees of freedom. The translational measurements have included: distance in x, y, z axis; left/right (L/R), anterior/posterior (A/P) and superior/inferior (S/I) and rotation: angle around x, y, z axis; pitch, roll and yaw. **(Figure 12)**

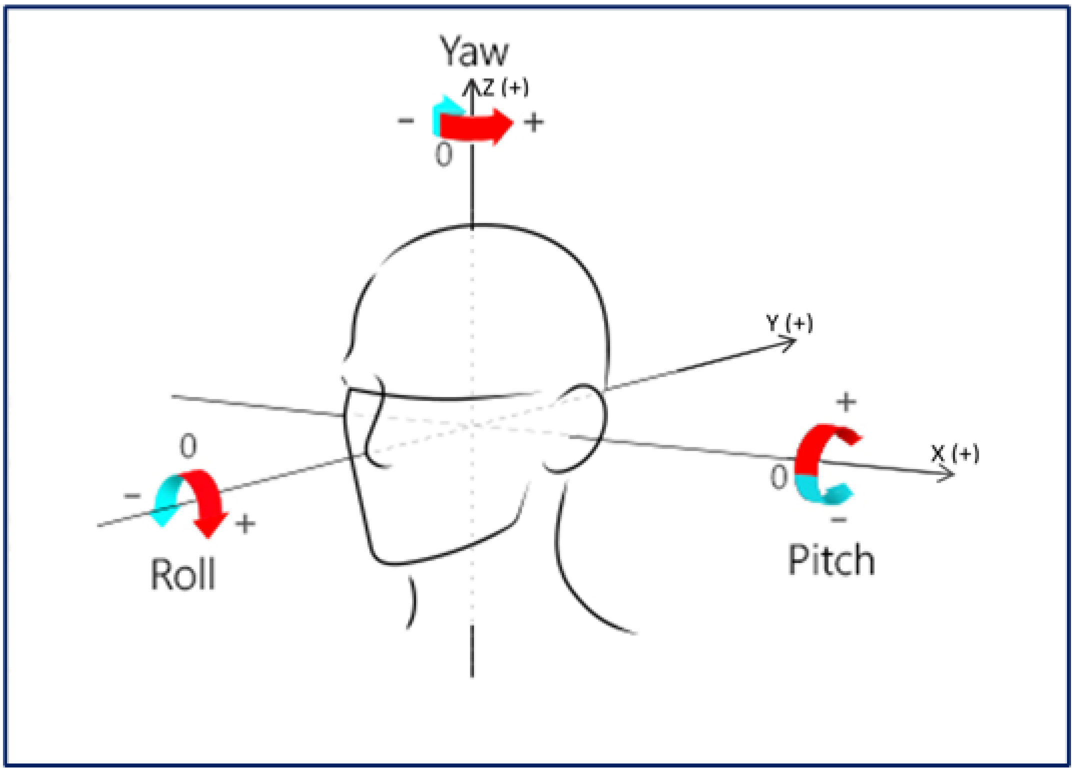

Figure 12. Illustration of translational and rotational movements. Translation: X-axis (left-right), Y-axis (posterior-anterior), and Z-axis (superior-inferior); a positive value indicates movement of the left, posterior, and superior. **Rotation:** around the X-axis axis (Pitch: clockwise rotation +, counterclockwise rotation −), Y-axis (Roll: clockwise rotation +, counterclockwise rotation −), and Z-axis (Yaw: counterclockwise rotation +, clockwise rotation −).

2.3 REPLACEMENT OF DISTORTED DENTITION

The recorded dentition of the CBCT scans lacked the required accuracy for the analysis due to limited resolution and the streak artefacts of the CBCT image caused by metallic fillings, implants, and orthodontic brackets. The distorted dentition of the CBCT scans need to be replaced with the scanned dental models for the accurate assessment of the quality of the pre-operative and immediate postoperative occlusion (Marradi et al, 2020). In order to assess the quality of occlusion, 4 parameters were defined:

1. The distribution of occlusal contact, 2. The number of the teeth in occlusal contact, 3. Overjet, 4. Overbite

2.3.1 Replacement of the defective dentition of the CBCT scans

The software package IPS Case Designer® (KLS Martin, Tuttlingen, Germany) was used for the replacement of the defective dentition of the pre-operative and immediate postoperative CBCT scans **(Figure 13)**. The maxillary and mandibular dentition of the 25 study models were scanned using the 3Shape intra-oral scanner (TRIOS3, 3shape A/S, Copenhagen, Denmark) and exported in the Standard Tessellation Language (STL) format. The DICOM files of the CBCT scan and the STL files of scanned dental models were imported to the same software to create a 3D virtual model of the skull, jaw bones and dentition.

The scanned dental models were rotated 90° around the *x*-axis to allow the accurate alignment within the same coordinate system of the captured CBCT scans using IPS Case Designer software®. A common frame of reference for the accurate replacement of the defective dentition of the CBCT scans was achieved by digitizing the right and left condylar heads, the mesio-buccal cusp of the upper right first molar, the mesio-buccal cusp of the upper left first molars and the point of contact between the two upper central incisors.

The IPS Case Designer® automatically aligned the Scanned dental models with the 3D virtual skull model based on contrast information at the tooth crown margin, the ICP algorithm. This allowed the generation of a virtual skull model which incorporated the accurate dental occlusion. The process was repeated for the 25 preoperative, and twenty-five 1-week post-operative CBCT scans. The final 3D models of the skull with incorporated actual dental occlusion were exported for further analysis. Total of 50 models were then loaded into VRMesh software (Virtual Grid, Seattle City, U.S.A) and arranged in two groups for analysis, the 25 models in pre-operative group and 25 models in 1-week post-operative group.

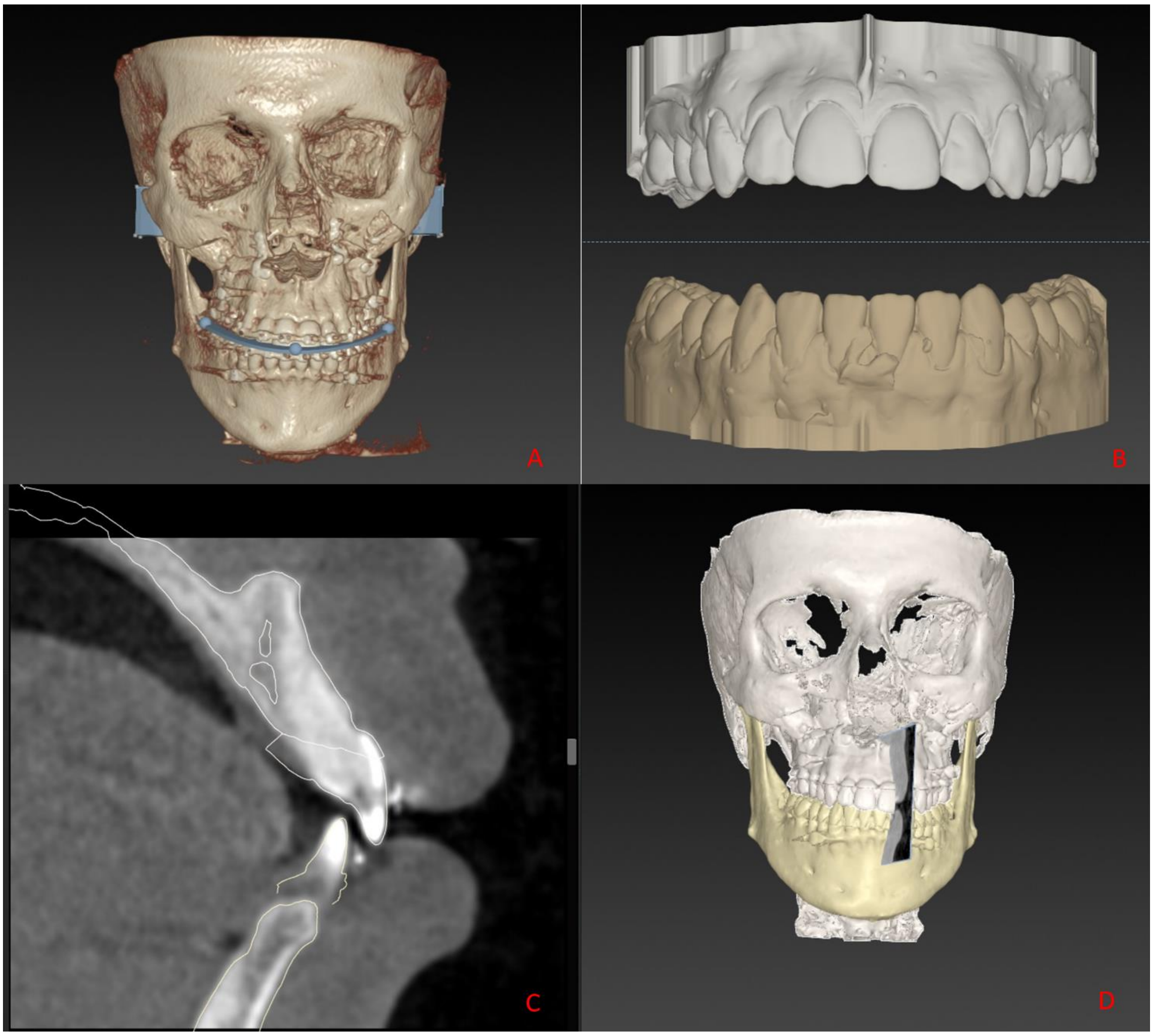

Figure 13. The process of replacement of defective dentition in IPS Case Designer® (KLS Martin, Tuttlingen, Germany), A: CBCT skull model in the IPS Case Designer® software after marking the left and the right condyles as well as the occlusion plane**. B**: Scans of maxilla-mandibular plaster models**. C:** Sagittal view of the 3D CBCT skull model and fused intra-oral scans**. D:** Frontal view of the result of the fusion of the intra-oral scans in the CBCT.

2.3.2 The Determination of occlusal threshold (Pilot Study)

The occlusion of ten randomly selected sets of study models were scanned by intraoral scanner (Trios; 3Shape, Copenhagen, Denmark) while held in position by melted utility wax. The scanned occlusions were imported into VRMesh software, the occlusal contacts were assessed using the colour map of the closest distances. The threshold of contact areas ranged from -0.5 to 0.5 and -0.2 to 0.2mm has been decided to detect the range of contacts. Based on this finding and the review of literature (Liao et al, 2022; Lo et al, 2019) the occlusal contact area was defined as interocclusal distance of -0.5 to 0.5mm. The -0.5 mm representing deep interdigitation to 0.5 representing edge to edge occlusion. Inter occlusal distance of more than 0.5 represent lack of contact.

2.3.3 Analysis of occlusal contact

The 25 Preoperative and twenty-five 1-week 3D models of the skull with incorporated dentition were imported into VRMesh software (Virtual Grid, Seattle City, U.S.A). The skull region was cropped and only the maxillary region was kept for the analysis. The “Analyz > inspection” function of the VRMesh software (Virtual Grid, Seattle City, U.S.A) allowed the visualisation of the occlusal contact by generating an occlusal map on maxillary dentition. The occlusogram is a colour map of the distances between the maxillary and mandibular dentition **(Figure 14).**

2.3.4 Analysis of contact distribution

The maxillary occlusogram was divided into the anterior region (from Right canine to Left canine) and Right and Left posterior regions extending from the Premolars to 2nd molars on each side. The distribution of occlusal contact was grouped into three categories; **A**: the Three regions group, **B**: the two regions and **C**: the one region. Occlusal measurements also included the number of the teeth in occlusal contacts.

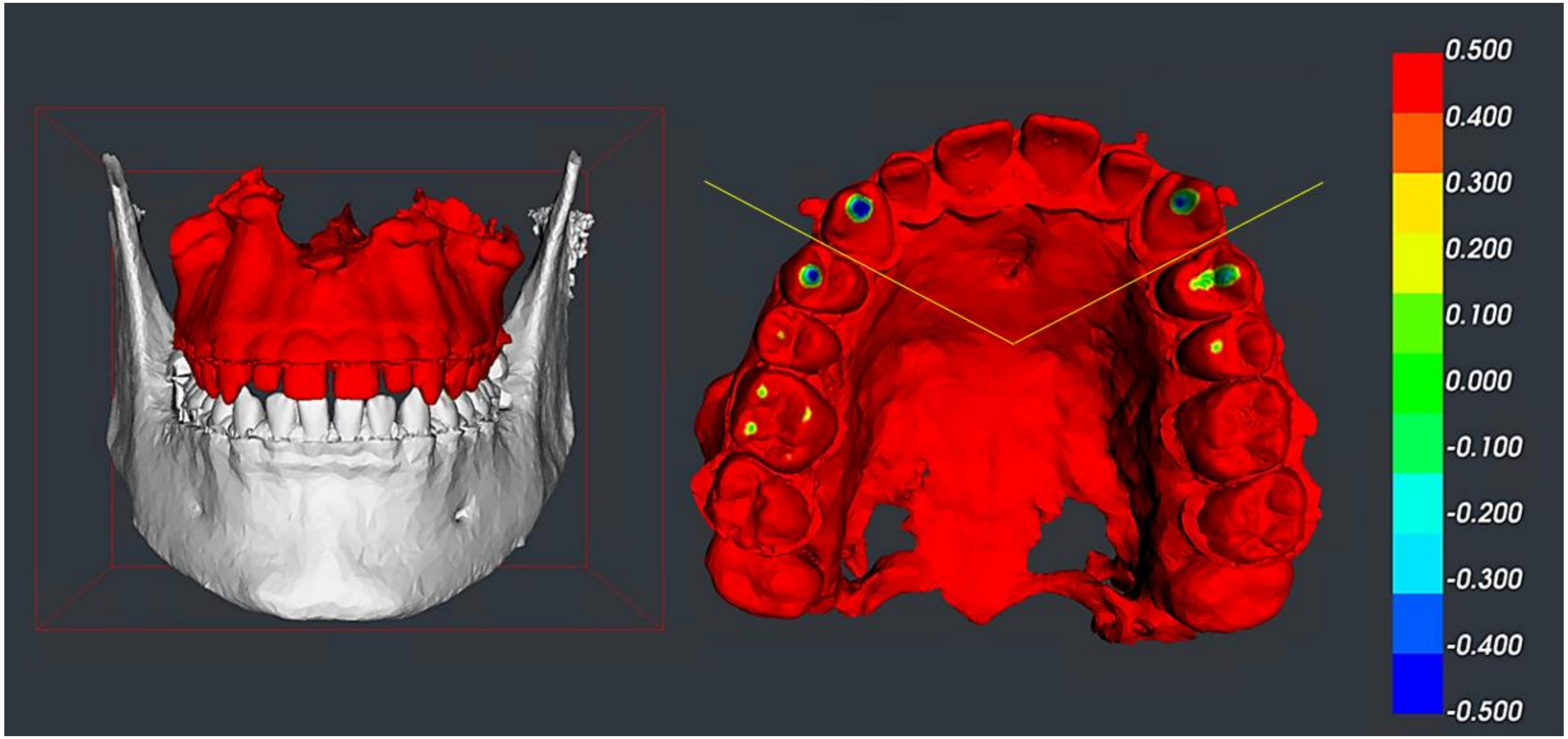

Figure 14. Visualisation of the occlusal contact by generating an occlusal map on maxillary dentition (Occlusogram), occlusal contact area was defined as interocclusal distance of -0.5 to 0.5mm.

2.3.5 Analysis of Overjet and Overbite

Two points were selected; the tip of right maxillary and the right mandibular central incisor. The measured distance between the *Z* value on tip of upper right central incisor and the *Z* value on the lower right central incisor represented the overbite.

The measured distance between the *Y* value on tip of upper right central incisor and the *Y* value on the lower right central incisor provided the measurement of the overjet. **(Figure 15)**

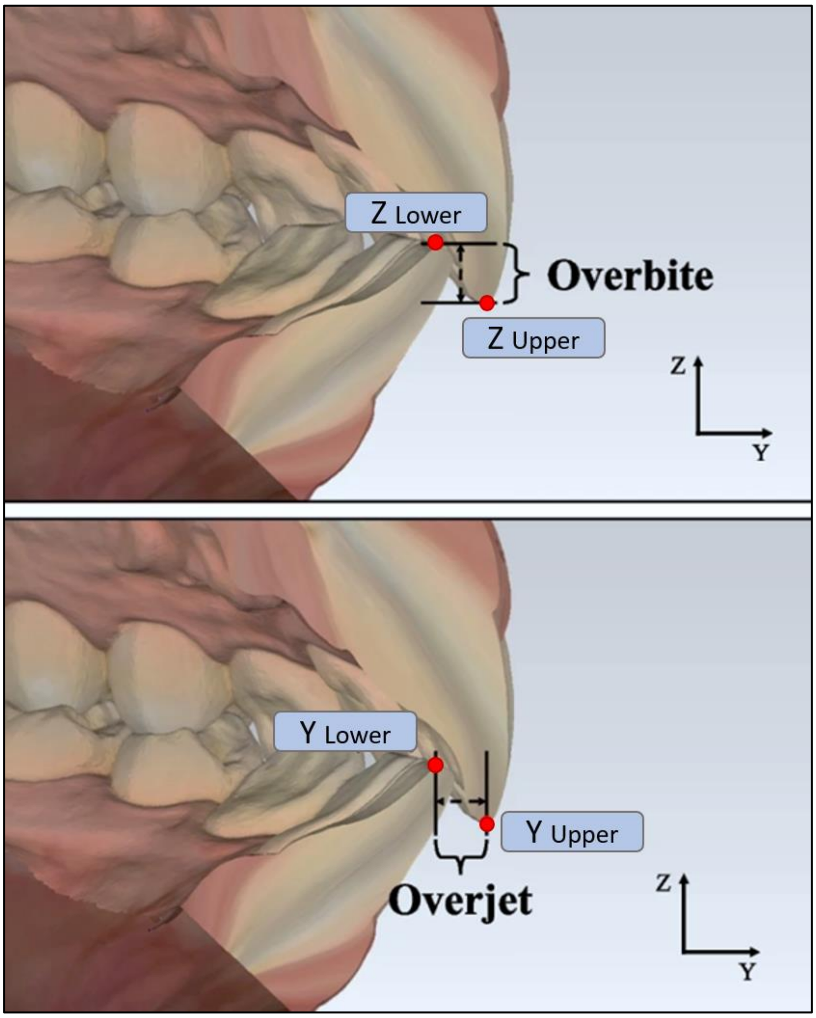

Figure 15. Illustration of 3D measurement of Overjet and Overbite

2.4 STATISTICAL ANALYSIS

Data were analysed using the SPSS version 23.0 software (IBM, New York, USA). The Shapiro-Wilk normality test was used to assess the normality of the data distributions. Descriptive statistics were expressed as means ± SD. The frequency and percentage were used to report on nominal variables.

The mean of surgical movements (T0-T1) and skeletal relapse (T1-T2) were measured. The analysis of the statistical significance was assessed with Paired t-test or Wilcoxon signed test for normal and non-normal distributed data, respectively.

The percentage of the relapse ratio was calculated by: (T1-T2) x 100 / (T0-T1).

Pearson's or Spearman's correlation analysis was applied to evaluate the relationship between skeletal changes at 6-month following surgery "relapse" and the quality of the achieved occlusion immediately following surgery. The correlation between magnitude of surgical movements and the stability at 6 months was measured. Probabilities of 0.05 or less were accepted as significant.

2.4.1 Reliability (Errors of the study)

The assessment of the landmarking errors was conducted to evaluate the intra-examiner reliability. The three anatomical landmarks for all the 25 sets of CBCTs were re-digitized by the same researcher following a 4-weeks interval, the x, y and z coordinates of the repeated digitisations were recorded. The reproducibility of the repeated measurements was analysed with Paired t-test or Wilcoxon signed test. The absolute differences between the two sets of measurements were calculated. For the analysis of the reliability of measurements the Intra-class correlation coefficient at 95% confidence interval were measured. The ICC value was presented as a value between 0 to 1. The closer the value to one, the better was the intra-examiner reliability.

2.4.2 Random error of measurement

In studies with fewer than 30 cases, accurate estimate of the true random error requires repeated measurements from all the cases.(Houston, 1983; Springate, 2012) The size of measurement error (ME) was calculated by Dahlberg's formula. The sum of squared differences between the repeated measurements (d) divided by the sample size (n) was calculated. The standard deviation provided the size of measurement error.

$$SD = \sqrt[2]{\frac{\sum_{i=1}^{n} d^2}{2n}}$$

Dahlberg Formula: where d is the difference between the pairs of repeated measurements, n is the number of cases, and SD is the statistical estimate of the 'true' error (standard deviation).

2.4.3 Systematic error

The one sample t-test was used to testing whether the mean difference between the repeated set of measurements differ from zero. The Bland and Altman plot represented the systematic error (bias) by plotting the mean difference (M1-M2) between the first (M1) and second (M2) measurements against the average (M1+M2)/2 obtained from the two measurements. The graph was plotted on an XY-axis, where Y illustrates the difference between measurements and X illustrates the average of the measurements, with 95% of the data points lie within ±2 SD of the mean difference. The mean difference is the estimated bias, and the SD of the differences measures the random fluctuations around this mean.

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2.5 SECTION B: COMPARISON BETWEEN SFA AND OFA

Introduction

The comparison of stability between orthodontic-first approach and surgery-first approach was discussed earlier (Section1.2.3). The unstable occlusion, and the high degree of orthodontic tooth movement in the post-operative phase may contribute to relapse in SFA cases. However, the post-operative occlusal quality was reported as the main concern with surgery-first approach. The relationship between skeletal stability and pre-operative/planned occlusion has been evaluated by 2D measurements of overjet and overbite (Akamatsu et al, 2016; Ann et al, 2016; Park et al, 2015). Furthermore, the analysis of occlusion was limited to incisors inclinations and overjet and overbite at debonding (Joh et al, 2013; Liao et al, 2010; Park et al, 2014). The heterogeneity of surgical methods and absence of reports of characteristics of post-operative occlusion, are the main drawbacks of current literature (Lo et al, 2019; Wei et al, 2018).

2.5.1 Aims

The **main** objective of this study was to determine if there was a statistically significant difference in the Skeletal Stability between two surgical approaches.

The **second** objective was to compare the postoperative occlusion and its impact on skeletal relapse between the two groups.

2.5.2 Sample

The study sample composed of the pre- and post-operative CBCT scans of 13 orthodontic-first and the 25 surgery-first class III patients who underwent Lefort I osteotomy. These CBCTs were selected from the total of 124 patients (55 OFA, 69 SFA) following the exclusion and inclusion criteria previously described (Section 2.1.1).

All the patients had orthognathic treatment to correct their facial deformity. The preoperative CBCT scans were acquired within one month of surgery and the postoperative scans were obtained at 1-week and 6-months following surgery. Only 13 (out of 39) orthodontic-first patients who underwent Le Fort I osteotomy had complete CBCT records. Incomplete CBCT records was the main reason of exclusion. Further 16 cases were excluded according to the study exclusion criteria (Section 2.1.1.3)

Table 6 shows the details of the classification of malocclusion and the surgical procedures undertaken for both groups.

Surgical Procedure	Orthodontic First Approach (OFA) Patients List			Surgery First Approach (SFA) Patients List		
	Class III	Class II	Class I + Asymmetry	Class III	Class II	Class I + Asymmetry
Lefort I Advancement	33	2		37		
Le Fort I Advancement + Genioplasty	6	7		10		
Bilateral Sagittal Split Osteotomy	0	2		2	4	1
Bilateral Sagittal Split Osteotomy + Genioplasty	0	0		2	2	
Bimaxillary surgery	1	0		6	3	1
Bimaxillary surgery + Genioplasty	2	2		1		
	42	13		58	9	2
Total: 124	55			69		

Table 6. Malocclusion and surgical classifications of SFA and OFA patients

2.5.3 Skeletal and occlusal analysis

The details of DICOM Image anonymization and replacement of distorted dentition were explained in section 2.2 and 2.3. As described previously, the superimposition of the pre-operative and post-operative 3D skull models was based on the anterior cranial base, zygomatic arches, and forehead to facilitate the surface-based registration.

The skeletal movements achieved by orthognathic surgery were measured by construction of maxillary triangle on right and left greater palatine foramen and incisive foramen selected on maxillary pre-operative and post-operative 3D models. Two transformation matrices were obtained which contained information on the translations and rotations from preoperative position to 1-week postoperative position “surgical movement” (T0-T1) and from 1-week postoperative position to 6-month postoperative position “skeletal relapse” (T1-T2). The details of the analysis of occlusion were described in section (2.3.3 and 2.3.4).

2.5.4 Statistical analysis

Data were analysed using the SPSS version 23.0 software (IBM, New York, USA). The Shapiro-Wilk normality test was used to assess the normality of the data distributions. Descriptive statistics were expressed as means ± SD.

The significance of surgical movements (T0-T1) and skeletal relapse (T1-T2) within each group was measured by One sample t test or Wilcoxon signed test and between SFA and OFA group by Two sample t-test or Mann Whitney test for data with normal or non-normal distribution, respectively.

Pearson's or Spearman's correlation analysis were used to evaluate the relationship between skeletal stability and different variables (Occlusal features and surgical movements) for data with normal or non-normal distribution, respectively.

Intra-examiner reliability was evaluated by analysing the differences between the repeated readings by intraclass correlation coefficient (ICC).

3 CHAPTER THREE: RESULTS

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3 CHAPTER THREE: RESULTS 103

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Introduction

Our data included 69 patients who underwent Surgery First approach. There were 47 class III who underwent Le fort I osteotomy, out of which 22 patients were excluded due to defective or missing CBCT records. Twenty-five patients who underwent Le Fort I maxillary advancement with or without genioplasty and had a complete CBCT record (T0, T1, T2) were included. The data of the 25 patients were successfully processed according to the research protocol. However, the magnitude of maxillary advancement and occlusal characteristics of excluded patients were quite similar to the study cohort. Further 22 patients were excluded according to our exclusion criteria (Section 2.1.1.3).

The studies of stability following orthognathic surgery suggested that the majority of the skeletal relapse occurs within the first few months following surgery, during the consolidation of the osteotomy segments, and the relapse rate is fairly minimal after one year (Fahradyan et al, 2018; Jung et al, 2013; Ko et al, 2013). Therefore, it is the routine practice of our team, and several orthognathic centres across Europe, to obtain the 6 months CBCT scan. This allows the objective assessment of the achieved skeletal stability, quantify relapse, and measure soft tissue changes. These outcome measures inform the decision-making process regarding the required surgical movements of future cases and informing the patients of the magnitude of expected relapse to obtain the informed consent. The pre-operative CBCT scan is necessary for treatment planning. The one-week postoperative CBCT scan is essential to assess the position of the osteotomy segments, fixation plates and screws. It also displays any displacement of the condylar segments which may require further surgical intervention.

3.1 PATIENTS' DEMOGRAPHIC DATA

A total of 25 skeletal class III cases who underwent surgery-first approach for correction of maxillary deficiency were eligible for the study. Baseline demographic data of the 25 patients are shown in **Table 7**. The mean age was 29.12 ±10.86 years, 14 patients were male and 11 were female. Four patients had simultaneous Genioplasty.

Characteristics	N (%)	Mean ± SD
Female	11 (44%)	
Male	14 (56%)	
Age		29.12 ± 10.86
Genioplasty	4 (16%)	

Table 7. Baseline demographics of patients (N=25)

3.2 ERRORS OF THE METHOD

The three landmarks used in this study were re-digitized for all the 25 sets of CBCT scans by the same researcher following a four-weeks interval. The absolute mean differences between the repeated landmark digitization were reported in three dimensions (x, y, and z). The reproducibility of the repeated measurements was measured, the absolute differences between the two sets of measurements were calculated. Intraclass correlations (ICCs) between the two sets of the repeated measurements were analysed using a 2-way mixed model, with a 95% confidence interval. The Shapiro-wilks normality test showed the data were not normally distributed. The Wilcoxon signed ranked test was applied to compare between repeated measurements.

Incisive foramen (IF)

The results of Shapiro-wilks normality test showed data are not normally distributed. There was no statistically significant difference between repeated landmarking of Incisive foramen of the Y and Z dimension. The X dimension, however, showed a significant difference. The absolute mean difference between repeated landmarking was 0.12 $\pm$ 0.29 mm, P=0.048, and -0.09 $\pm$ 0.26 mm, P=0.011 of the T0 and T2 respectively. **(Table 8)**

There was a strong positive correlation between the repeated measurements in X, Y and Z dimensions at T0, T1 and T2.

Intra-examiner reliability of the repeated landmarking of IF									
Landmark: Coordinates		**Mean difference (mm)$\pm SD$**	**Median**	**St Error (SE)**	**95% Confidence Interval**		***P* value**	***r* Value**	***Shapiro Wilks (Sig)***
					Lower	**Upper**			
Pre-operative (T0)	**X**	0.12 $\pm$0.29	0.14	0.058	0.001	0.244	**0.048**	0.985	0.100
	Y	-0.08$\pm$0.37	-0.32	0.075	-0.236	0.075	0.279	0.997	0.006
	Z	0.03$\pm$0.20	0.06	0.041	-0.054	0.115	0.397	0.999	0.831
1wk Postoperative (T1)	**X**	0.02$\pm$0.28	0.01	0.056	-0.096	0.138	0.424	0.981	0.050
	Y	-0.04$\pm$0.27	0.00	0.054	-0.155	0.067	0.651	0.999	0.023
	Z	0.00$\pm$0.21	0.00	0.042	-0.081	0.094	0.961	0.999	0.190
6M Postoperative (T2)	**X**	-0.09$\pm$0.26	-0.03	0.052	-0.206	0.009	**0.011**	0.985	0.004
	Y	-0.12 $\pm$0.44	-0.10	0.088	-0.303	0.061	0.306	0.996	0.024
	Z	0.04$\pm$0.24	0.06	0.049	-0.055	0.147	0.367	0.998	0.348

Table 8. Intraclass Correlation Coefficient and Wilcoxon Signed Ranked test of the Landmarking error study, (IF: Incisive Foramen)

Right greater palatine (RGP)

The results of Shapiro-wilks normality test showed data are normally distributed except for Z dimension at T0 and T2. There was no statistically significant difference between repeated landmarking of right greater palatine (RGP) at X, Y and Z dimension. There was a strong positive correlation between the repeated measurements in X, Y and Z dimensions at T0, T1 and T2. **(Table 9)**

Left greater palatine (LGP)

The results of Shapiro-wilks normality test showed data are normally distributed except for Y dimension at T0 and T2. There was no statistically significant difference between repeated landmarking of left greater palatine (LGP) at X, Y and Z dimension. There was a significant correlation between the repeated measurements in X, Y and Z dimensions at T0, T1 and T2. **(Table 10)**

Intra-examiner reliability of the repeated digitization of RGP									
Landmark Coordinates		**Mean difference (mm)$\pm SD$**	**Median**	**St Error (SE)**	**95% Confidence Interval**		***P* value**	***r* Value**	***Shapiro Wilks (Sig)***
					Lower	**Upper**			
Pre-operative (T0)	**X**	-0.00 ±0.40	0.07	0.081	-0.169	0.168	0.861	0.992	0.044
	Y	-0.03±0.28	0.00	0.056	-0.154	0.077	0.573	0.997	0.408
	Z	0.02±0.34	0.09	0.068	-0.115	0.169	0.389	0.999	**0.033**
1wk Postoperative (T1)	**X**	0.09±0.41	0.07	0.082	-0.072	0.269	0.346	0.993	0.229
	Y	0.03±0.26	0.04	0.052	-0.074	0.143	0.484	0.999	0.122
	Z	0.05±0.25	0.03	0.050	-0.052	0.155	0.260	0.998	0.449
6M Postoperative (T2)	**X**	-0.00±0.41	0.00	0.083	-0.172	0.171	0.958	0.992	0.397
	Y	-0.12 ±0.30	-0.08	0.061	-0.254	-0.001	0.052	0.999	0.131
	Z	-0.04±0.29	-0.01	0.058	-0.162	0.079	0.369	0.997	**0.047**

Table 9. Intraclass Correlation Coefficient and Wilcoxon Signed Ranked test of the Landmarking error study, (RGP: Right Greater Palatine foramen)

Intra-examiner reliability of the repeated digitization of LGP									
Landmark: Coordinates		**Mean difference (mm)±SD**	**Median**	**St Error (SE)**	**95% Confidence Interval**		***P* value**	***r* Value**	***Shapiro Wilks (Sig)***
					Lower	**Upper**			
Pre-operative (T0)	**X**	0.08 ±0.32	0.01	0.064	-0.048	0.218	0.182	0.991	0.176
	Y	-0.01±0.30	-0.04	0.060	-0.140	0.111	0.861	0.997	**0.043**
	Z	-0.01±0.26	0.01	0.052	-0.124	0.091	0757	0.999	0.467
1wk Postoperative (T1)	**X**	-0.02±0.40	-0.04	0.081	-0.193	0.141	0.747	0.984	0.734
	Y	0.03±0.30	0.01	0.060	-0.094	0.156	0.559	0.999	0.281
	Z	-0.00±0.30	0.01	0.060	-0.131	0.118	0.875	0.999	0.871
6M Postoperative (T2)	**X**	-0.07±0.40	-0.27	0.081	-0.244	0.093	0.466	0.986	0.079
	Y	-0.04 ±0.34	0.01	0.068	-0.180	0.100	0.989	0.998	**0.034**
	Z	0.01±0.31	0.00	0.063	-0.115	0.145	0.626	0.996	0.170

Table 10.Intraclass Correlation Coefficient and Wilcoxon Signed Ranked test of the Landmarking error study, (LGP: Left Greater Palatine foramen)

3.3 RANDOM ERROR OF THE REPEATED MEASUREMENTS

The size of measurement error (ME) was calculated by Dahlberg's formula. At T0-T1, the results showed measurement error of 0.19 mm, 0.17mm and 0.15mm for translation along X, Y and Z-axis. The error in the repeated measurement of the maxillary translation between T1-T2 was 0.14mm, 0.14mm and 0.11 mm along the X, Y and Z-axis**. (Table 11).** The random errors of the repeated measurements of the pitch, roll, and yaw were less than 1 degree of each one.

The size of measurement errors was calculated for 3 landmarks of each of the CBCT scants of T0, T1 and T2, these were less than 0.5 mm error for each landmark. **Table 12** shows a high reproducibility of the measurements.

Size of Measurement error	T0-T1	T1-T2
Translation (mm)		
X-axis (Left/right)	0.19 mm	0.14 mm
Y-axis (Posterior/anterior)	0.17 mm	0.14 mm
Z-axis (Superior/inferior)	0.15 mm	0.11 mm
Rotation (°)		
Pitch (X)	0.63 °	0.48 °
Roll (Y)	0.86 °	0.68 °
Yaw (Z)	0.58 °	0.44 °

Table 11. The size of measurement error between the repeated measurements at T0-T1 and T1-T2 using Dahlberg's formula

Size of landmarking error		Incisive Foramen	Right Greater Palatine Foramen	Left Greater Palatine Foramen
Pre-operative (T0)	**X**	0.221	0.283	0.231
	Y	0.267	0.196	0.211
	Z	0.144	0.239	0.181
1wk Postoperative (T1)	**X**	0.197	0.295	0.281
	Y	0.189	0.184	0.212
	Z	0.147	0.178	0.209
6M Postoperative (T2)	**X**	0.195	0.288	0.288
	Y	0.318	0.230	0.238
	Z	0.173	0.205	0.219

Table 12. The size of measurement error between the repeated landmarking at T0, T1 and T2 using Dahlberg's formula.

3.4 SYSTEMATIC ERRORs OF THE REPEATED MEASUREMENTS

The reproducibility of the measurements was calculated in terms of the absolute mean difference between the repeated set of measurements. Intraclass correlations (ICCs) between the two measurements were computed using a 2-way mixed model to test for the absolute agreement, with a 95% confidence interval. The Shapiro-wilks normality test showed the data did not follow the normal distribution pattern. The Wilcoxon signed ranked test was applied to compare between repeated measurements.

The Bland and Altman plot displayed the systematic error by plotting the absolute mean difference (M1-M2) between the first measurements (M1) and second measurements (M2) against the average (M1+M2) divided by two. The Y axis illustrated the difference between the mean of repeated measurements and X illustrated the average of the two measurements. The data points were plotted within ± 2SD of the absolute mean difference.

<u>The repeated measurements of the surgical movements (T0-T1):</u>

The result showed no statistically significant difference between the repeated measurements in X, Y and Z dimensions **(Table 13).** The absolute mean differences and the SD between the repeated measurements were -0.05 ± 0.27 mm, 0.04 ± 0.24 mm, 0.07 ± 0.20 mm in the X, Y and Z dimensions respectively.

There was no statistically significant difference in the repeated measurements of the Roll (Y) (-0.36 ± 1.18 mm) and Yaw (Z) (0.10 ± 0.84 mm) dimensions. The only significant difference was noted in the repeated measurement of the surgical rotational movement of pitch (*P* = 0.048, -0.32 ± 0.84).

There was an excellent correlation (> 0.90) between the repeated translational surgical movements. However, the repeated measurements of the surgical Roll and Yaw showed a good correlation (r = 0.747, r=0.733).
Figures (15-20) show Bland-Altman plots for the translation and rotations along X, Y and Z-axis.

Measurement (T0-T1)	Mean Difference ±SD	Median	St. Error	95% Confidence Interval		*P* value	*r* value	Shapiro Wilks (Sig)
				Upper	Lower			
Translation (mm)								
(Left/right)	-0.052±0.271	-0.086	0.054	0.059	-0.164	0.216	0.944	**<0.001**
(Posterior/anterior)	0.048±0.245	-0.036	0.049	0.149	-0.052	0.637	0.994	**0.143**
(Superior/inferior)	-0.079±0.208	-0.056	0.041	0.006	-0.165	0.076	0.983	**0.024**
Rotation (°)								
Pitch	-0.323±0.849	-0.293	0.169	0.027	-0.674	**0.048**	0.917	**<0.001**
Roll	-0.361±1.186	-0.424	0.237	0.127	-0.851	0.166	**0.747**	**<0.001**
Yaw	0.102±0.840	0.034	0.168	0.449	-0.244	0.619	**0.733**	**0.085**

Table 13.Systematic error: Intraclass Correlation Coefficient and Wilcoxon Signed Ranked Test of the repeated measurements (T0-T1)

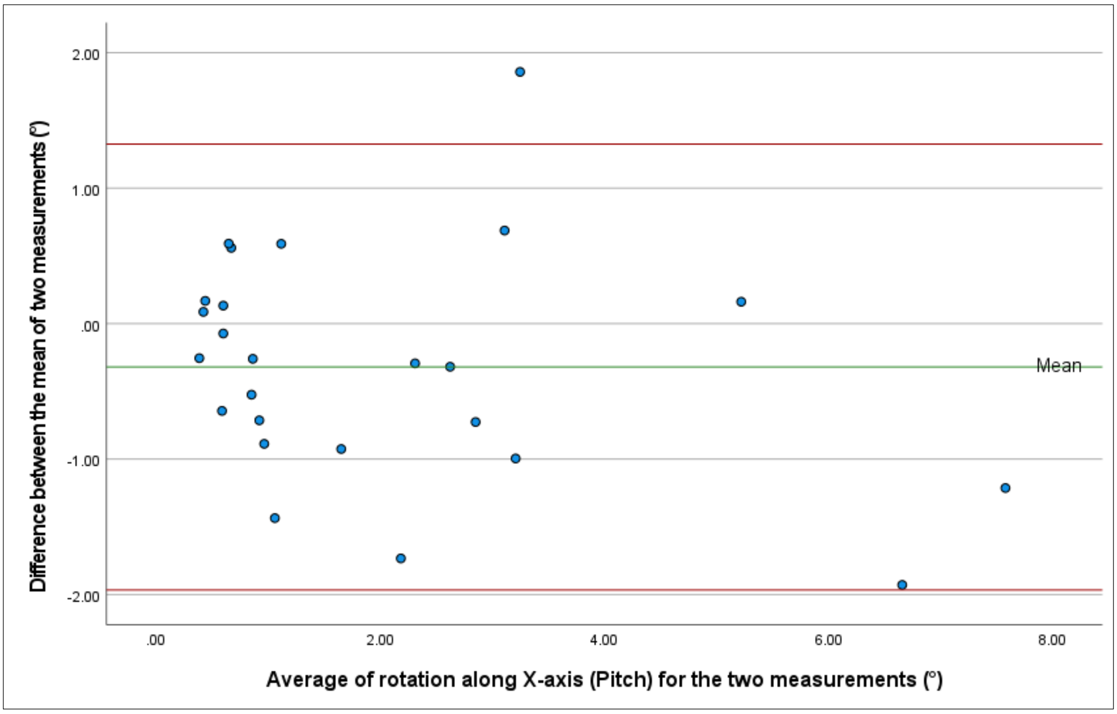


Figure 16. Bland Altman Plot of repeated measurements of rotation along X (Pitch) at (T0-T1)

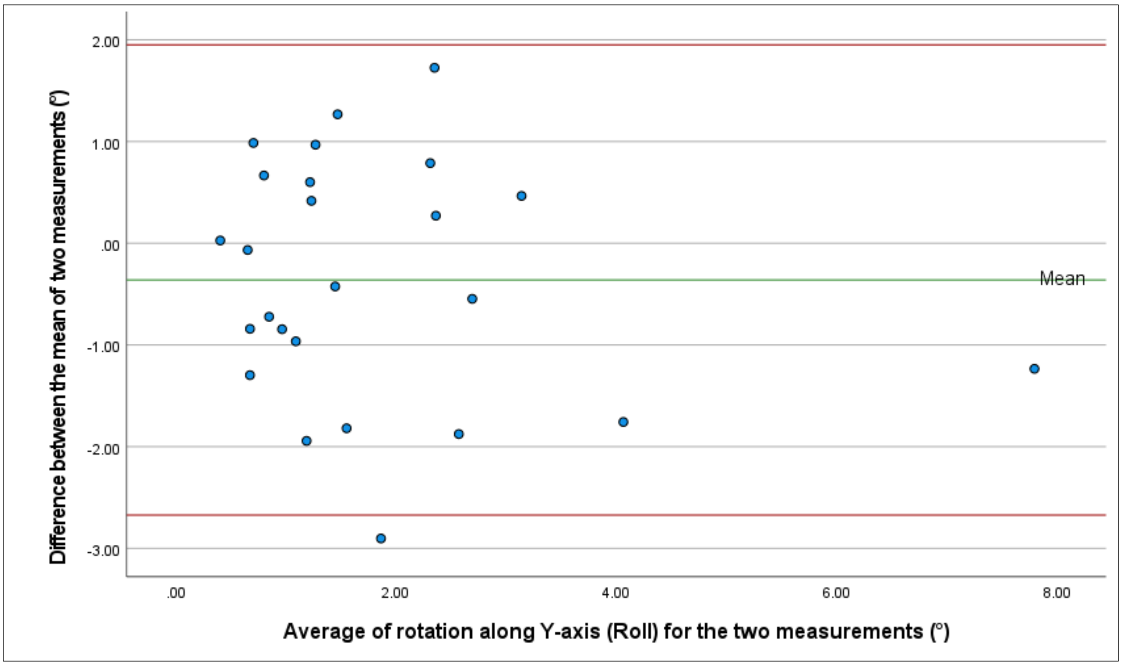


Figure 17. Bland Altman Plot of repeated measurements of rotation along Y (Roll) at (T0-T1)

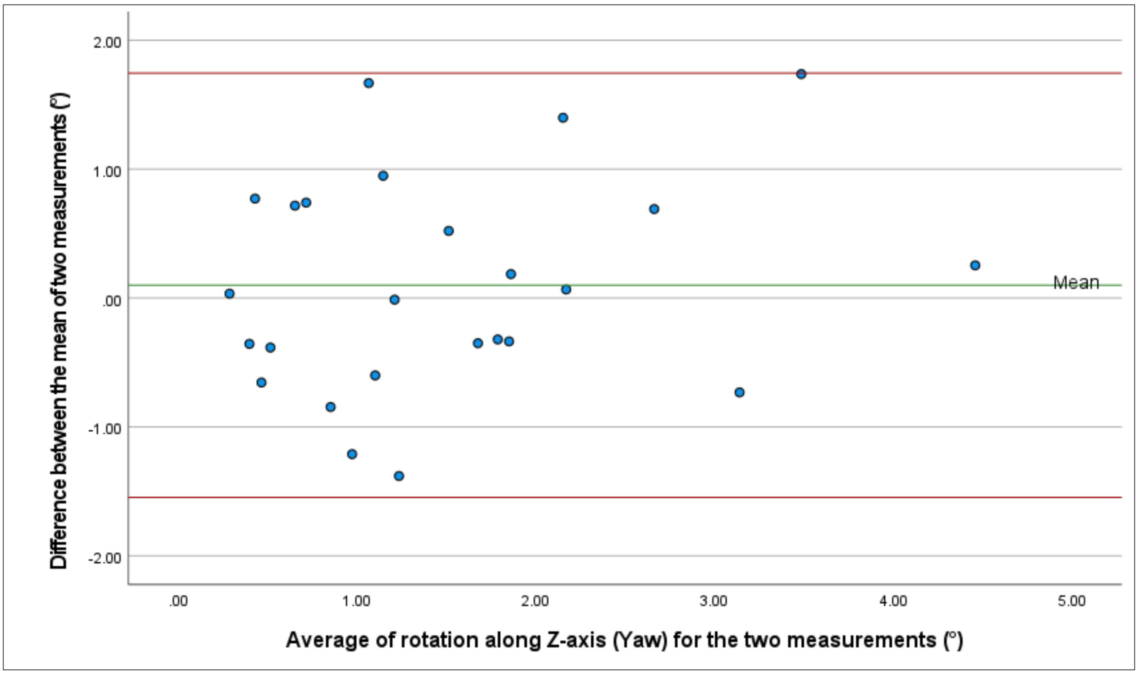


Figure 18. Bland Altman Plot of repeated measurements of rotation along Z (Yaw) at (T0-T1)

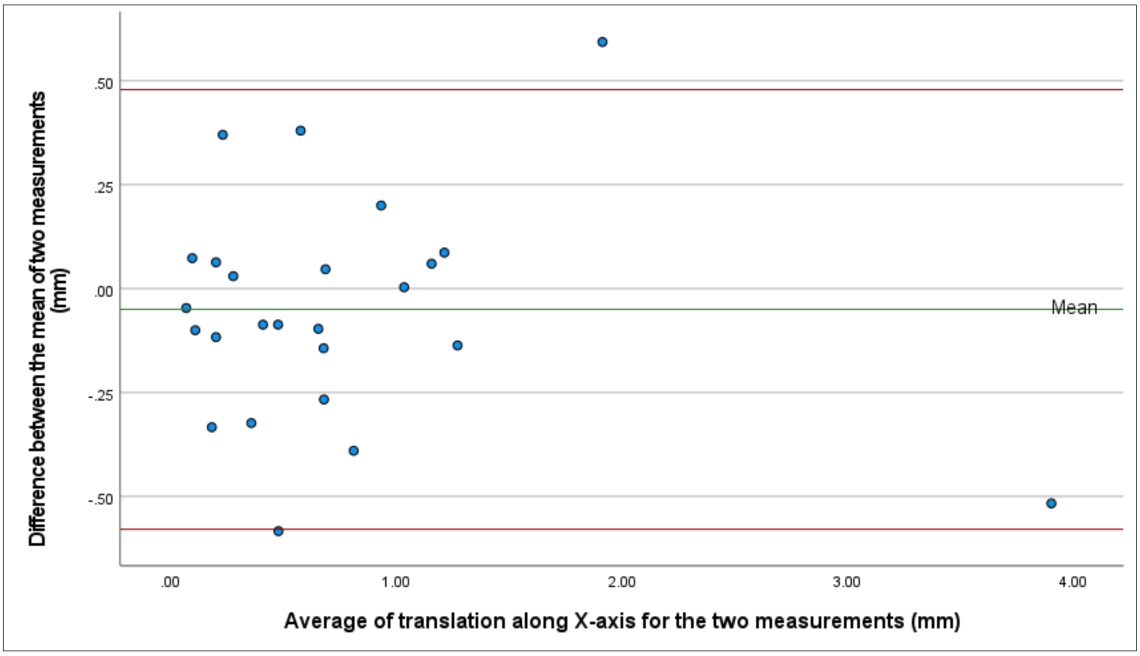


Figure 19. Bland Altman Plot of repeated measurements of translation along X-axis at (T0-T1)

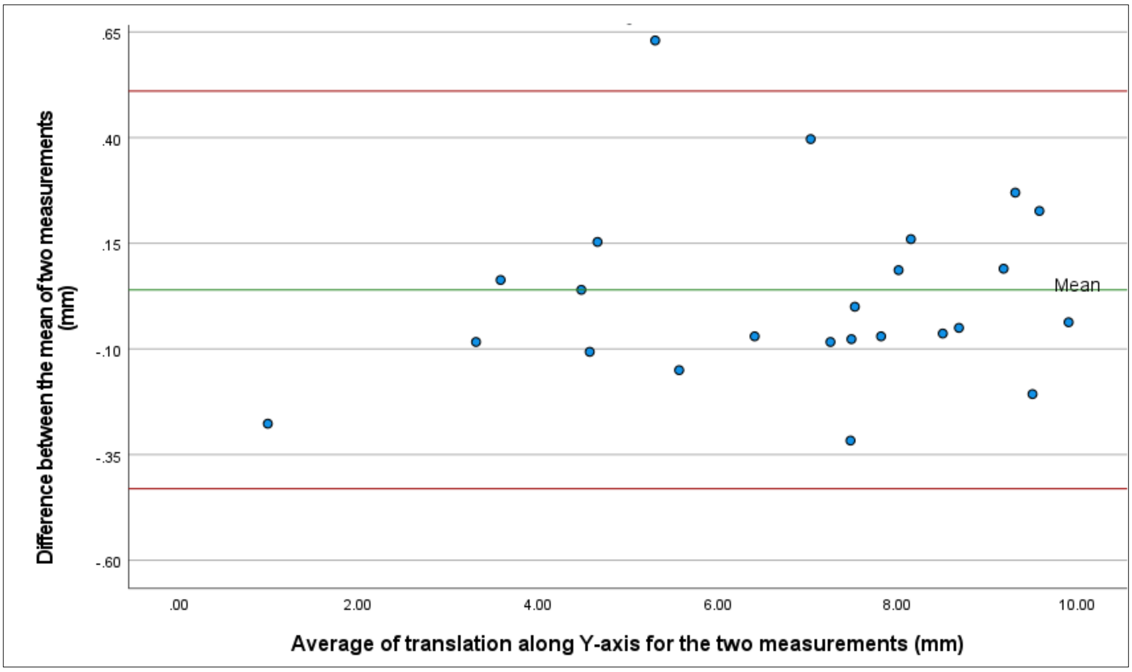


Figure 20. Bland Altman Plot of repeated measurements of translation along Y-axis at (T0-T1)

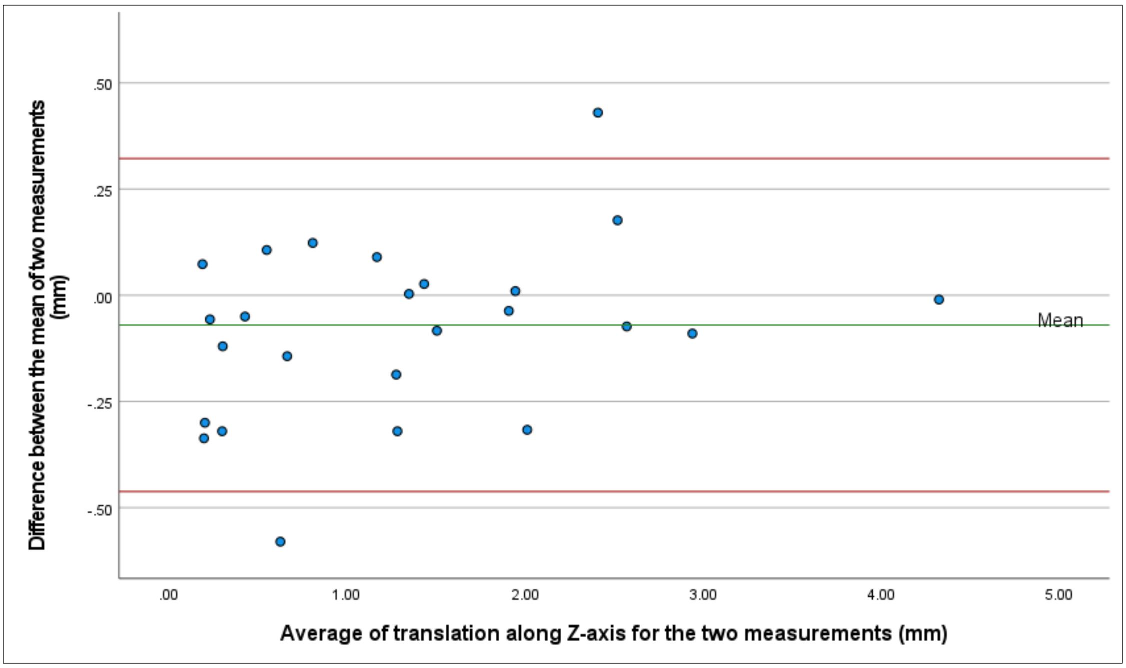


Figure 21. Bland Altman Plot of repeated measurements of translation along Z-axis at (T0-T1)

The repeated measurements of the relapse (T1-T2):

The result showed no statistically significant difference between the repeated measurements in X and Z dimensions at T1-T2 **(Table 14).** The absolute mean difference between the repeated measurements of the relapse were -0.06 ± 0.19 mm and 0.05 ± 0.15 mm in the X and Z dimensions respectively.
There was a statistically significant difference between the two sets of measurements in Y dimension 0.12 ± 0.16mm, *P= 0.001.* There was no statistically significant difference in the repeated measurements of the Pitch (X) -0.02±0.69, Roll (Y) -0.14 ± 0.98 and Yaw (Z) 0.07 ± 0.63.
Excellent correlation was detected between the repeated measurements and only moderate correlation of the Roll (Y) and Yaw (Z) (r = 0.435, r=0.655).

Figures (21-26) show Bland-Altman plots for the translation and rotations along X, Y and Z-axis.

Measurement (T1-T2)	**Mean Difference ±SD**	**Median**	**St. Error**	**95% Confidence Interval**		***P* value**	***r* value**	**Shapiro Wilks (Sig)**
				Upper	**Lower**			
Translation (mm)								
(Left/right)	-0.062±0.194	-0.020	0.038	0.018	-0.142	0.208	0.841	0.001
(Posterior/anterior)	0.123±0.162	0.90	0.032	0.190	0.056	**0.001**	0.927	0.073
(Superior/inferior)	0.058±0.156	0.90	0.031	0.123	-0.006	0.094	0.945	0.003
Rotation (°)								
Pitch (X)	-0.029±0.698	-0.260	0.139	0.258	-0.317	0.375	0.882	0.004
Roll (Y)	-0.146±0.981	-0.130	0.196	0.258	-0.551	0.609	**0.435**	0.439
Yaw (Z)	0.074±0.635	0.090	0.127	0.336	-0.188	0.297	**0.655**	0.056

Table 14. Systematic error: Intraclass Correlation Coefficient and Wilcoxon Signed Ranked Test of the repeated measurements (T1-T2)

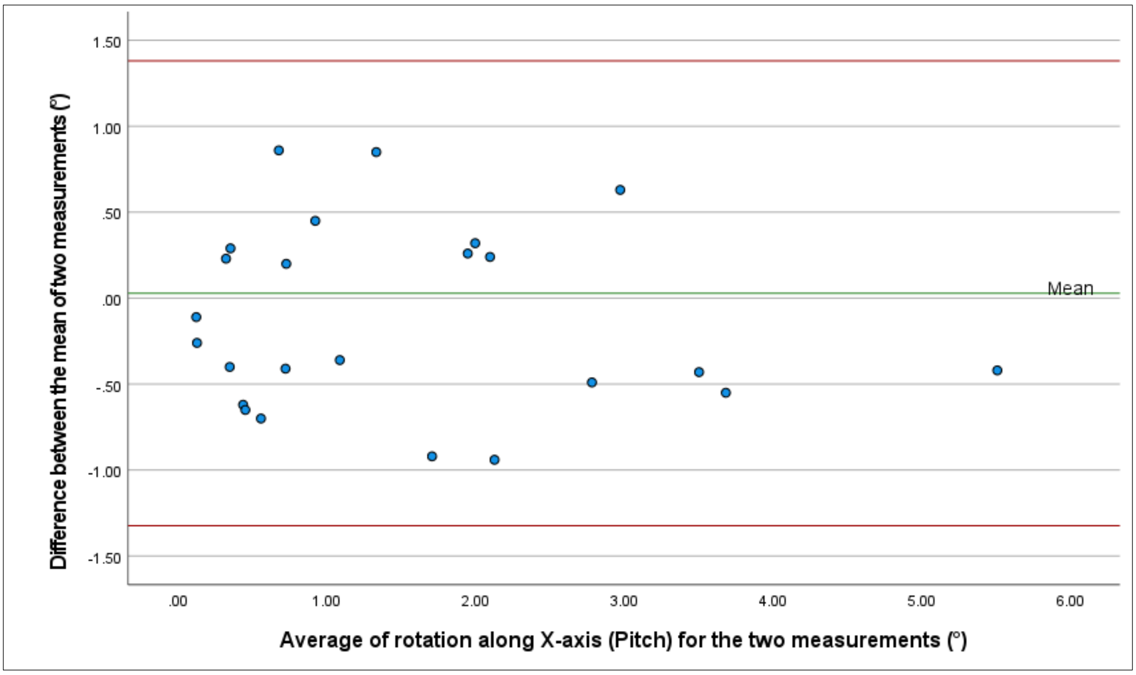


Figure 22. Bland Altman Plot of repeated measurements of rotation along X (Pitch) at (T1-T2)

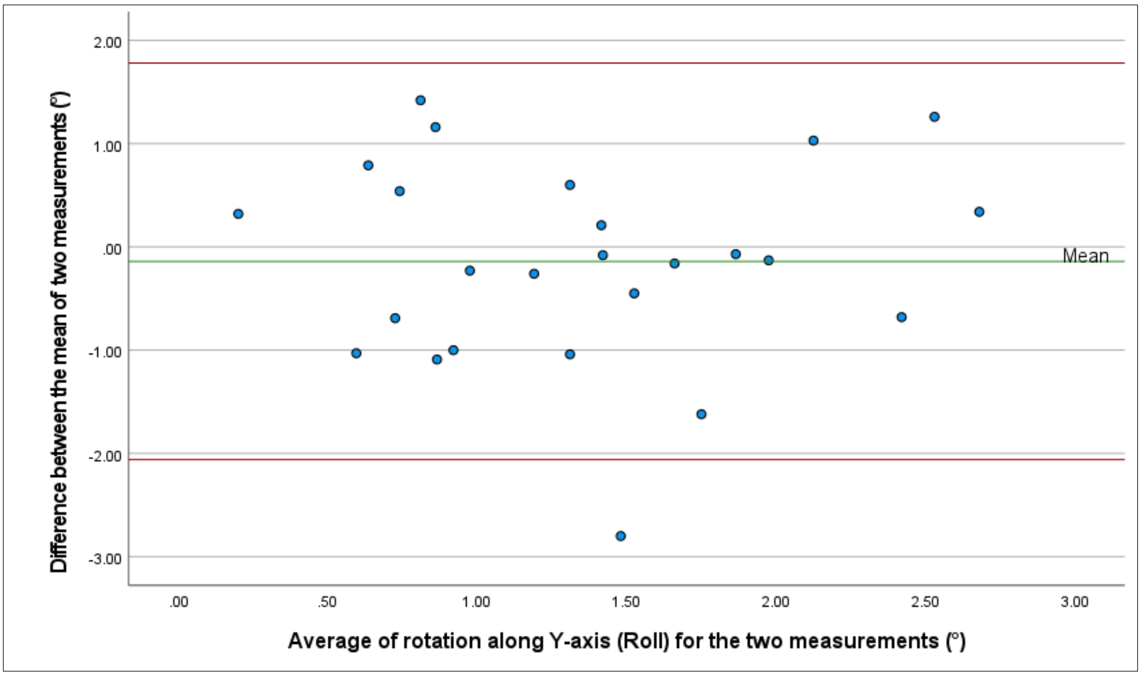


Figure 23. Bland Altman Plot of repeated measurements of rotation along Y (Roll) at (T1-T2)

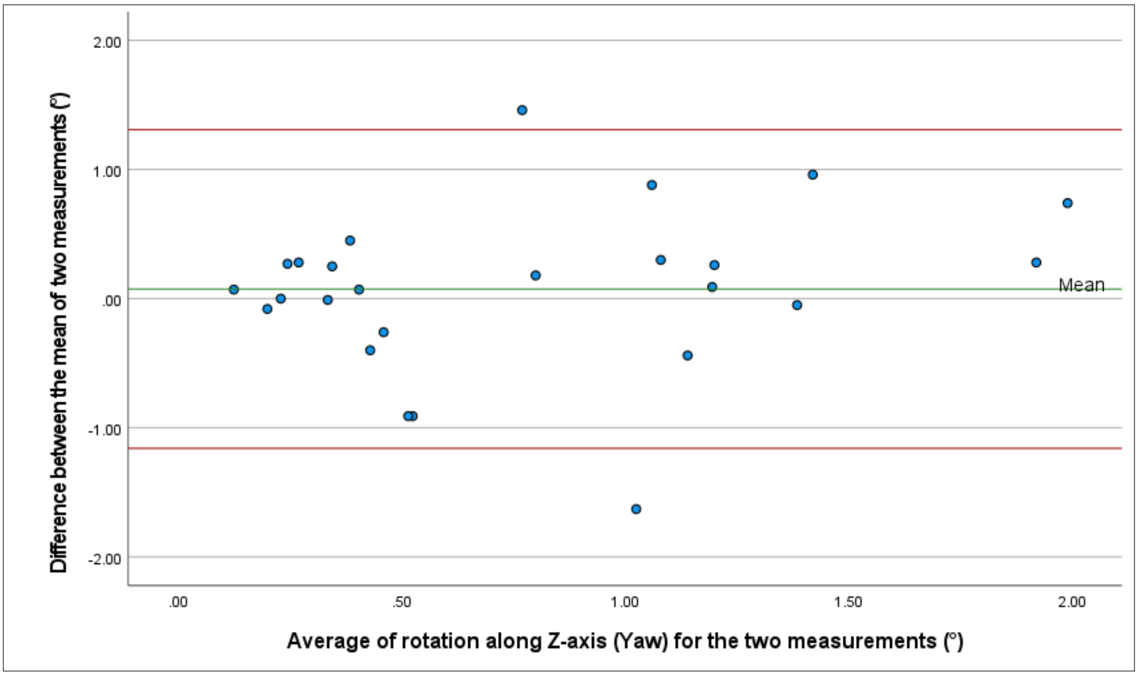


Figure 24. Bland Altman Plot of repeated measurements of rotation along Z (Yaw) at (T1-T2)

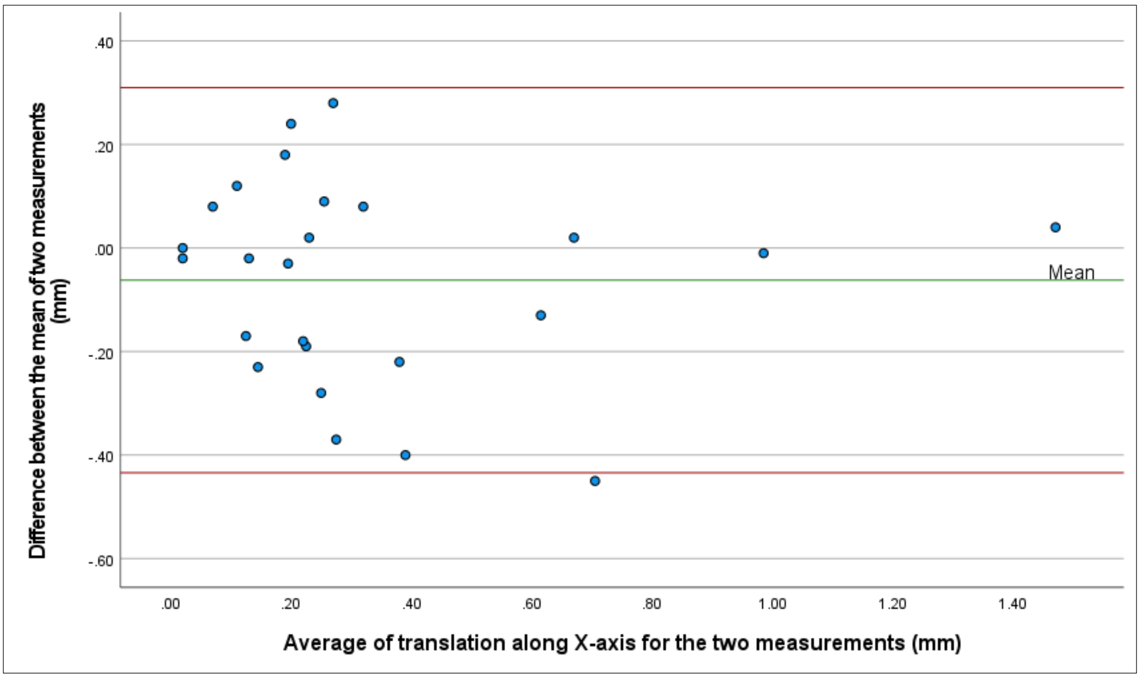


Figure 25. Bland Altman Plot of repeated measurements of translation along X-axis at (T1-T2)

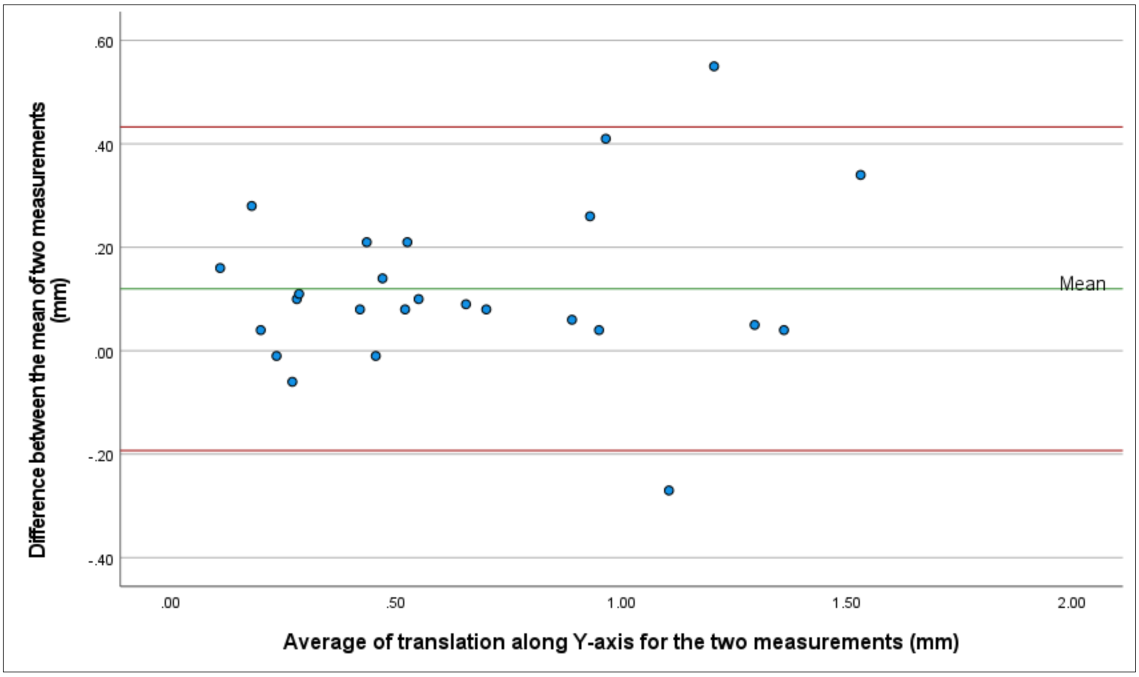


Figure 26. Bland Altman Plot of repeated measurements of translation along Y-axis at (T1-T2)

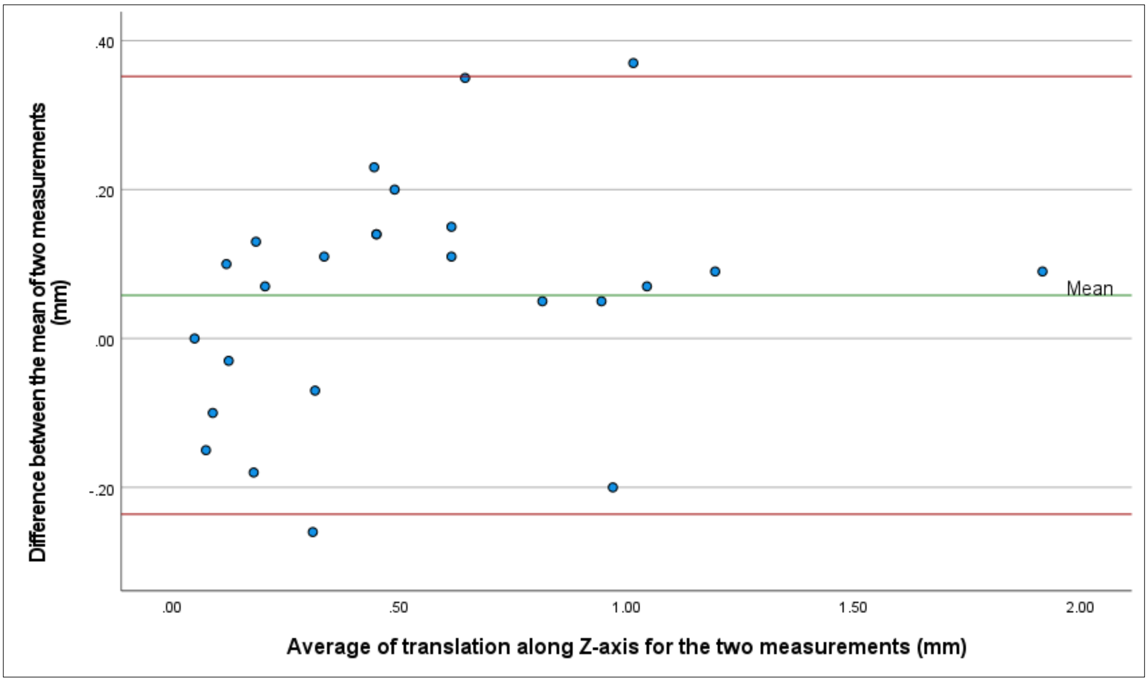


Figure 27. Bland Altman Plot of repeated measurements of translation along Z-axis at (T1-T2)

3.5 THE MEASURED MOVEMENTS OF THE MAXILLA

3.5.1 The Surgical movements (T0-T1)

The Shapiro-Wilk normality test showed the data were normally distributed except the maxillary translation in the medio-lateral direction. **Table 15** shows the descriptive statistics of skeletal surgical movements.

There was a significant movement of the maxilla in forward direction (6.79±2.3mm). In average the maxilla moved by (1.28±1.09 mm) in vertical direction, by 60% moved upward (mean: 1.26mm) and 40% moved downward by mean:1.31 mm.

The absolute mean of maxillary medio-lateral movement was (0.71±0.79mm), by 48% moved to the left (Mean: 0.41) and 52% toward the right side (Mean: 1.00mm).

The absolute mean of maxillary pitch rotation was (1.86±1.88°), with 56% (mean: 2.35°) rotated in downward (clockwise) and 44% (mean: 1.24°) rotated upward (counterclockwise) direction.

The absolute mean of maxillary roll rotation was (1.63±1.54°), with 52% (mean: 1.67°) rotated to the right (clockwise) and 48% (mean: 1.59°) rotated to the left (counterclockwise) direction.

The absolute mean of maxillary yaw rotation was (1.56±1.21°), with 52% (mean: 1.55°) rotated to the left (counterclockwise) and 48% (mean: 1.57°) rotated to the right (clockwise) direction.

Table 16 shows the details of the surgical movement for 25 cases.

Measurement	Mean ± SD	Absolute mean ± SD	Median	95% Confidence Interval		Minimum	Maximum	Shapiro-Wilk (Sig)
				Upper	Lower			
Translation (mm)								
Right/Left	-0.32 ± 1.02	0.71±0.79	-0.04	0.1	-0.74	-3.64	1.19	**0.011**
Posterior/anterior	-6.79 ± 2.3	6.79±2.30	-7.32	-5.84	-7.75	-9.89	-0.86	0.162
Superior/inferior	-0.23 ± 1.69	1.28±1.09	-0.14	0.46	-0.92	-2.89	4.32	0.422
Rotation (°)								
Pitch	0.76 ± 2.56	1.86 ±1.88	0.51	1.82	-0.29	-3.45	6.97	0.069
Roll	0.1 ± 2.26	1.63±1.54	0.02	1.04	-0.83	-3.37	7.18	0.086
Yaw	0.05 ± 2.0	1.56±1.21	0.22	0.88	-0.77	-4.59	4.35	0.979

Table 15. Surgical movements from T0 to T1

Patient	Right/Left	Anterior/Posterior	Superior/Inferior	Pitch (°)	Roll (°)	Yaw (°)
1	0.20	-9.23	0.34	5.30	0.41	-0.43
2	0.29	-7.21	-0.87	1.19	2.71	0.31
3	-0.05	-3.27	-1.18	-3.45	-0.62	0.82
4	0.23	-5.50	-1.85	0.34	1.14	1.90
5	0.14	-5.62	-0.05	-0.26	-1.63	-0.32
6	1.19	-9.40	-0.23	-0.56	-1.24	1.95
7	-0.37	-9.45	0.60	-1.32	-0.22	0.22
8	0.61	-3.62	-1.35	-2.16	2.42	-1.62
9	-1.20	-7.45	0.20	0.52	0.49	-0.14
10	-0.77	-4.50	0.24	-0.66	-1.75	-2.20
11	-0.19	-7.78	1.95	2.46	1.20	2.77
12	-0.42	-9.89	2.61	1.41	-2.50	1.09
13	-0.62	-7.53	-2.62	0.73	-1.44	-1.01
14	0.43	-0.86	-2.53	-2.71	7.18	-4.59
15	0.13	-7.32	-1.46	-0.46	0.54	-2.85
16	-1.26	-4.74	-1.45	5.69	0.25	-1.50
17	-0.55	-9.69	-0.40	-0.95	-2.10	0.55
18	0.06	-5.36	-0.03	-0.26	-0.42	1.21
19	-0.71	-7.23	4.32	-0.94	3.19	-3.01
20	-3.64	-8.06	1.21	6.97	0.03	1.68
21	-2.21	-8.23	-0.14	4.18	-3.21	-0.37
22	0.61	-6.38	1.12	0.59	0.64	4.35
23	0.02	-4.52	-2.89	0.52	-0.61	-0.80
24	-1.04	-8.47	0.59	0.56	1.52	1.63
25	1.03	-8.66	-1.89	2.49	-3.37	1.77
Mean	**-0.32**	**-6.79**	**-0.23**	**0.76**	**0.1**	**0.05**
Absolute Mean	**0.71**	**6.79**	**1.28**	**1.86**	**1.63**	**1.56**

Table 16. The mean and absolute mean of surgical movement (T0-T1), Translation: A positive value indicates movement of the left, posterior, and superior. A negative value indicates movement of the right, anterior and inferior. **Rotation:** (Pitch: clockwise rotation +, counterclockwise rotation −), (Roll: clockwise rotation +, counterclockwise rotation −), (Yaw: counterclockwise rotation +, clockwise rotation −).

3.5.2 Skeletal relapse at 6-months follow up (T1-T2)

The skeletal changes from one-week to 6 months following surgery are shown in **Table 17**. The one sample T-test analysed the measured relapse in all dimensions except for translation among X axis, where the Wilcoxon Signed Ranked Test was applied. Statistically significant relapse (*P*: 0.001) was detected, the maxilla moved backward of an average of (0.72±0.43 mm).

The absolute mean vertical relapse of the maxilla was (0.57±0.47mm) with 60% relapsed for 0.51mm in downward direction and 40% relapsed for 0.63mm in upward direction.

The absolute mean of medio-lateral relapse of the maxilla was (0.30±0.33mm), with 0.31mm (48%) relapse in right and 0.30mm (52%) relapse in left direction.

There was statistically significant relapse in maxillary pitch (1.56 ± 1.42°, *P*: 0.007). In average 44% (mean: 1.57°) rotated in downward (clockwise) and 56% (mean: 1.49°) rotated upward (counterclockwise) direction.

The absolute mean of maxillary roll showed rotational relapse of (1.28 ± 0.82°, *P*: 0.186) with 52% (mean: 1.41°) rotated to the left (counterclockwise) and 48% (mean: 1.09°) rotated to the right (clockwise) direction.

The absolute mean of maxillary rotational relapse of Yaw was (0.81± 0.68°, *P*: 0.560). Fifty-two percent (mean: 0.78°) rotated to the right (clockwise) and 48% (mean: 0.83°) rotated to left (counterclockwise) direction.

Table 18 shows the details of the relapse for 25 cases.

Measurement	Mean ± SD	Absolute mean ± SD	*P* value	Median	95% Confidence Interval		Minimum	Maximum	Shapiro-Wilk (Sig)
					Upper	Lower			
Translation (mm)									
(Left/right)	0.005±0.45	0.30±0.33	0.737	0.01	0.19	-0.18	-0.98	1.49	**0.027**
(Posterior/anterior)	0.72 ± 0.43	0.72 ± 0.43	**0.001**	0.60	0.9	0.54	0.19	1.70	0.060
(Superior/inferior)	-0.03±0.75	0.57 ± 0.47	0.814	0.00	0.27	-0.34	-1.24	1.96	0.574
Rotation (°)									
Pitch	1.08 ±1.82	1.56 ±1.42	**0.007**	0.90	1.83	0.32	-3.41	5.30	0.783
Roll	-0.4±1.49	1.28 ± 0.82	0.186	-0.78	0.21	-1.02	-3.16	2.85	0.834
Yaw	0.12±1.06	0.81±0.68	0.560	0.07	0.56	-0.31	-1.90	2.36	0.875

Table 17. Skeletal changes (Relapse) from T1 to T2

Patient	Right/Left	Anterior/Posterior	Superior/Inferior	Pitch (°)	Roll (°)	Yaw (°)
1	-0.32	0.56	1.2	2.16	0.08	1.23
2	-0.19	0.24	0.67	0.15	-1.3	-1.33
3	-0.18	0.33	0.04	5.3	-2.64	0.07
4	-0.55	0.34	1.96	1.11	-1.38	0.41
5	-0.41	0.54	-0.39	1.15	1.58	2.06
6	-0.24	0.63	-0.17	-0.5	2.85	-0.44
7	-0.3	1.48	-0.84	3.91	1.06	-0.23
8	-0.11	0.54	0.24	-1.25	1.01	0.89
9	1.49	1.17	0.82	0.13	-3.16	-1.24
10	0.68	1.06	-0.52	2.54	-0.32	2.36
11	-0.02	0.92	-1.24	0.52	-0.79	0.61
12	0.27	0.22	0.09	0.91	-1.52	0.33
13	0.01	1.32	0.56	2.22	-0.86	0.38
14	-0.36	0.7	0.11	-3.41	-0.36	-0.23
15	0.04	0.97	-0.97	0	-1.52	-0.92
16	0.03	1.38	-0.87	0.13	1.44	0.33
17	0.11	0.74	0	3.29	-0.94	1.36
18	0.17	0.23	0.59	-0.83	-1.61	-1.9
19	-0.12	0.45	-1.08	3.29	-1.91	-1.5
20	0.48	1.7	-0.52	1.66	0.08	0.06
21	0.13	0.6	0.18	0.21	2.08	-0.21
22	0.13	0.46	-0.69	0.44	0.38	0.16
23	0.09	0.19	-0.05	1.76	0.42	1.5
24	0.28	0.32	-0.28	0.07	-1.03	-0.16
25	-0.98	0.97	0.25	2.08	-1.83	-0.47
Mean	**0.005**	**0.72**	**-0.03**	**1.08**	**-0.4**	**0.12**
Absolute Mean	**0.30**	**0.72**	**0.57**	**1.56**	**1.28**	**0.81**

Table 18. The mean and absolute mean of relapse (T1-T2), Translation: A positive value indicates movement of the left, posterior, and superior. A negative value indicates movement of the right, anterior and inferior. **Rotation:** (Pitch: clockwise rotation +, counterclockwise -), (Roll: clockwise rotation +, counterclockwise rotation −), (Yaw: counterclockwise rotation +, clockwise rotation −).

3.5.3 The relationship between surgical movement (T0-T1) and skeletal relapse (T1-T2)

The Shapiro Wilks normality test showed data were not normally distributed. The results of Spearman correlation coefficient showed a weak correlation between the magnitude of surgical movement of the maxilla and the relapse at T2. There was a weak correlation between the Roll, Yaw, and Pitch of the surgical movements and the detected relapse at T2. **(Table 19).** Interestingly, there was no statistically significant correlation between the magnitude of the maxillary advancement and the detected relapse at T2. **(Figure 27-29)**

Surgical movement (T0-T1)	**r value**	***P* value**	**Shapiro-Wilk (Sig) (T0-T1)**	**Shapiro-Wilk (Sig) (T1-T2)**
Translation (mm)				
(Medio-lateral)	0.209	0.316	0.001	0.001
(Posterior/anterior)	0.204	0.329	0.162	0.061
(Superior/inferior)	0.058	0.784	0.029	0.038
Rotation (°)				
Pitch	0.271	0.190	0.001	0.019
Roll	0.143	0.495	0.001	0.308
Yaw	0.147	0.482	0.018	0.009

Table 19. Spearman Correlation coefficient (r) between skeletal relapse (T1-T2) and surgical movement (T0-T1)

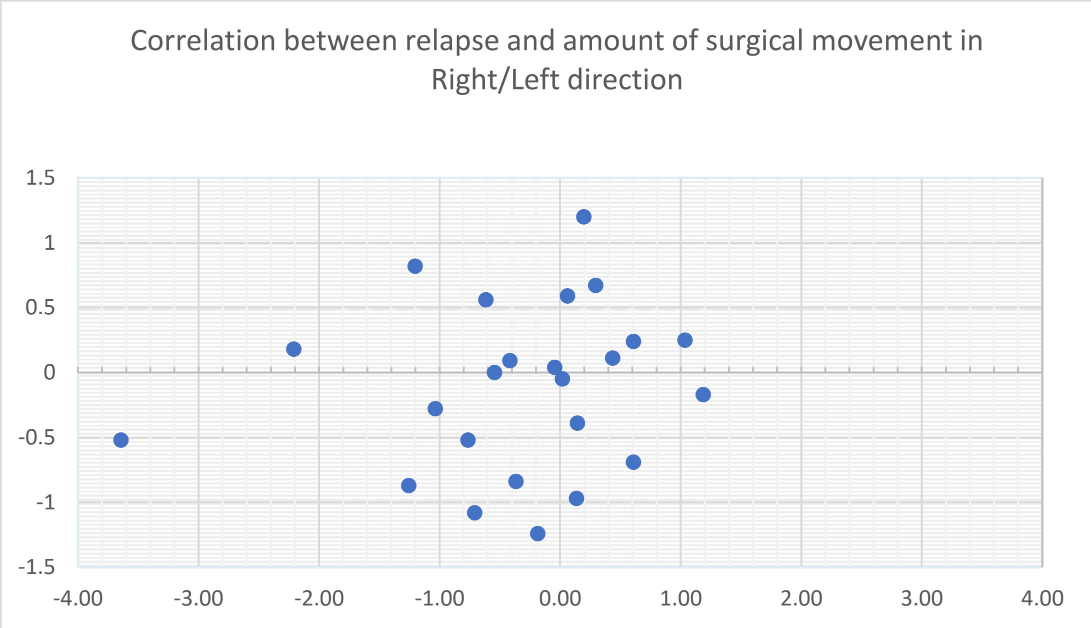


Figure 28. Scatterplot of correlation between Relapse and amount of surgical movement in right/left direction. The Y-axis indicates the relapse (mm); the X-axis indicates the amount of surgical movement (mm).

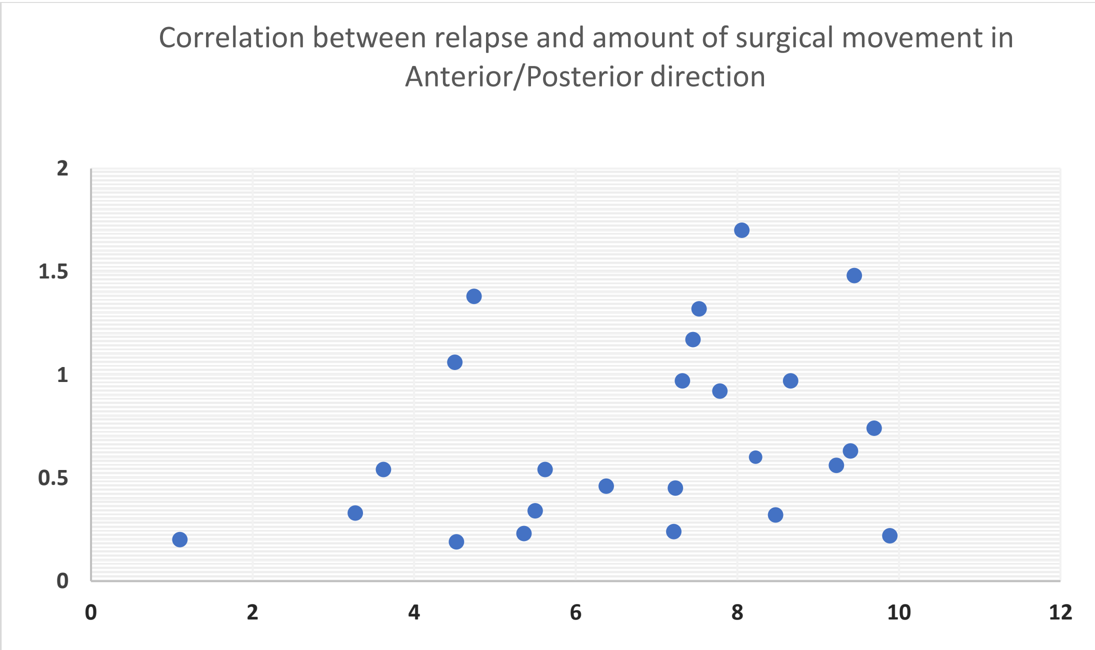


Figure 29. Scatterplot of correlation between Relapse and amount of surgical movement in anterior/posterior direction. The Y-axis indicates the relapse (mm); the X-axis indicates the amount of surgical movement (mm).

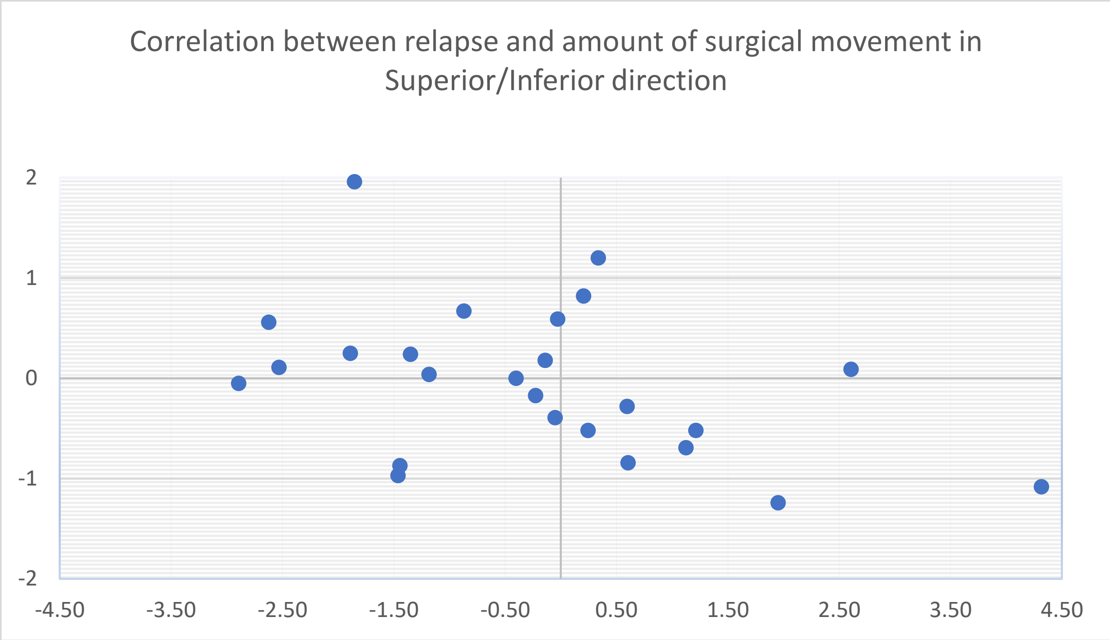


Figure 30. Scatterplot of correlation between Relapse and amount of surgical movement in superior/inferior direction. The Y-axis indicates the relapse (mm); the X-axis indicates the amount of surgical movement (mm).

3.5.4 Detailed analysis of the antero-posterior maxillary relapse ratio at T2

Table 20 shows the distribution of the patients across the four categories of the measured relapse in anterior / posterior direction. In most of the cases (76%) the relapse did not exceed 1 mm. The distribution of the cases according to the magnitude of antero-posterior surgical movements is also demonstrated. **(Figure 30)**

Relapse range	Patients (N / %)
< 0.5 mm	9 (36%)
0.5 – 1 mm	10 (40%)
1 – 1.5 mm	5 (20%)
1.5 – 2 mm	1 (4%)
Surgical movement (Maxillary Advancement)	
< 4 mm	3 (12%)
4-6 mm	6 (24%)
6-8 mm	7 (28%)
8-10 mm	9 (36%)

Table 20. Distribution of patients in 4 categories of relapse range in antero-posterior direction, and according to the magnitude of maxillary advancement (Anterior-Posterior).

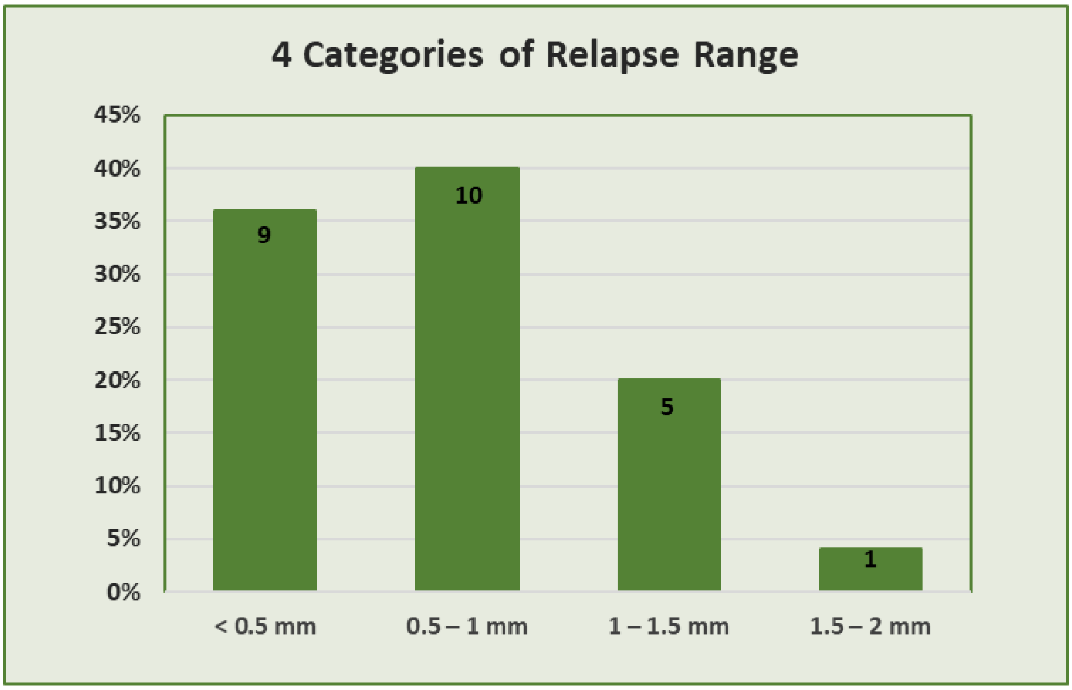


Figure 31. Distribution of cases according to the antero-posterior relapse. The Y-axis indicates the percentage of the patients; **the X-axis** indicates the magnitude of the relapse range.

The percentage of the relapse in relation to the surgical movements was calculated (T1-T2) x 100 / (T0-T1). Figure 31 shows the distribution of the cases according to the calculated percentage of the detected relapse at T2. The relapse ratio was less than 10% of the achieved surgical movements in most of the case. **(Figure 31)**

The details of relapse ratio of the 25 cases are shown in **Table 21**.

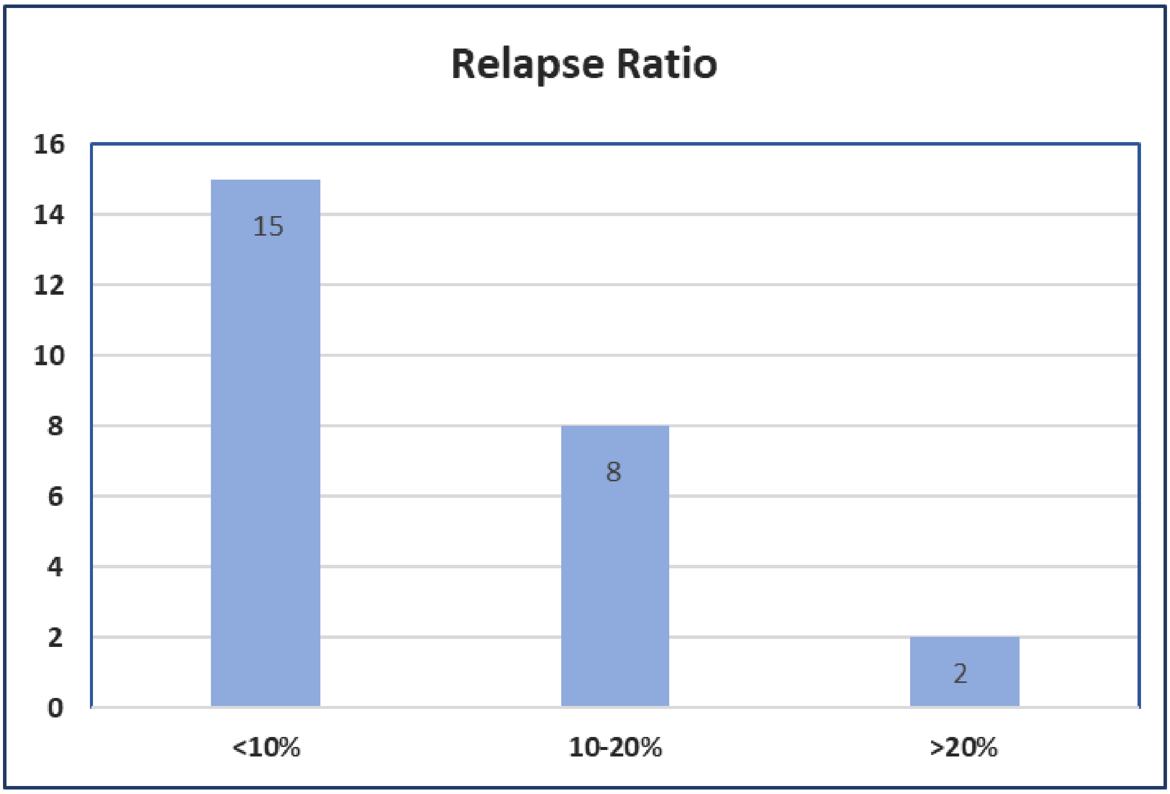


Figure 32. Distribution of the cases according to the percentage of relapse in relation to surgical movements, the X-axis indicates the three main categories of relapse ratio**. The Y-axis** indicates the number of the patients in each category.

Patient	T0-T1 : Surgical movement (mm)	T1-T2 : Relapse (mm)	Relapse Ratio (%)
1	9.22	0.56	6%
2	7.21	0.24	3.3%
3	3.27	0.33	10%
4	5.49	0.34	6.1%
5	5.62	0.54	9.6%
6	9.4	0.63	6.7%
7	9.44	1.48	15.6%
8	3.61	0.54	14.9%
9	7.45	1.17	15.7%
10	**4.50**	**1.06**	**23.5%**
11	7.78	0.92	11.8%
12	9.88	0.22	2.2%
13	7.52	1.32	17.5%
14	4.08	0.7	18.1%
15	7.32	0.97	13.2%
16	**4.75**	**1.38**	**29.1%**
17	9.69	0.74	7.6%
18	5.35	0.23	4.2%
19	7.23	0.45	6.2%
20	8.05	1.7	2.1%
21	8.23	0.6	7.2%
22	6.37	0.46	7.2%
23	4.52	0.19	4.2%
24	8.5	0.32	3.7%
25	8.66	0.97	11 %

Table 21. The details of percentage of relapse in relation to magnitude of surgical movement in SFA patients

3.6 THE QUALITY OF POSTOPERATIVE OCCLUSION AND ITS IMPACT ON THE SKELETAL RELAPSE

3.6.1 Intra-examiner reliability

To assess intra-examiner reliability of occlusal contact analysis using the IPS Case Designer® (KLS Martin, Tuttlingen, Germany), the same researcher repeated the replacement of the distorted dentition for 50% of the cases in 4 weeks interval. The reproducibility of the procedure was analysed using a one sample t-test. The intra-examiner mean difference was between 0.00±0.048 and 0.077±0.277 for the number of the regions and the teeth in contact, which was not significant (*P* :1.00, 0.336, 0.338, 0.337). There was an excellent correlation between the repeated measurements (r = 0.992), (r = 0.971), (r = 0.991), (r = 0.927). **(Table 22)**

Variable	**Mean Difference ±SD**	**SE**	**95% Confidence Interval**		***P* value**	**r value**
			Lower mm	**Upper mm**		
Number of teeth in contact **(PRE)**	0.00±0.408	0.113	-0.247	0.247	1.00	0.992
Regions of occlusal contact **(PRE)**	0.077±0.277	0.077	-0.092	0.244	0.336	0.971
Number of teeth in contact **(1-WK)**	0.076±0.277	0.076	-0.090	0.245	0.338	0.991
Regions of occlusal contact **(1-WK)**	0.077±0.277	0.077	-0.091	0.245	0.337	0.927

Table 22. Intra-examiner reliability (one sample t-test & Intraclass Correlation Coefficient (ICC))

3.6.2 The characteristics of the pre-operative occlusion

The mean and the standard deviation of the pre-operative overjet was -2.75 $\pm$ 2.04 and overbite was -2.04 $\pm$ 2.53. No occlusal contacts prior to surgery were noted in 5 (20%) of the cases. In patients with vertical maxillary deficiency, intra-occlusal wax wafer was used during scanning to avoid mandibular over closure due to the lack of anterior occlusal contact. This eliminated the distortion of the soft tissue morphology of the naso-labial region to maximise the accuracy of the 3D prediction planning. This might have contributed to lack of occlusal contact in 5 cases. **Table 23** shows the pre-operative occlusal characteristics of the 25 patients.

Characteristics		Mean ± SD	N, (%)
Overjet		-2.75 $\pm$ 2.04	
Overbite		-2.04 $\pm$ 2.53	
Number of teeth in contact		3.44 $\pm$ 3.28	
Occlusal regions (Between 0-3)		1.56 $\pm$ 1.1	
Occlusal Contact regions	Anterior		12, (48%)
	Right Posterior		14, (56%)
	Left Posterior		12, (48%)
Occlusal contact category	**A.** Three regions		7, (28%)
	B. Two regions		5, (20%)
	C. One region		8, (32%)

Table 23. The pre-operative occlusion characteristics of SFA patients (N=25)

3.6.3 The characteristics of the occlusion at one week following surgery

The mean and the standard deviation of the overjet were 4.19$\pm$2.31 and of the overbite were 0.52 $\pm$ 1.39 mm. All the patients had occlusal contacts at 1 week following surgery. **Table 24** shows the 1-week post-operative occlusal characteristics of the 25 patients.

At 1-week following surgery 52% of cases had occlusal contacts in 2 regions. Occlusal contact in 3 regions was noted in 28% of the cases. The comparison of occlusal contact distribution is shown in **Figure 32** and **33.**

Characteristics		Mean ± SD	N, (%)
Overjet		4.19 ± 2.31	
Overbite		0.52 ± 1.39	
Number of teeth in contact		3.85 ± 1.89	
Occlusal regions (Between 0-3)		2.12 ± 0.71	
Occlusal Contact regions	Anterior		16, (64%)
	Right Posterior		19, (76%)
	Left Posterior		17, (68%)
Occlusal contact category	**A.** Three regions		7, (28%)
	B. Two regions		13, (52%)
	C. One region		5, (20%)

Table 24. One-week post-operative occlusion characteristics of SFA patients (N=25)

3.6.4 The surgical Occlusal changes at one-week post-operative

The Shapiro-Wilk normality test showed the data are normally distributed except for occlusal regions. **Table 25** shows the descriptive statistics of occlusal surgical changes. There was a significant difference in overjet (mean = 6.94 $\pm$ 2.42, *P:* <0.001), overbite (mean = 2.56 $\pm$ 2.58, *P:* <0.001) and the category of the occlusal contact (mean = 0.53 $\pm$ 1.27, *P:* 0.041).

Variable	Mean Difference (mm)$\pm$SD	Median	SE	95% Confidence Interval		*P* value
				Lower	Upper	
Overjet	6.94 $\pm$ 2.42	6.82	0.475	5.965	7.924	**<0.001**
Overbite	2.56 $\pm$ 2.58	2.08	0.507	1.522	3.611	**<0001**
Number of teeth in contact	0.38 $\pm$ 3.69	0.00	0.726	-1.110	1.879	0.601
Occlusal contact category	0.53 $\pm$1.27	0.50	0.249	0.025	1.052	0.041

Table 25. Occlusal changes of 25 SFA patients from T0 to T1

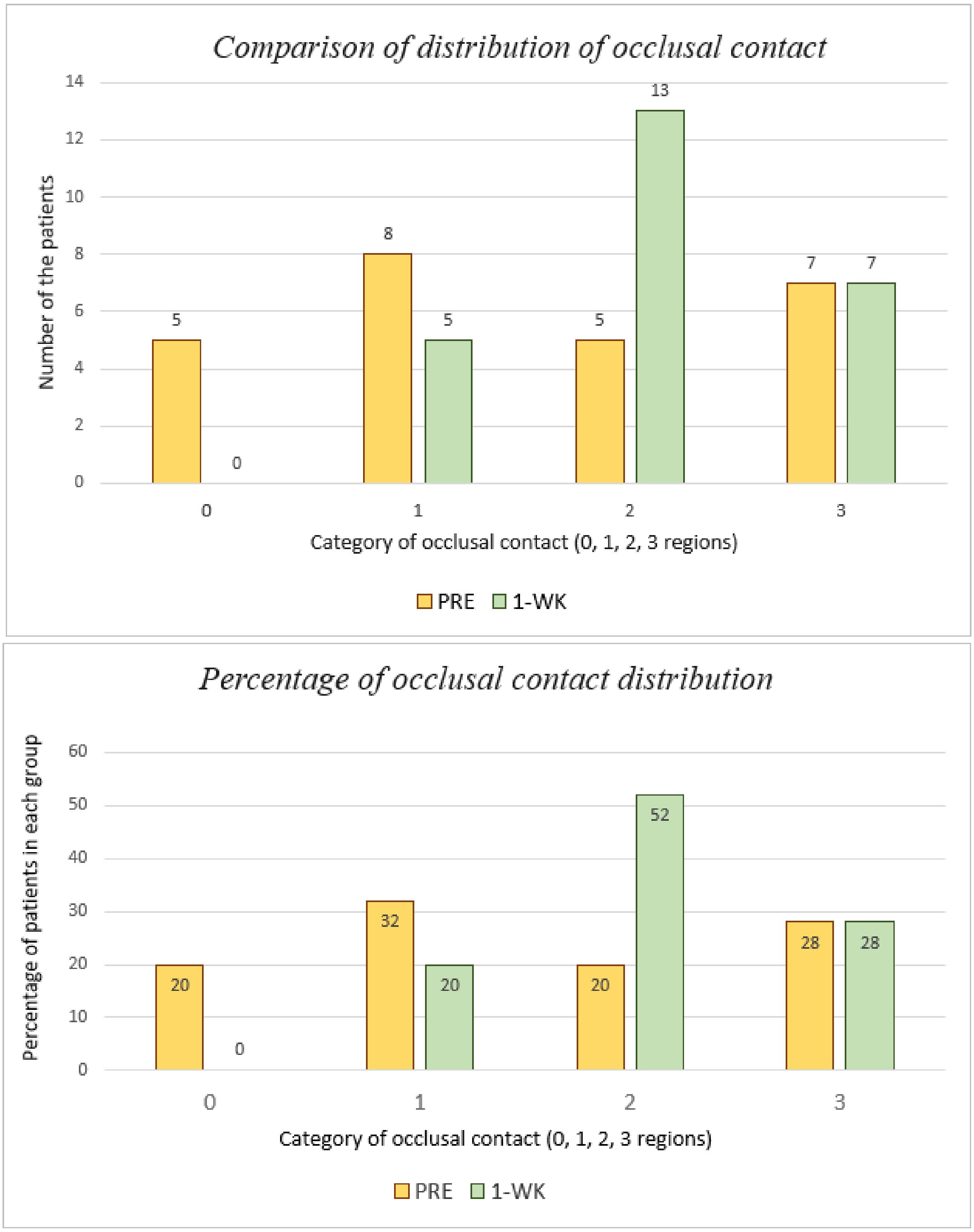
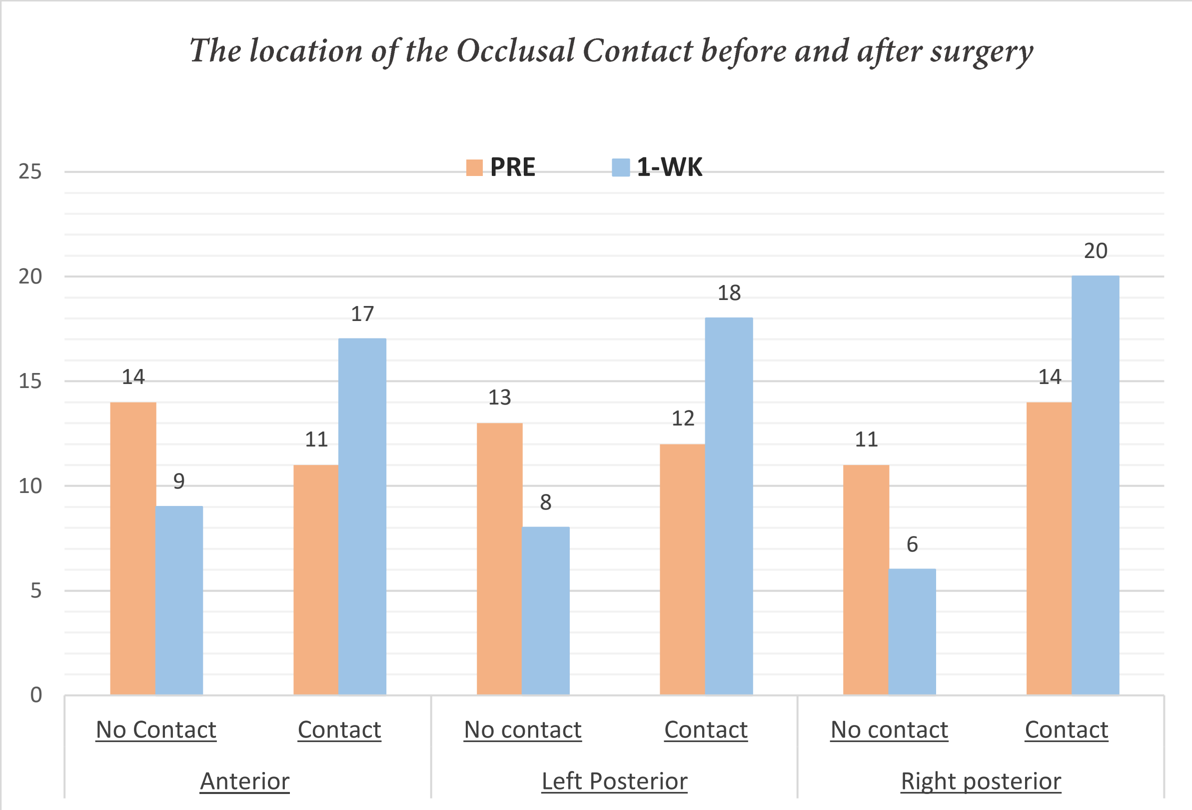


Figure 33. Bar chart of the distribution of Occlusal contact before surgery and at 1 week postoperatively.



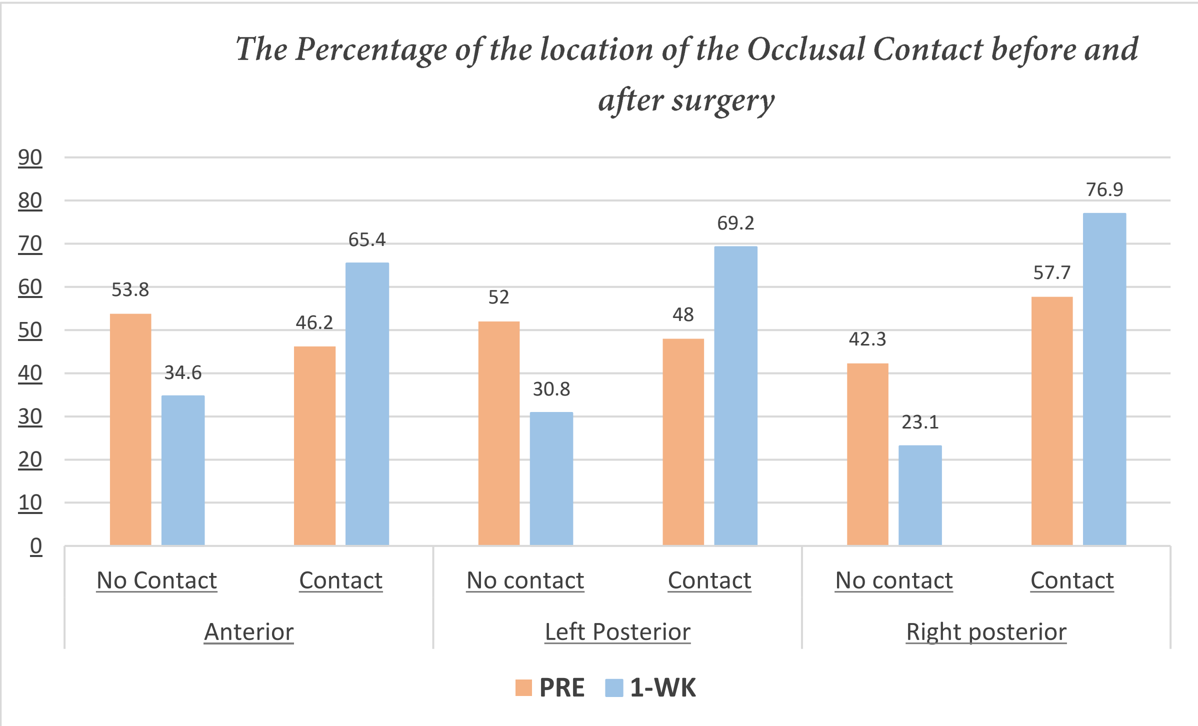


Figure 34. Bar chart of location of the Occlusal contacts before and after surgery.

3.6.5 The relationship between post-operative occlusion and Relapse (T1-T2)

The Shapiro Wilks normality test showed data were not normally distributed except for maxillary rotation (Roll), overbite, and number of the teeth in occlusal contacts. The results of Spearman correlation coefficient showed a weak correlation between relapse (T1-T2) and the quality of occlusion immediately following surgery **(Table 26).** We detected a weak negative correlation (R: -0.434, *P*: 0.030) between number of the teeth in contact and the relapse of the maxillary roll.

(T1-T2) Relapse	Distribution of Occlusal Contact		No of teeth in Contact		Overjet		Overbite	
	r value	*P* value	r value	*P* value	r value	*P* value	r value	*P* value
Translation (mm)								
(Left/right)	0.138	0.512	0.065	0.757	-0.159	0.449	0.179	0.392
(Posterior/anterior)	-0.104	0.621	-0.255	0.219	0.249	0.231	-0.165	0.430
(Superior/inferior)	0.273	0.187	0.182	0.385	0.072	0.733	0.324	0.114
Rotation (°)								
Pitch	-0.083	0.694	-0.075	0.721	0.289	0.161	-0.080	0.705
Roll	0.255	0.219	**-0.434**	**0.030**	0.151	0.472	-0.073	0.730
Yaw	0.310	0.132	-0.367	0.071	0.299	0.147	0.291	0.158

Table 26. Spearman Correlation coefficient (r) between skeletal relapse (T1-T2) and the quality of occlusion at 1 week following surgery.

Summary of the Results

The difference between the repeated landmarking was not significant for all 3 landmarks. Only at the X dimension of Incisive foramen there was statistically significant differences (0.12 ±0.29 mm, *P*:0.048, and -0.09±0.26 mm) at T0 and T2. There was an excellent correlation between the repeated landmarking in X, Y and Z dimensions of the repeated digitization of the CBCT scans of T0, T1 and T2.
The size of measurement error calculated by Dahlberg formula was minimal.
The mean forward surgical movement of the Maxilla was 6.79mm±2.30. In average the maxilla moved upward (1.28mm±1.09) and to the right (0.71mm±0.79).

The maxilla was rotated surgically (Yaw) toward the left side (Z: 1.56° ±1.21°) to correct the central midline, downward (Pitch) 1.86° ± 1.88° to increase the incisal show and tilted in a clockwise direction on the right side (Roll) of an average 1.63° ±1.54° to correct the occlusal canting.

During T1-T2, the relapse in the vertical and mediolateral directions was not significant. Likewise, the measured relapse of the clockwise surgical rotation (Roll) of maxilla was not significant (1.28 ± 0.82°). There was statistically significant further downward rotation of the maxilla (Pitch) of an average of 1.56 ± 1.42°, *P*: 0.007. The relapse of the maxillary Roll and Yaw was not statistically significant (1.28 ± 0.82°) and (0.81 ± 0.68°). The significant relapse of the achieved surgical movements was in the antero-posterior translational shift (0.72 ± 0.43 mm).

There was a weak correlation between the Roll, Yaw, and Pitch of the surgical movements and the detected relapse at T2. There was no statistically significant correlation between the magnitude of the maxillary advancement and the detected relapse at T2. A weak negative correlation (R: -0.434, *P*: 0.030) between number of the teeth in contact and the relapse of the maxillary (Roll) was detected.

SECTION B

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3.7 SECTION B: COMPARISON BETWEEN SFA AND OFA

3.7.1 Patients' demographic data

A total of 13 skeletal class III cases who underwent orthodontic-first approach for correction of maxillary deficiency were eligible for the study. Baseline demographic data of these patients are shown in **Table 27**. The mean age was 30.69 ±7.87 years, 7 patients were male and 6 were female. Three patients had simultaneous Genioplasty.

Characteristics	N (%)	Mean ± SD
Female	6 (47%)	
Male	7 (53%)	
Age		30.69 ± 7.87
Genioplasty	3 (23%)	

Table 27. Baseline demographics of OFA patients (N=13)

3.7.2 The surgical movement of the maxilla (T0-T1)

The Shapiro-Wilk normality test showed the data were normally distributed. **Table 28** and **29** shows the descriptive statistics of skeletal surgical movements. There was a significant movement of the maxilla in forward direction (6.75±1.56 mm). In average the maxilla moved (2.57±1.81 mm) in vertical direction, by 69% moved downward (mean: 3.25mm) and 31% moved upward by mean:1.07 mm.

The absolute mean of maxillary medio-lateral movement was (0.53±0.39 mm), by 46% moved to the left (Mean: 0.43) and 54% toward the right side (Mean: 0.62mm).

The absolute mean of maxillary pitch rotation was (2.86±2.60°), with 46% (mean: 2.18°) rotated in downward (clockwise) and 54% (mean: 3.49°) rotated upward (counterclockwise) direction.

The absolute mean of maxillary roll rotation was (Y: 2.01±2.01°), with 85% (mean: 2.27°) rotated to the right (clockwise) and 15% (mean: 0.57°) rotated to the left (counterclockwise) direction.

The absolute mean of maxillary yaw rotation was (1.56±1.50°), with 69% (mean: 1.99°) rotated to the left (counterclockwise) and 31% (mean: 0.62°) rotated to the right (clockwise) direction.

Measurement	Mean ± SD	Absolute mean ± SD	Median	95% Confidence Interval		Minimum	Maximum	Shapiro-Wilk (Sig)
				Upper	Lower			
Translation (mm)								
Right/Left	-0.13±0.66	0.53±0.39	-0.10	0.26	-0.53	-1.07	1.10	0.048
Posterior/anterior	-6.75±1.56	6.75±1.56	-6.78	-5.81	-7.70	-9.66	-4.42	0.088
Superior/inferior	1.92±2.55	2.57±1.81	2.45	3.46	0.37	-3.41	5.79	0.430
Rotation (°)								
Pitch	-0.87±3.87	2.88±2.60	-0.05	1.46	-3.21	-7.88	3.45	0.711
Roll	1.84±2.18	2.01±2.01	1.03	3.15	0.51	-0.85	7.31	0.715
Yaw	1.18±1.84	1.56±1.50	0.57	2.29	0.06	-1.38	5.12	0.871

Table 28. Surgical movements of OFA patients from T0 to T1

Patient	Right/Left	Anterior/Posterior	Superior/Inferior	Pitch (°)	Roll (°)	Yaw (°)
1	-0.93	-5.98	3.81	-7.85	4.42	5.12
2	0.43	-9.18	3.07	1.29	2.52	1.72
3	-0.97	-4.42	4.51	-3.93	3.34	-0.46
4	0.58	-6.78	-0.84	-0.26	1.29	3.15
5	-0.29	-6.78	1.60	2.75	-0.28	-0.58
6	-1.07	-7.62	0.72	1.74	0.17	-1.38
7	-0.25	-5.43	5.79	-7.88	7.31	2.96
8	-0.10	-5.55	3.18	2.78	0.96	0.55
9	-0.72	-6.09	-3.41	1.09	0.98	0.57
10	0.06	-5.05	2.45	-4.16	0.86	2.70
11	1.1	-7.68	-0.01	-0.30	1.03	0.35
12	0.01	-7.63	4.09	3.45	2.14	0.73
13	0.40	-9.66	-0.01	-0.05	-0.85	-0.07
Mean	**-0.13**	**-6.75**	**1.92**	**-0.87**	**1.84**	**1.18**
Absolute Mean	**0.53**	**6.75**	**2.57**	**2.88**	**2.01**	**1.56**

Table 29. The mean and absolute mean of surgical movement (T0-T1), Translation: A positive value indicates movement of the left, posterior, and superior. A negative value indicates movement of the right, anterior and inferior. **Rotation:** (Pitch: clockwise rotation +, counterclockwise rotation −), (Roll: clockwise rotation +, counterclockwise rotation −), (Yaw: counterclockwise rotation +, clockwise rotation −).

3.7.3 Skeletal relapse at 6-months follow-up (T1-T2)

The skeletal changes from one-week to 6 months following surgery are shown in **Table 30, 31**. The Shapiro-Wilk normality test showed the data were not normally distributed. The Wilcoxon Signed Ranked Test was applied. Statistically significant relapse (*P*: 0.001) was detected, the maxilla moved backward of an average of (0.48±0.38mm).

The absolute mean vertical relapse of the maxilla was (0.46±0.54mm) with 61% relapsed for 0.50mm in upward direction and 39% relapsed for 0.43mm in downward direction. These were not statistically significant.

The absolute mean of medio-lateral relapse of the maxilla was (0.54±0.61mm), with 0.59 mm (53%) relapse in right and 0.48mm (46%) relapse in left direction. These were not statistically significant.

There was a non-significant relapse of maxillary pitch (2.08 ±1.62°, *P*: 0.370). In average 53% (mean: 2.56°) rotated in downward (clockwise) and 46% (mean: 1.53°) rotated upward (counterclockwise) direction.

The absolute mean of maxillary roll showed rotational relapse of 1.13± 1.11°, (*P*: 0.139) with 69% (mean: 1.29°) rotated to the left (counterclockwise) and 31% (mean: 0.79°) rotated to the right (clockwise) direction.

The absolute mean of maxillary rotational relapse of Yaw was 1.19± 2.07°, (*P*: 0.507). Fifty-four percent (mean: 0.84°) rotated to the left (counterclockwise) and 46% (mean: 1.62°) rotated to right (clockwise) direction.

Measurement	Mean ± SD	Absolute mean ± SD	*P* value	Median	95% Confidence Interval		Minimum	Maximum	Shapiro-Wilk (Sig)
					Upper	Lower			
Translation (mm)									
Left/right	-0.10±0.83	0.54±0.61	0.672	-0.04	0.40	-0.60	-2.37	0.92	0.216
Posterior/anterior	0.48±0.38	0.48±0.38	**0.001**	0.46	0.70	0.24	-0.01	1.36	0.013
Superior/inferior	-0.07±0.73	0.46±0.54	0.729	-0.12	0.36	-0.51	-1.98	1.29	0.001
Rotation (°)									
Pitch	0.67±2.61	2.08±1.62	0.370	0.22	2.25	-0.90	-3.90	5.28	0.001
Roll	-0.65±1.48	1.13±1.11	0.139	-0.63	0.24	-1.50	-4.01	2.13	0.332
Yaw	-0.29±2.40	1.19±2.07	0.507	0.33	1.15	-1.74	-7.92	1.84	0.001

Table 30. Skeletal changes (Relapse) of OFA patients from T1 to T2

Patient	Right/Left	Anterior/Posterior	Superior/Inferior	Pitch (°)	Roll (°)	Yaw (°)
1	-0.57	0.79	-0.45	3.45	-1.79	-0.67
2	0.01	0.65	-0.31	1.73	-0.68	-0.85
3	0.92	0.06	-0.22	5.28	-2.14	0.79
4	-0.04	0.31	0.31	-0.31	0.15	-0.21
5	0.80	-0.01	-1.98	-0.90	-0.05	0.79
6	-0.45	0.76	-0.18	-0.96	0.50	-0.04
7	-2.37	0.46	0.23	3.78	-0.86	-7.92
8	-0.43	0.10	-0.24	2.89	-4.01	1.04
9	-0.19	0.21	1.29	-1.15	2.13	0.44
10	-0.11	0.31	-0.12	-3.90	-0.97	0.33
11	0.38	0.71	0.13	0.22	-0.47	-0.02
12	0.59	0.48	0.43	0.57	0.39	0.65
13	0.16	1.36	0.18	-1.92	-0.63	1.84
Mean	**-0.10**	**0.48**	**-0.07**	**0.67**	**-0.65**	**-0.29**
Absolute Mean	**0.54**	**0.47**	**0.46**	**2.08**	**1.13**	**1.19**

Table 31.The mean and absolute mean of relapse (T1-T2), Translation: A positive value indicates movement of the left, posterior, and superior. A negative value indicates movement of the right, anterior and inferior**. Rotation:** (Pitch: clockwise rotation +, counterclockwise rotation −), (Roll: clockwise rotation +, counterclockwise rotation −), (Yaw: counterclockwise rotation +, clockwise rotation −).

3.7.4 The relationship between surgical movement (T0-T1) and skeletal relapse (T1-T2)

The Shapiro Wilks normality test showed data were not normally distributed. The results of Spearman correlation coefficient showed a moderate correlation (R: 0.654) between the maxillary rotational movement (Pitch) at (T0-T1) and relapse at 6 months which was statistically significant (*P*:0.015). **(Table 32).** No statistically significant correlation between the translational surgical movements and the detected relapse at T2 was detected.

Surgical movement (T0-T1)	R value	*P* value	Shapiro-Wilk (Sig) (T0-T1)	Shapiro-Wilk (Sig) (T1-T2)
Translation (mm)				
(Medio-lateral)	0.106	0.730	0.048	0.216
(Posterior/anterior)	0.578	0.059	0.088	0.013
(Superior/inferior)	0.372	0.211	0.430	0.001
Rotation (°)				
Pitch	**0.654**	**0.015**	0.711	0.001
Roll	0.286	0.344	0.715	0.332
Yaw	0.109	0.748	0.871	0.001

Table 32. Pearson / Spearman Correlation coefficient (r) between skeletal relapse (T1-T2) and surgical movement (T0-T1)

3.7.5 Detailed analysis of the antero-posterior maxillary relapse ratio at T2

Table 33 shows the distribution of the patients across the four categories of the measured relapse in anterior / posterior direction. In 12 cases the relapse did not exceed 1 mm. The distribution of the cases according to the magnitude of antero-posterior surgical movements is also demonstrated in **Figure 34**.

Relapse range	Patients (N / %)
< 0.5 mm	8 (61%)
0.5 – 1 mm	4 (31%)
1 – 1.5 mm	1 (8%)
1.5 – 2 mm	0
Surgical movement (Maxillary Advancement)	
< 4 mm	0
4-6 mm	5 (38%)
6-8 mm	6 (46%)
8-10 mm	2 (16%)

Table 33. Distribution of patients in 4 categories of relapse range in antero-posterior direction, and according to the magnitude of maxillary advancement (Anterior-Posterior).

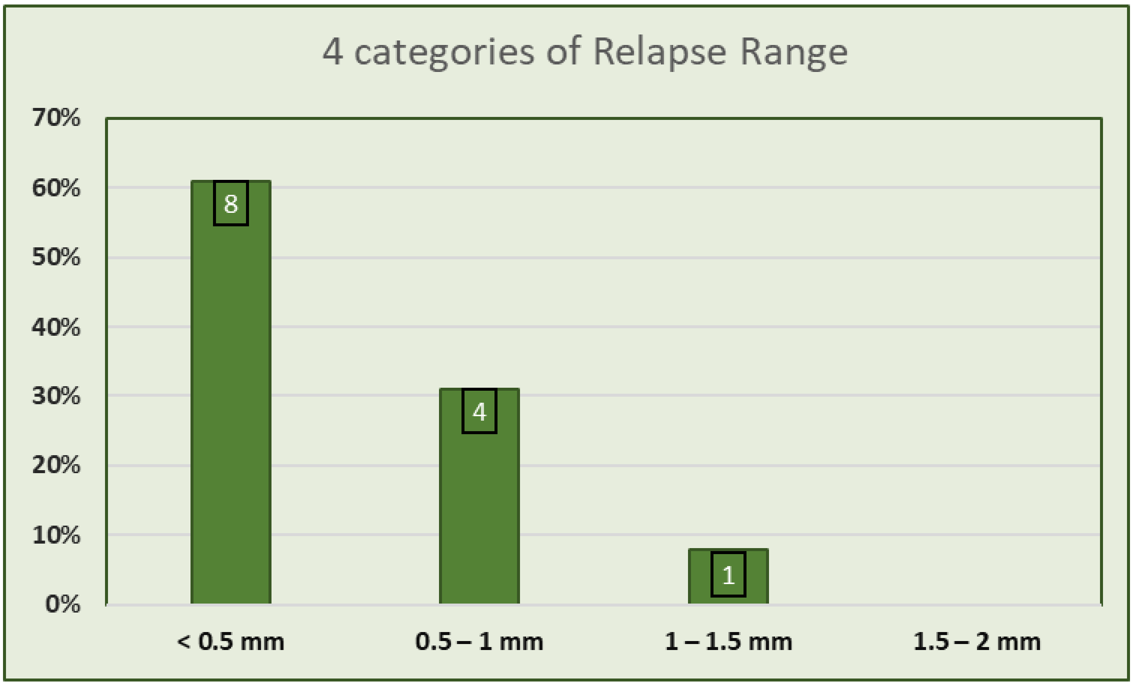

Figure 35. Distribution of cases according to the antero-posterior relapse. The Y-axis indicates the percentage of the patients; the X-axis indicates the magnitude of the relapse range.

The percentage of the relapse in relation to the surgical movements was calculated (T1-T2) x 100 / (T0-T1)). **Figure 35** shows the distribution of the cases according to the calculated percentage of the detected relapse at T2. The relapse ratio was less than 10% of the achieved surgical movements in 90% of the cases. The details of relapse ratio for the 13 OFA cases are shown in **Table 34**.

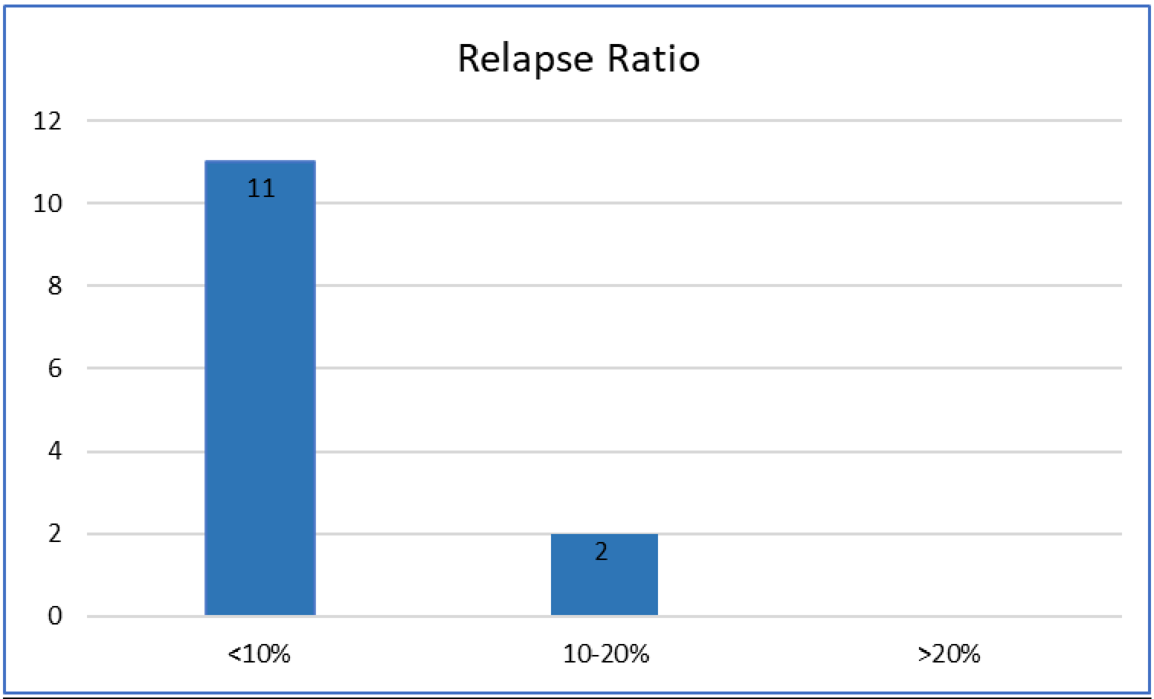

Figure 36. Distribution of the cases according to the percentage of relapse in relation to surgical movements, the X-axis indicates the three main categories of relapse ratio. The Y-axis indicates the number of patients in each category.

Patient	T0-T1 : Surgical movement (mm)	T1-T2 : Relapse (mm)	Relapse Ratio (%)
1	**5.98**	**0.79**	**13.2%**
2	9.18	0.65	7%
3	4.42	0.06	1.3%
4	6.78	0.31	4.5%
5	6.78	0.01	0.1%
6	7.62	0.76	9.9%
7	5.43	0.46	8.4%
8	5.55	0.1	1.8%
9	6.09	0.21	3.4%
10	5.05	0.31	6.1%
11	7.68	0.71	9.2%
12	7.63	0.48	6.2%
13	**9.66**	**1.36**	**14.0%**

Table 34. The details of percentage of relapse in relation to magnitude of surgical movement in OFA patients

3.7.6 Comparison of surgical movement and skeletal relapse between OFA and SFA

The results of Mann Whitney test showed a statistically significant difference between SFA and OFA for the surgical movement in superior-inferior direction (Mean: 1.29, *P*: 0.032). The mean maxillary upward movement was greater in OFA (2.57mm) than SFA (1.28mm). The result of Mann Whitney U test showed no statistically significant difference for relapse between the two groups in other directions. **(Table 35)**

Variable	SFA (N=25) Absolute Mean ± SD	OFA (N=13) Absolute Mean ± SD	Absolute Mean difference	*P* value
Surgical movement (T0-T1)				
Right/Left	0.71±0.79	0.53±0.39	0.18	0.693
Posterior/anterior	6.79±2.30	6.75±1.56	0.03	0.716
Superior/inferior	1.28±1.09	2.57±1.81	**1.29**	**0.032**
Pitch	1.86 ±1.88	2.88±2.60	1.01	0.286
Roll	1.63±1.54	2.01±2.01	0.37	0.671
Yaw	1.56±1.21	1.56±1.50	0.00	0.856
Relapse (T1-T2)				
Right/Left	0.30±0.33	0.54±0.61	0.232	0.178
Posterior/anterior	0.72 ± 0.43	0.48±0.38	0.244	0.104
Superior/inferior	0.57±0.47	0.46±0.54	0.106	0.394
Pitch	1.56 ±1.42	2.08±1.62	0.521	0.272
Roll	1.28 ± 0.82	1.13±1.11	0.150	0.411
Yaw	0.81±0.68	1.19±2.07	0.384	0.856

Table 35. Comparison of Surgical changes and the relapse between SFA and OFA group

3.7.7 The Occlusion characteristics

3.7.7.1 The characteristics of the pre-operative occlusion

The mean and the standard deviation of the pre-operative overjet was -3.06 ± 1.73 mm and over-bite was -1.96±1.49 mm. **Table 36** shows the pre-operative occlusal characteristics of the 13 patients.

Characteristics		Mean ± SD	N, (%)
Overjet		-3.06 ± 1.73	
Overbite		-1.96±1.49	
Number of teeth in contact		5.38 ±2.39	
Occlusal regions (Between 0-3)		2.07±0.64	
Occlusal Contact regions	Anterior		6 (46%)
	Right Posterior		11 (84%)
	Left Posterior		10 (76%)
Occlusal contact category	**A.** Three regions		3 (23%)
	B. Two regions		8 (61%)
	C. One region		2 (16%)

Table 36. The pre-operative occlusion characteristics of OFA patients (N=13)

3.7.7.2 The characteristics of the occlusion at one week following surgery

The mean and the standard deviation of the overjet were 3.73 ± 1.47mm and of the overbite were 1.18 ± 1.17 mm. **Table 37** shows the 1-week post-operative occlusal characteristics of the 13 patients.

Characteristics		Mean ± SD	N, (%)
Overjet		±	
Overbite		1.18±1.17	
Number of teeth in contact		6.53±1.66	
Occlusal regions (Between 0-3)		2.76±0.43	
Occlusal Contact regions	Anterior		10 (76%)
	Right Posterior		13 (100%)
	Left Posterior		10 (76%)
Occlusal contact category	**A.** Three regions		10 (76%)
	B. Two regions		3 (24%)
	C. One region		0

Table 37. One-week post-operative occlusion characteristics of OFA patients (N=13)

3.7.7.3 The surgical Occlusal changes at one-week post-operative

The Shapiro-Wilk normality test showed the data are not normally distributed. **Table 38** shows the descriptive statistics of occlusal changes following surgery. There was a significant difference in overjet (mean = 5.67 $\pm$ 2.65, *P:* 0.001), overbite (mean = 3.15$\pm$ 1.30, *P:* 0.001) and the distribution of the occlusal contact (mean = 0.69 $\pm$ 0.75, *P:* 0.014). No difference was detected in the number of the teeth in occlusal contact.

Variable	Mean Difference (mm)$\pm$SD	Median	SE	95% Confidence Interval		*P* value
				Lower	Upper	
Overjet	5.67 $\pm$ 2.65	5.60	0.736	4.072	7.284	**0.001**
Overbite	3.15 $\pm$ 1.30	3.00	0.362	2.360	3.939	**0.001**
Number of teeth in contact	1.15 $\pm$ 3.15	1.00	0.876	0.755	3.062	0.178
Occlusal contact category	0.69 $\pm$ 0.75	1.00	0.208	0.238	1.146	**0.014**

Table 38. Occlusal changes from T0 to T1, (N=13)

3.7.7.4 The relationship between post-operative occlusion and relapse (T1-T2)

The Shapiro Wilks normality test showed data were not normally distributed. The results of Spearman correlation coefficient showed a weak correlation between relapse at T2 and the quality of occlusion immediately following surgery **(Table 39).** We detected moderate correlation (r: 0.683, *P*: 0.010) between the distribution of the occlusal contact (contacts on 1, 2 or 3 regions) with maxillary relapse in clockwise rotation (Pitch) which was statistically significant.

(T1-T2) Relapse	Distribution of Occlusal Contact		No of teeth in Contact		Overjet		Overbite	
	r value	***P* value**	**r value**	***P* value**	**r value**	***P* value**	**r value**	***P* value**
Translation (mm)								
(Left/right)	0.146	0.633	-0.120	0.742	-0.204	0.505	0.111	0.915
(Posterior/anterior)	-0.415	0.158	0.114	0.755	-0.234	0.441	-0.352	0.239
(Superior/inferior)	-0.049	0.874	-0.172	0.573	0.322	0.284	0.110	0.837
Rotation (°)								
Pitch	**0.683**	**0.010**	-0.250	0.410	0.116	0.707	-0.171	0.637
Roll	-0.098	0.751	0.057	0.852	0.179	0.559	0.385	0.272
Yaw	0.195	0.522	-0.108	0.726	0.147	0.631	0.164	0.650

Table 39. Spearman Correlation coefficient (r) between skeletal relapse (T1-T2) and the quality of occlusion at 1 week following surgery.

3.7.8 Comparison of occlusion at 1-week following surgery between OFA and SFA

The occlusion at 1 week following surgery was compared between the two groups by Mann Whitney U test. The results showed no significant difference between the two groups for overjet and overbite at 1 week following surgery**. (Table 40)**

The OFA patients had more occlusal regions (*P*: 0.001) and number of teeth in contact (*P*: 0.003) than SFA group. **(Figures 36-39)**

Variable	Mean Difference	SE	95% Confidence Interval		*P* value
			Lower	Upper	
Overjet	0.174	0.68	-1.34	1.44	0.914
Overbite	0.665	0.40	-1.35	0.31	0.381
Number of teeth in contact	2.94	0.59	1.55	3.99	**0.001**
Occlusal regions (1,2,3)	0.72	0.18	0.31	1.06	**0.003**

Table 40. Difference between the occlusion at 1week following surgery (SFA vs OFA)

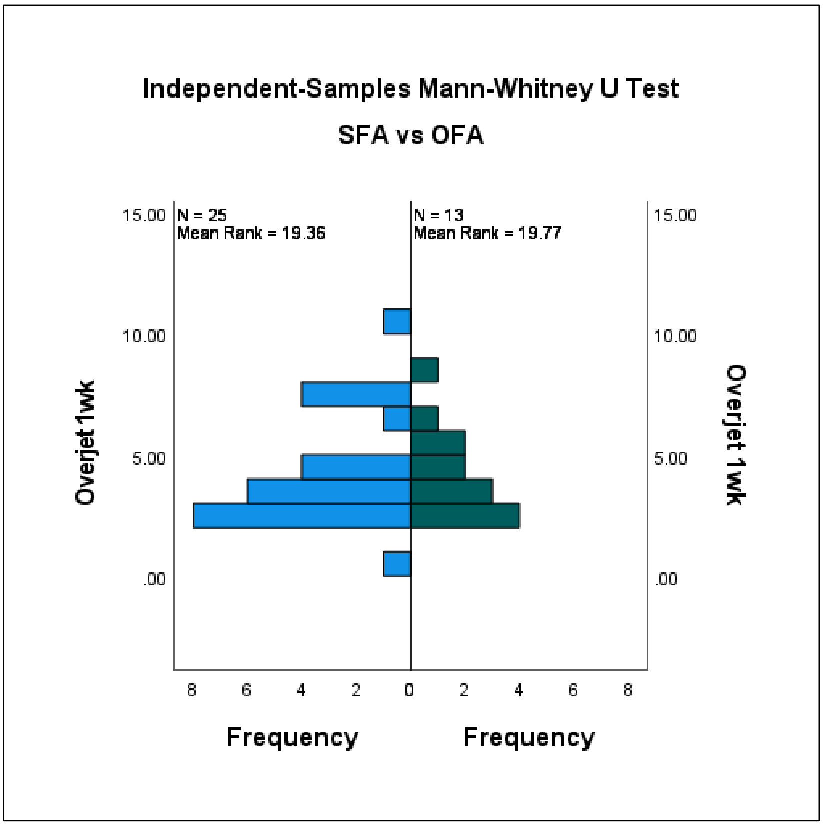

Figure 37. Comparison of over-jet between SFA and OFA

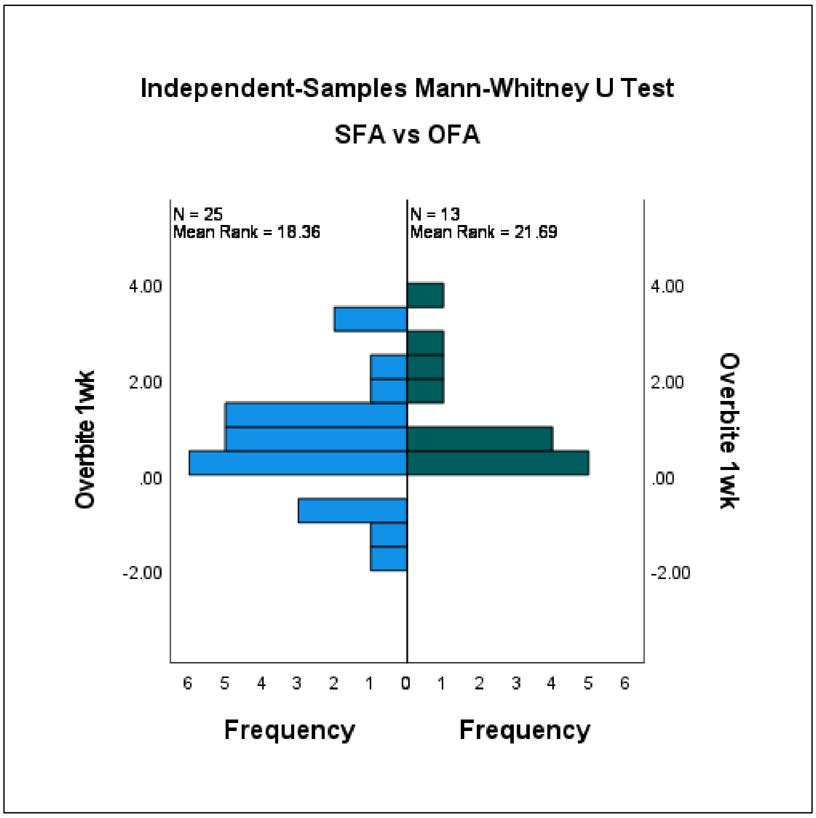

Figure 38. Comparison of over-bite between SFA and OFA

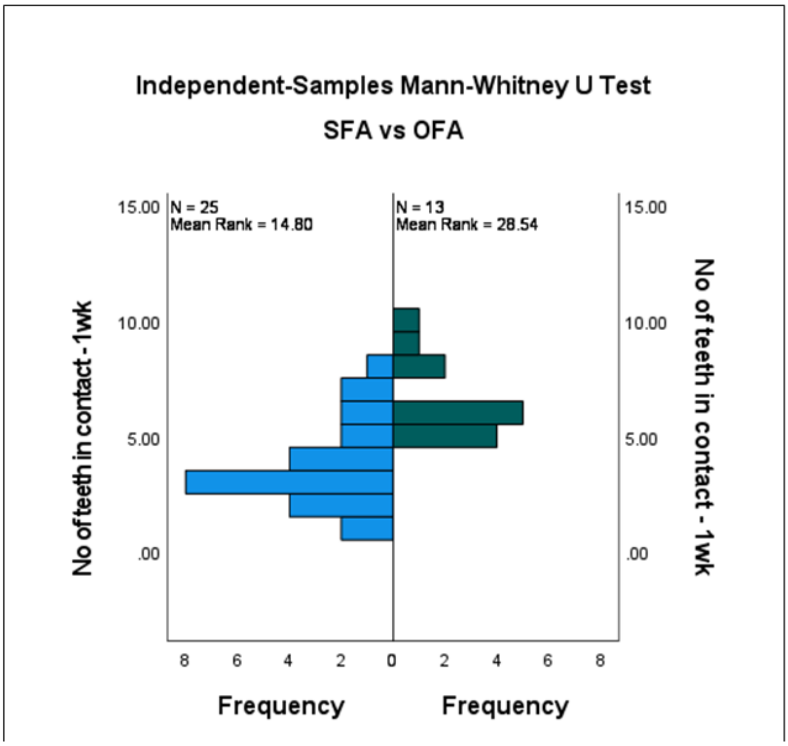

Figure 39. Comparison of Number of the teeth in contact at 1-week following surgery between SFA and OFA

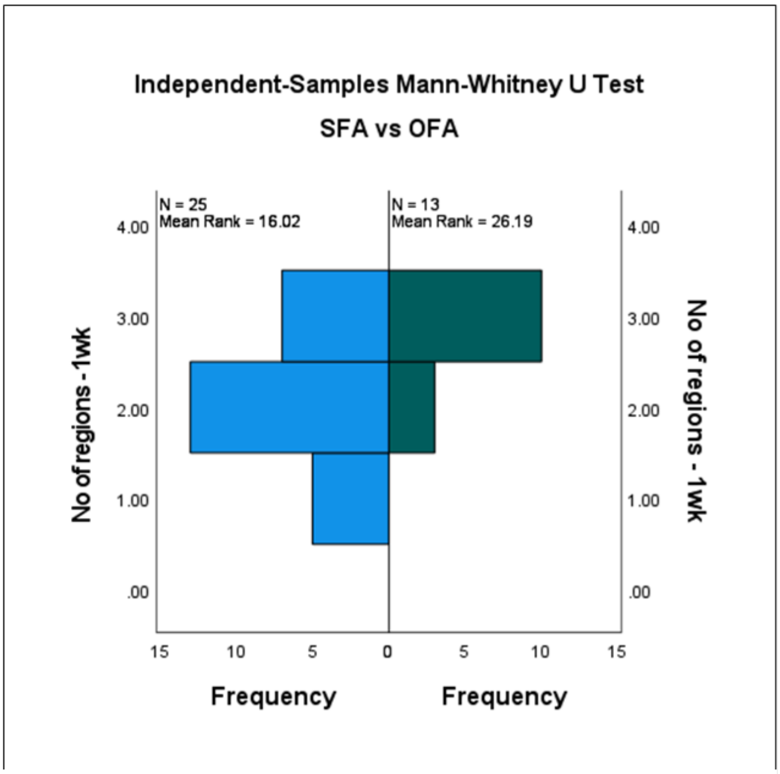

Figure 40. Comparison between Number of regions of contact between SFA and OFA

4 CHAPTER FOUR: DISCUSSION

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4.1 THE HIERARCHY OF STABILITY

Conventional orthognathic treatment commences with orthodontic treatment, followed by surgical repositioning of the osteotomy segments for the correction of the dento-facial deformities. The repositioning of the maxilla, distal mandibular segment and/or chin into a desirable position, not only corrects the facial profile but also influences the occlusion and in some cases the breathing of the patients. The introduction of the surgery-first approach (SFA) has changed the order of treatment; the surgical procedure being carried out first, followed by the orthodontics. It has been shown that the SFA reduces the total treatment time, and provides an immediate improvement in facial profile, which positively affects the patient's quality of life (Anwar et al, 2022; Saghafi et al, 2020; Yang et al, 2017).

The impact of the immediate post-operative occlusion on skeletal stability has been considered to be a potential disadvantage of the SFA (Choi et al, 2019; Park et al, 2016). It has been reported that a well-interdigitated occlusion resulting from pre-surgical orthodontics decreases the possibility of skeletal relapse. (Akamatsu et al, 2016; Wei et al, 2018). However, most of the studies were limited to 2D cephalometric analysis (Kim et al, 2014b; Mah et al, 2017; Park et al, 2015) and there is a lack of evidence relating the true 3D objective quantification of post-surgical skeletal relapse and the quality of the occlusion.

With the increasing availability of 3D imaging facilities and the relatively low radiation dose, CBCT scanning is gradually replacing 2D cephalometry. Nevertheless, skeletal relapse is still one of the least studied complications using 3D imaging.

The main objectives of this study were to assess the 3D skeletal relapse following Le Fort I maxillary advancement, and to study the relationship between the stability of the achieved surgical movements and the quality of the post-operative occlusion in SFA patients.

The classic hierarchy of stability of orthognathic surgery is based on data collected from more than 1500 patients operated on at the University of North Carolina (Proffit et al, 2007). It classified the stability at one year following conventional orthognathic surgery when skeletal changes were likely to be greatest. **(Figure 40)**

The hierarchy of stability was based on the number of patients who experienced changes of at least 2mm of the achieved surgical movements, which was considered clinically significant. This was based on cephalometric landmark analysis. A relapse of less than 2 mm was considered within the error of the method and clinically insignificant. Skeletal relapse between 2-4mm was considered mild to moderate, and greater than 4mm was considered severe (Proffit et al, 1996) . It has been considered that maxillary advancement of 8mm or less is a stable surgical procedure as only 20% of the patients showed relapse of between 2-4mm and the relapse was within 2mm for the remaining cases (Proffit et al, 1991; Proffit et al, 2007).

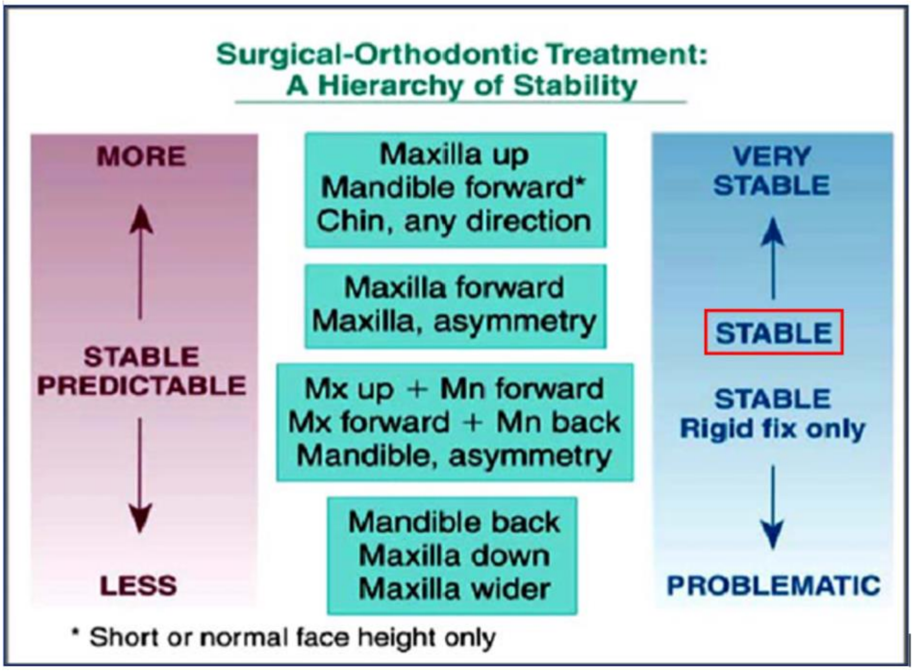

Figure 41. The classic hierarchy of post-surgical stability at 1 year following conventional orthognathic surgery.

The concept of the hierarchy of stability has been followed by almost all the studies which assessed the stability of surgery-first orthognathic treatments. Interestingly, the hierarchy of orthognathic procedures was based on conventional orthognathic correction of dentofacial deformity. In most of the studies the classic cephalometric analysis was based on landmarks which are affected by surgery. This includes points A and B, which are subjected to remodelling due to the post-surgical orthodontic tooth movements. Moreover, the two-dimensional (2D) cephalometric radiographs suffer from several inherent flaws, including magnification, distortion, and the technical difficulty in landmark registration. Moreover, the studies were limited to cases of reduced facial height. The reported post-surgical skeletal changes of the maxillary position of less than 2mm was considered insignificant. This may be true following 10mm surgical advancement of the maxilla, but the 2mm relapse in a 4mm advancement case counts for 50% of surgical movement. There is a notable research gap concerning the radiographic data that were analysed to evaluate the relapse and stability of orthognathic surgical procedures. There are no systematic reviews on the 3D analysis of CBCT scans of orthognathic patients (Haas et al, 2019).

4.2 THE 3D METHOD OF ANALYSIS

Significant variability has emerged in the choice of reference points, planes and angles that have defined the skeletal relapse in 2D analysis (Soverina et al, 2019). Despite the lack of methodological rigor, 2D lateral cephalometric analysis has been considered by many researchers to compare the stability between conventional and surgery-first orthognathic approaches (Romero et al, 2020; Soverina et al, 2019). The reason for this might have been the unavailability of the 3D CBCT scans.

The manual landmark identification of the 2D/3D cephalometry has been the most commonly used method to quantify the surgical movements and skeletal relapse. The manual landmarking is prone to human error and the reliability is questionable and dependent on observers' experience. The error of manual landmark identification has been reported between 0.3 to 2.8mm (Gaber et al, 2017).

Over the last decade, artificial intelligence (AI) has made significant progress in the field of medical imaging and has been applied to achieve semi-automatic and fully automated 2D cephalometric analysis (Kim et al, 2020). However, 2D images have a reduced diagnostic accuracy, as the developed AI models were only trained in two dimensions, which is not suitable for facial asymmetry (Hung et al, 2020).

Deep Learning (DL), a state-of-the art AI technique, is highly effective in image recognition and has been used for diagnostic purposes and treatment planning (Shen et al, 2017). DL algorithms such as convolutional neural networks (CNN) have proved efficient for the automatic detection of landmarks on both 2D and 3D radiographs (Mohammad-Rahimi et al, 2021; Yasaka et al, 2018).

Shahidi et al., 2014 proposed an AI algorithm to automatically locate 14 craniofacial landmarks on 28 CBCT images. The mean error (3.40mm) of the automatically identified landmarks was higher than the mean error (1.41mm) of the manually detected landmarks (Shahidi et al, 2014).

Montufar et al. (2018) developed two different landmark localization systems; the active shape model (ASM) and the hybrid algorithm, to automatically locate 18 landmarks on 24 CBCT images. The mean deviation of the automatically identified landmarks for the two methods were 2.51mm and 3.64mm (Montúfar et al, 2018a; b). Recently, Gillot et al. (2023) assessed an AI algorithm for full automation of 32 landmarks on 143 CBCT scans. The average error of landmark detection was 1.53 ± 0.85 mm and 1.61 ± 0.93mm for the maxillary and mandibular points respectively (Gillot et al, 2023).

To evaluate the accuracy of the AI in automatically detecting 35 landmarks on 114 CBCT scans, Blum et al. (2023) compared the mean error of automatic landmarking by the AI algorithm with the mean values of manual landmarking by three experts. The results showed AI was more accurate than manual localization in 28.5% of the cases, less accurate in 23.1% of the cases, and equal in 48.4% of the cases. The total error of all landmarks combined was 2.73mm for the AI and 2.79mm for the 3 experts. (Blum et al, 2023).

The error of automated landmarking is still equal to, or higher than, that for manual landmarking. Therefore, the existing AI systems are not yet accurate enough to meet the requirements for the precise analysis of 3D images. There is still a lack of fully automated and reliable software for the analysis of 3D images of facial deformities and the prediction planning of orthognathic surgery. Therefore, in this study, automated landmarking was not considered and specific anatomical points, which were not affected by surgery, were used for the analysis of maxillary stability.

The 3D radiographic scanning provides a more realistic representation of the patient’s face and has provided an insight for the diagnosis and management of dentofacial deformities. During the last decade, CBCT has been used routinely in oral & maxillofacial surgery because of its reduced radiation dose in comparison to the multi-slice computed tomography (MSCT) (Van Vlijmen et al, 2010). In comparison to MSCT, CBCT reduces the exposure to ionizing radiation without compromising on the quality of the captured image (Sukovic, 2003). It is also used for the diagnosis of orofacial clefts and in orthodontic 3D analysis (Aksoy et al, 2016).

The introduction of CBCT in combination with planning software tools, facilitated the preoperative orthognathic planning. The 3D prediction planning for the surgical correction of dento-facial deformities has gained popularity in recent years (Naudi et al, 2013). The prediction of magnitude and direction of the surgical movements, as well as prediction of the expected soft tissue changes, has improved the communication between orthodontist, surgeon, and patient (Stokbro et al, 2014). Furthermore, the superimposition of the preoperative and postoperative 3D CBCT can be used to evaluate skeletal changes following orthognathic surgery. Unlike conventional cephalometric radiographic analysis, the iterative closest point (ICP) algorithm of voxel-based registration (VBR) or surface-based registration (SBR) allows a precise superimposition of corresponding 3D CBCT images for assessment of surgical movements and stability (Section: 1.1.1 and 1.1.2) (Dot et al, 2020).

In this study, to measure the skeletal changes, the SBR of CBCT images was applied. The superimposition of 3D CBCT images to compare hard tissue changes showed good reliability and reproducibility of measurements. Almukthar et al. (2014) performed a comparison between voxel-based and surface-based registrations. Both methods were based on the ICP algorithm for superimposition of 3D surface models of the hard tissues. There was a strong positive correlation between VBR and SBR hard tissue superimpositions ($r = 0.886$). The superimposition of the hard tissue models did not show variability between the two methods, and SBR for hard tissue was as accurate and consistent as VBR (Almukhtar et al, 2014).

Koerich et al. (2016) assessed the accuracy and reproducibility of the 3D CBCT superimposition methods using ICP algorithm and colour maps. The intra-class correlation coefficient of the repeated superimposition of the corresponding radiographs was higher than 0.98, indicating reproducibility of the 3D CBCT superimposition (Koerich et al, 2016).

The 3D method that was applied for the assessment of the maxillary surgical movement and relapse in this study was novel and has been developed and validated within this PhD project. The method utilised the ICP algorithm for SBR, which proved reproducible, and accurate in analysing the skeletal changes in three dimensions. The 3D analysis of maxillary translation and rotations was based on the landmarks that were not subjected to remodelling and therefore considered stable reference points. The 3D triangle was constructed by valid and reproducible landmarks including the incisive foramen and greater palatine foramina bilaterally. The virtual triangles constructed on the bony surface of the maxilla allowed a more accurate assessment of the changes following surgery. The assessment of maxillary movements in six directions of rotation included pitch, role, and yaw. The results showed an excellent correlation (>0.9) between the repeated measurements. The Bland-Altman plots showed that the mean difference for repeated measurements of the translational and rotational movements was close to zero, thereby confirming the reproducibility and the reliability of the method.

To maintain the homogeneity of the sample only Le Fort I maxillary advancement cases were included in the study. All followed the same approach and similar direction of the surgical movement of the maxilla to facilitate the interpretation of postsurgical movements and the achieved stability. Skeletal relapse of 1mm at six months was considered to be clinically significant in this study, whereas the level of statistical significance for relapse has generally been set at 2mm in the literature. The rationale for this was the recognition that relapse of 1mm is a third of a 3mm surgical movement. In addition, 2D cephalometric analysis, has a large margin of error (2mm) due to magnifications, distortions, and inaccuracies in landmark identification. In this study, which contributed to the robustness of the 3D analysis. It is important to quantify the errors of the method for the accurate interpretation of the results.

4.3 ASSESSMENT OF SKELETAL STABILITY

Multiple studies reported that most relapse occurs during the first 6 months postoperatively, when bone healing, physiological adaptation, and post-surgical orthodontics have the potential to affect skeletal stability. (Dowling et al, 2005; Fahradyan et al, 2018; Jakobsone et al, 2011; Kim et al, 2014b; Zhou et al, 2016) Therefore, in this study, the 6-months post-operative CBCT scans provided invaluable information regarding the stability of the archived surgical movements of the maxilla.

Recently, two studies (Liao et al, 2022; Lo et al, 2019) reported on 3D evaluation of the relapse at completion of orthodontic treatment in skeletal class III patients who underwent bi-maxillary surgery, Le Fort I maxillary advancement and bilateral sagittal split mandibular setback.

The study by Lo et al. (2019) assessed the skeletal stability in forty-two patients who underwent the surgery-first approach. The relapse at debonding showed that maxillary stability was good in the vertical direction while significant posterior relapse occurred at point A (1.0 ± 0.9, $P<0.001$) and ANS (1.5 ± 1.2, $P<0.001$).

The surgical maxillary movement of 2.1 ± 1.6mm was measured at ANS and point A respectively, while the vertical movement was limited to 0.5 ± 1.8mm. Therefore, the relapse in their study was at least 50% of the total horizontal surgical movement. This is an interesting finding, which highlights the concept that relapse still occurs despite the limited surgical movements.

The study by Liao et al. (2022) reported negligible relapse of the maxilla in all directions (<0.5mm and <0.5°) for 58 SFA patients. The relapse of the mandible was -1.9 ± 1.7mm forwards, 1.3 ± 1.5mm upwards, and $-3.1\pm2.4°$ of counter-clockwise rotation, which was significant ($p<0.001$). However, the maxillary surgical movement was limited to 1.8 ± 1.4mm advancement. In contrast to the study by Lo et al. (2019), smaller relapse was reported despite the similar magnitude of maxillary advancement.

It is difficult to compare the results of this project with these two studies, due to the difference in the magnitude of the surgical movement, the dissimilarity of the selected landmarks for the analysis, and the type of surgical correction. The magnitude of maxillary advancement in our study was 6.79 $\pm$ 2.30mm for SFA and 6.75$\pm$1.56mm for OFA, while in the two studies the maxilla was advanced by 2.1 ±1.6mm and 1.8±1.4mm respectively. Mandibular stability may impact on the relapse of the maxillary surgical movements. The patients included in the two previous studies must have had different types of deformity, which required bi-maxillary surgical correction. The majority of their cases had mild maxillary deficiency and most of the correction was based on mandibular set back. Their studies didn't report on the method of CBCT registration, which is important in 3D analysis of skeletal changes.

Class III is the most common dentoskeletal malocclusion that was reported in the literature. Mid-face hypoplasia has a higher prevalence in the Asian population than in the white population. Most of the studies (>90%) were undertaken in Asia, specifically in Taiwan, South-Korea, China, and Japan.

The bi-maxillary surgery (Le Fort I osteotomy and bilateral sagittal split osteotomy) was the most frequently performed surgery (>70%). In most of the studies the stability was assessed following bi-maxillary osteotomy (Barone et al, 2021). There are facial variations among ethnic and racial groups (Lee et al, 2011). The normal Asian facial profile is often described as flat or straight with upper and lower lip fullness. This may explain the high rate of bi-maxillary surgery in the published literature, while the predominance of maxillary Le Fort I surgery in the current sample was due to the prevalence of maxillary retrognathism associated with skeletal class III deformities in the West of Scotland.

4.3.1 The post-surgical wafer and occlusal considerations

There is a considerable debate in the literature regarding the importance of the guiding occlusal wafer during the first few weeks after surgery (Hernández-Alfaro et al, 2014; Nagasaka et al, 2009). There is not enough evidence that maintaining the occlusal wafer, during the post-operative period, contributes to skeletal stability. Multiple studies have recommended maintaining a surgical occlusal wafer to improve postoperative stability for the SFA patients (Ann et al, 2016; Baek et al, 2010; Kim et al, 2014a; Park et al, 2016).

In a study by Baek et al. (2010), the 2D cephalometric analysis of 11 patients who underwent bi-maxillary surgery, all following the SFA, showed a statistically significant horizontal relapse of 1.15mm (P<0.03) measured at point A, and 2mm (P<0.01) measured at Pogonion. The maxillary advancement was limited to 1.30mm, while mandibular setback was 10mm.The authors reported some post-operative occlusal interferences have contributed to the relapse and highlighted the importance of the occlusal wafer following the surgery-first approach to achieve stable occlusions and to prevent the possibility of skeletal relapse (Baek et al, 2010). However, there was no control group to compare the effectiveness of the wafer in preventing relapse. There was no report on objective assessment of occlusal quality and its correlation with the measured relapse. It is difficult to draw a robust conclusion based on a limited number of SFA patients who had minimal maxillary advancement (1.30mm) measured at point A and ANS. Point A is subject to remodelling, while ANS is trimmed during surgery. Although the occlusal wafer was kept in place for 4 weeks following surgery, the measured relapse was almost 100%. Its impact on the stability of orthognathic surgery, therefore, was debatable.

Similarly, Kim et al., (2014), reported that the surgical wafer was kept attached to teeth for 2 weeks post-operatively, which contributed to the limited maxillary relapse of 0.32mm and 0.6mm at point A and ANS respectively, at 6 months following surgery. However, the 37 SFA cases underwent maxillary advancement of 0.8 ±1.3mm without notable vertical movements.

Most of the surgical movement was associated with mandibular setback (mean=11.2 ± 5.4mm) with reported relapse of 2.9±1.4mm (Kim et al, 2014b).The limited relapse was associated with 0.8mm maxillary advancement measured at point A and ANS. The selected landmarks undergo changes as a result of surgery and orthodontic treatment. The 2D cephalometric analysis is prone to magnification, distortion, and inaccuracy of landmark localisation. The effectiveness of the occlusal wafer in minimizing the relapse is therefore questionable, because the magnitude of advancement is relatively small (mean=0.8mm).

Park et al. (2016) stated that the unstable occlusion following the SFA may hinder long-term skeletal stability, leading to relapse. This was based on their comparative study between 20 SFA and 20 OFA cases. All the cases had bi-maxillary osteotomy for the correction of skeletal class III malocclusion. To overcome the relapse in SFA cases the maxillary occlusal wafer was kept in place for 4 weeks following surgery, They reported posterior relapse of the maxilla of 1.422±2.238mm in the OFA cases and 1.169± 2.307mm in the SFA cases, measured at PNS 6 months post-operatively. (Park et al, 2016). Considering the mean anterior advancement of the maxilla (3.07 to 3.52mm), the reported relapse was almost 50% of the total movement. This highlights the limited impact of the occlusal wafer on maxillary stability. The study did not report on occlusal characteristics of SFA patients that may have contributed to the relapse following surgery. No significant differences in the stability between SFA and OFA patients were reported. This might have been as a result of the mild deformity and the limited surgical movements.

Ann et al. (2016) reported the same antero-posterior relapse at PNS in 12 SFA and 12 OFA patients who underwent bi-maxillary osteotomy. The authors stated that the inter-maxillary wafer was kept in place for 2 weeks after surgery, which contributed to similar relapse in SFA patients. Both groups showed minor horizontal relapse of the maxilla (0.14±0.66mm) measured at PNS, and significant relapse of 0.78±0.62mm in the OFA, and 0.68±1.02mm in the SFA ($P<0.01$) measured at ANS, during the first post-operative year. However, the maxillary advancement was limited to 1.28mm in the OFA and 2.06mm in the SFA.

The surgical maxillary impaction measured at PNS was 5.7mm in the OFA and 5.3mm in the SFA, with relapse of 0.59±0.78 mm in the OFA and 0.63±0.58mm in the SFA, which was statistically significant $P<0.01$ (Ann et al, 2016).

The relapse of less than 1mm might be due to the limited advancement of the maxilla (1.28mm to 2.06mm). However, in our cohort, despite the larger maxillary advancement (mean=6.79mm), the relapse was less than 1mm. It is important to highlight that in our cases, the occlusal wafer was not used after surgery which supports the argument that its impact on the maxillary stability is doubtful, contrary to what has been reported by Ann et al. (2016), and Kim et al. (2014). In their studies the impact of the quality of postoperative occlusion on the stability of the results was not assessed.

Wolford et al. (2020) recommended the use of a surgical wafer to enhance the skeletal stability in multiple segmental maxillary or mandibular osteotomies, and in surgical narrowing or widening of the maxilla or the mandible. It has been also recommended for occlusal support when teeth are missing in a particular quadrant. In addition, an occlusal wafer could be helpful in cases with severe attrition or erosion (Wolford, 2020). However, no evidence was provided to support these recommendations.

Likewise, Alfaro et al. (2014) recommended the limited use of an occlusal wafer for 2 weeks post-operatively following segmental maxillary osteotomy only (Hernández-Alfaro & Guijarro-Martínez, 2014).

However, Nagasaka et al. (2009) (Nagasaka et al, 2009) proposed the routine use of an occlusal wafer post-operatively, to improve the stability of the occlusion in the SFA. The authors did not detect an increase in maxillary relapse without using the occlusal wafer. On the other hand, it has been suggested that the period of postoperative occlusal stabilization with the surgical wafer should be minimized, to take the advantage of any enhanced tooth movement facilitated by the regional acceleratory phenomenon (Hernández-Alfaro et al, 2014).

The regional acceleratory phenomenon (RAP) is a complex physiologic process including an accelerated bone turnover and reduced regional bone density due to an increased rate of remodelling (Keser & Naini, 2022). RAP increases tissue reorganization and healing by transient bursts of localized osteoclastic and osteoblastic activities, which start at 1 week and 1 month following surgery, respectively. Orthognathic surgery triggers 3 to 4 months of RAP in the dento-alveolar region, which accelerates postoperative bone resorption and apposition in response to orthodontic forces (Liou et al, 2011). The use of an occlusal wafer beyond the first two weeks following surgery may interfere with the orthodontic tooth movement which may commence in the early postoperative phase in SFA patients.

4.3.2 Minimal preoperative orthodontic treatment (MPO)

Minimal preoperative orthodontic treatment (MPO) has been suggested on the basis that the instability of postsurgical occlusion will reduce the stability of the achieved surgical movement in SFA. Wang et al. (2010) commented on the importance of 2 to 6 months preoperative orthodontic treatment to minimize the occlusal interferences, resolve the major crowding, and enhance the arch coordination (Wang et al, 2010). In this context, dental extractions to reduce the severe crowding, space closure, and decompensations of midline deviations was considered to improve the quality of post-operative occlusion. It has been highlighted that the accurately fitting occlusion might help to maintain the osteotomy segments in the achieved postsurgical position. (Sugawara et al, 2010).

Some studies (Jeong et al, 2018; Joh et al, 2013; Park et al, 2015; Zhou et al, 2016) claimed that a higher relapse rate is associated with SFA due to occlusal instability, or vertical and transverse arch discrepancies. They recommended that 2 to 6 months of MPO should reduce the relapse in SFA. However, the correlation between the quality of occlusal contacts and the surgical stability was not assessed. The criteria for the assessment of the post-operative occlusion were not defined in these studies.

Park et al. (2015) compared the relapse at debonding between 19 SFA and 19 OFA patients who underwent bi-maxillary surgery. The maxillary horizontal and vertical relapse was <1mm, which was not statistically significant. The study concluded that the Le Fort I maxillary posterior impaction in skeletal class III patients is a highly stable procedure. In their study, the maxillary antero-posterior surgical movement, measured at PNS, was limited to 1.2mm in OFA and 0.1mm in SFA, and posterior impaction was measured at 4.5mm in OFA and 3.8mm in SFA. The MPO of an average of 3 months was carried out in SFA patients. Immediately after surgery, there was no significant difference in overjet (3.68mm vs 3.16mm) and overbite (1.40mm vs 1.46mm) for OFA and SFA respectively (Park et al, 2015). One of the limitations of this study was the small maxillary surgical movement. Larger surgical movements may have shown more relapse. The strict definition of the SFA was not observed in this study as all the patients in the SFA group had MPO. The correlation between maxillary stability and post-operative overjet and overbite was not assessed.

Jeong et al. (2018) found no differences in changes at point A at 1 year following surgery in 14 OFA and 17 SFA patients who had bi-maxillary osteotomy. The surgical maxillary advancement was limited to 0.8 ± 2.2mm in the OFA group and 0.1 ± 2.7mm in the SFA group. The authors reported that 3 months of MPO was carried out to overcome the higher relapse associated with SFA. The final wafer was removed 3 weeks following surgery (Jeong et al, 2018). The magnitude of maxillary advancement was less than 1mm, which is relatively small to draw a robust conclusion about the relationship between MPO and maxillary stability. The accuracy of 2D analysis to detect relapse of less than 1mm is questionable, as the margin of measurement error is within 2mm. Furthermore, the study did not comment on the characteristics of postoperative occlusion and its relationship with the stability of the surgical outcome.

The following three studies (Zhou et al., 2016, Kim et al., 2014, Joh et al., 2013) debated the importance of the minimum preoperative orthodontic treatment (MPO) in the SFA. Zhou et al. (2016) compared 20 SFA and 20 OFA bi-maxillary cases. At 12 months following surgery, there was no significant difference in relapse measured at point A (*P*:0.29). However, the SFA patients underwent 3 months of MPO and the forward movement of the maxilla was limited to approximately 3mm, measured at point A (Zhou et al, 2016).

In a study by Kim et al. (2014) 37 SFA patients, who underwent bi-maxillary surgery, showed less than 0.2mm of relapse at 12 months follow-up. However, the measured surgical movement of the maxilla at point A was 0.75 ± 1.3mm anteriorly, and 0.21 ± 1.79mm superiorly. Furthermore, the SFA cases underwent 2 months of MPO. There was no control group to compare the impact of pre-operative orthodontic treatment on the relapse (Kim et al, 2014b).

In a comparison of 16 OFA with 16 SFA, who underwent bi-maxillary surgery, Joh et al. (2013) reported similar stability measured at the time of debonding. However, the SFA patients underwent 6 months of MPO and the extent of the maxillary surgical movement and relapse were not reported (Joh et al, 2013). The PAR index for occlusal evaluation of the pre-operative dental casts showed no significant difference between the 2 groups. This is understandable, since the MPO carried out in the SFA patients had provided a similar baseline occlusion for the assessment.

These studies didn’t report on the correlation between relapse and immediate post-operative occlusion. The strict definition of SFA does not include the MPO. Therefore, it is expected that the immediate postoperative occlusion is less than ideal, which is considered in the prediction planning. This requires a comprehensive 3D surgical simulation and planning, clear interdisciplinary communication, close postoperative follow-up, and an accurately manufactured occlusal wafer to guide the surgical procedure.

In our SFA cohort of patients no pre-surgical orthodontic treatment was considered. However, careful patient selection was considered a critical factor for the success of SFA. The 3D digital evaluation to establish an effective treatment plan was performed for patients both in SFA and OFA groups. Furthermore, the feasibility of the correction of the post-operative occlusion (secondary malocclusion) was carefully evaluated. The orthodontist was experienced in using temporary anchorage devices, such as mini screws, which were used routinely as part of the SFA management protocol.

4.3.3 Selection Criteria for the surgery first approach:

In our study, the selection criteria for the SFA were largely dependent on the experience of the surgeon and the orthodontist. There is no consensus on the indications and contraindications for the SFA (Choi et al, 2019). The patients with well-aligned to mildly crowded anterior teeth, flat to mild curve of Spee, normal to mild incisor proclination or retroclination and adequate transverse relationship of the dental arches were considered suitable candidates for SFA (Liou et al, 2011; Uribe & Farrell, 2020). Baek et al. (2010) reported that the SFA is indicated when there is only little or no transverse discrepancy, no extractions involved, and at least three occlusal contact points between the dental casts (Baek et al, 2010).

Choi et al. (2015) suggested that severe dental crowding, severe transverse discrepancy requiring surgically assisted rapid palatal expansion, accentuated or asymmetric curves of Spee of the upper dental arch, are contra-indications to SFA. Class II division 2 malocclusion with deep overbite that needs extractions is also considered a contraindication for SFA (Choi et al, 2015). In our cases, dental extractions are carried out, when indicated, during surgery, and are not considered to be an absolute contra-indication to SFA.

Significant facial asymmetry with chin deviation was reported as a contraindication for SFA. However, some authors have shown that SFA could be successfully applied to the cases with severe facial asymmetry (Uribe et al, 2013; Watanabe et al, 2019). It is still unclear how much of asymmetry or transverse discrepancy could be pre-planned and completed successfully with SFA (Jeong et al, 2017). The relative contraindications for SFA include the presence of premature contacts or high points as well as uneven tooth wear (Lima et al, 2010). In the cases which require root separation to allow segmental osteotomies, a short course of MPO may be required. These clinical scenarios might lead to an unsatisfactory orthodontic result and are, therefore, considered contraindications for SFA (Benington et al, 2023).

4.3.4 The duration of the treatment:

The SFA is advantageous for the management of class III skeletal deformity. It has been reported that when these patients are treated with the conventional approach, involving preoperative dental alignment, arch coordination, and decompensation, the treatment time is prolonged, adversely affecting the patients' quality of life (Saghafi et al, 2020). **Figures 41 and 42** show the profile and occlusion of a skeletal class III OFA patient, in whom pre-operative orthodontic preparation accentuated the prognathic profile. The profile and occlusion of a skeletal class III SFA patient are shown in **Figures 43 and 44**. The pre-operative orthodontic phase is eliminated and an immediate improvement in the facial profile is noticed.

Figure 42. The facial profile of skeletal class III orthodontic-first approach patient. A: Facial profile before start of orthodontic treatment. **B:** Facial profile after completion of pre-operative orthodontic treatment and before the surgery, demonstrating the worsening of the facial deformity. **C:** Facial profile at the completion of post-operative orthodontics and debonding, demonstrating the improved facial profile.

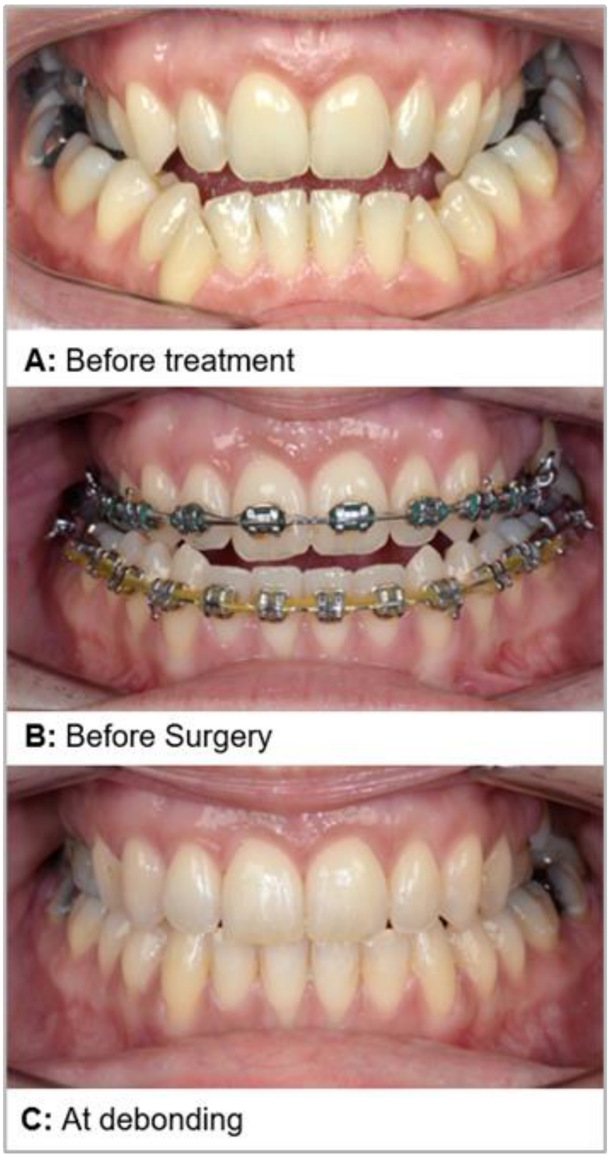

Figure 43. The occlusion of skeletal class III orthodontic-first patient. A: The occlusion before start of orthodontic treatment. **B:** The occlusion after completion of pre-operative orthodontic treatment and before the surgery, demonstrating the increase in reverse overjet. **C:** The occlusion at the completion of post-operative orthodontics at debonding, demonstrating the improved overjet and overbite.

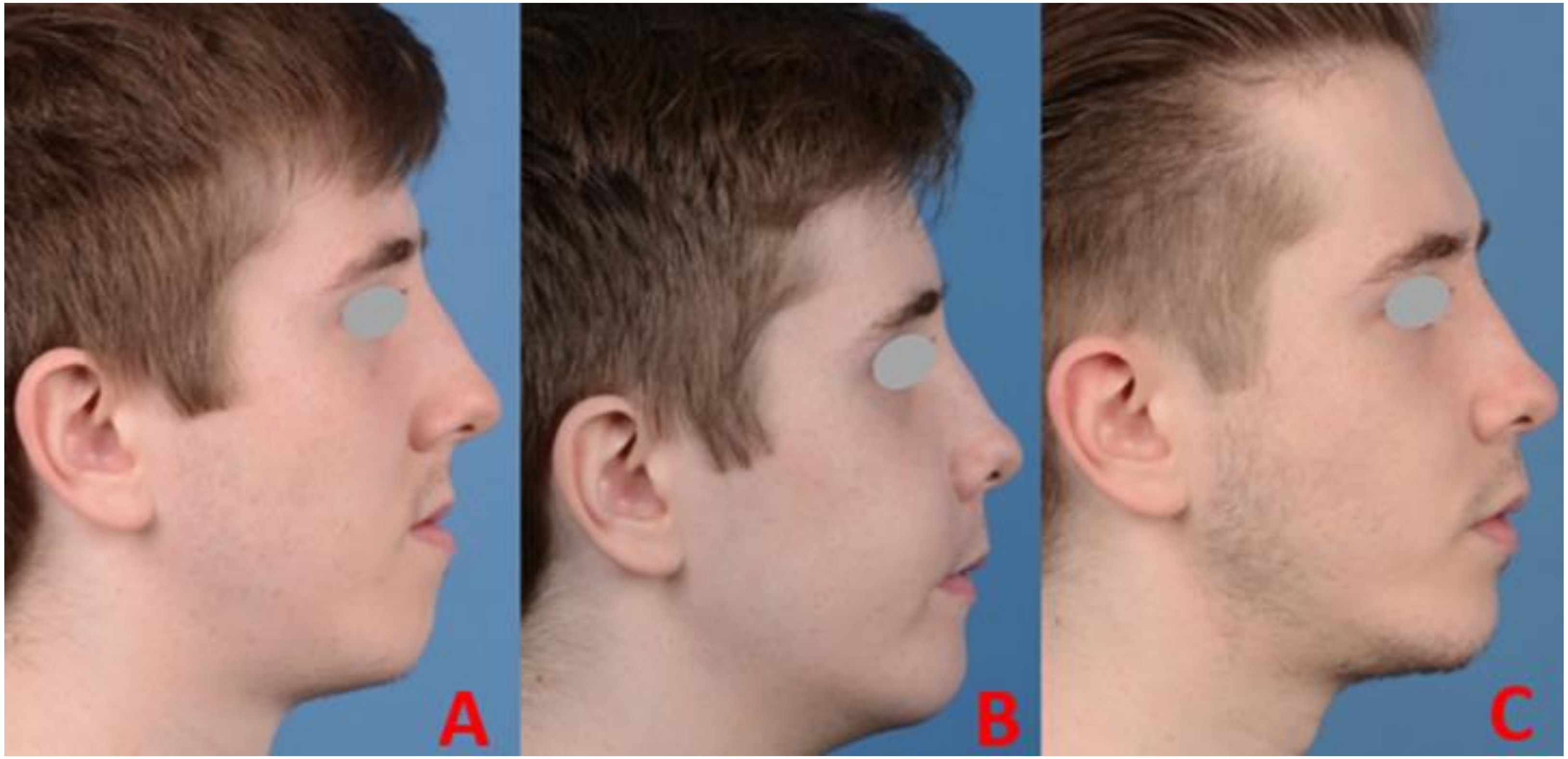

Figure 44. The facial profile of skeletal class III surgery-first approach patient. A: Facial profile before surgery. **B:** Facial profile at 1-week following surgery, demonstrating the immediate improvement. **C**: Facial profile at the completion of post-operative orthodontics at debonding, demonstrating the final facial profile.

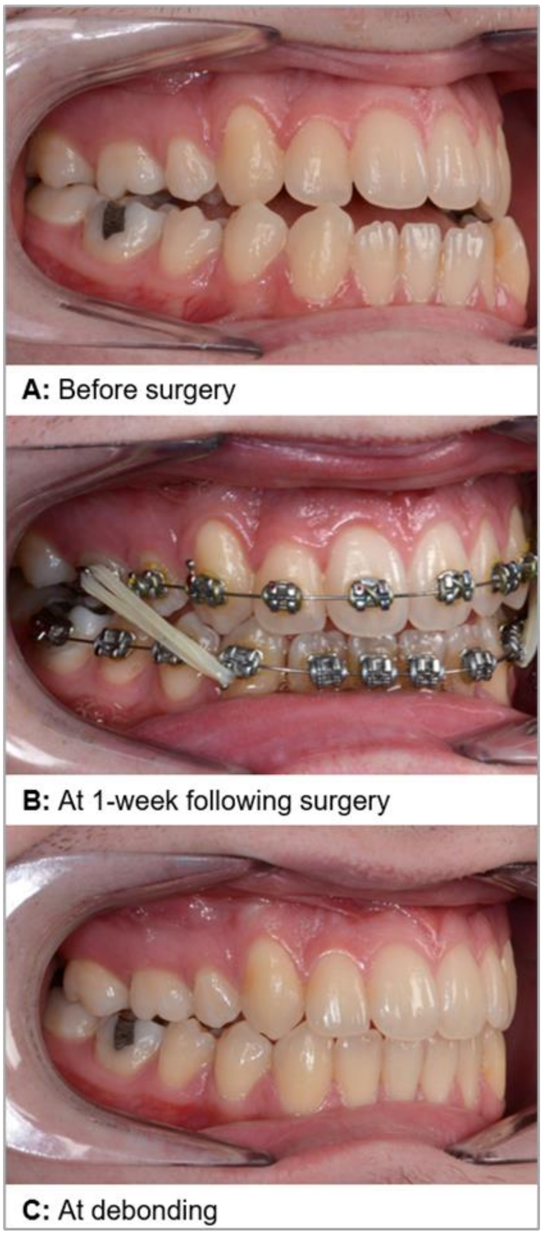

Figure 45. The occlusion of skeletal class III surgery-first patient. A: The occlusion before start of orthognathic treatment. **B:** The occlusion at one week following surgery and start of orthodontic treatment. **C:** The occlusion at the completion of post-operative orthodontics at debonding, demonstrating the improved overjet and overbite.

In conventional orthognathic treatment, the surgical hooks, placed on the orthodontic arch wires, are commonly used to facilitate the application of inter-maxillary elastics. Inter-maxillary traction is often important in counteracting the effect of the stretched muscles on the osteotomy segments (Girard et al, 2022; Wolford, 2020). In the SFA, the orthodontic arch wires are thin and flexible and do not allow the application of hooks, which is not the case in OFA. In SFA cases, bone anchorage is used instead of the surgical hooks (Kwon & Han, 2019). Bone screws, or temporary anchorage devices (TADs), allow the traction to be applied to the skeletal bases of the osteotomy segments, rather than the teeth. Zhou et al. (2016) explained that running elastics between TADs in the early postsurgical stage were effective in achieving favourable horizontal stability of the maxilla in the SFA group. The authors reported that the SFA increases the risk of relapse due to the relatively poor postsurgical occlusion (Zhou et al, 2016). Similarly, Alfaro et al. (2011) reported that temporary anchorage devices permit a wider range of orthodontic vectors and avoid premature bracket loading, which is advantageous in the early post-surgical phase (Hernández-Alfaro et al, 2011).

In summary, there are similarities between the previous studies; inclusion of bi-maxillary cases, the use of an occlusal wafer postoperatively, minimum pre-operative orthodontics for 3 to 6 months, and the small maxillary surgical movements. Furthermore, the analysis of stability and relapse was limited to 2D cephalometric analysis. Considerable heterogeneity exists in the literature, including the differences in skeletal deformity (Class II and III), the length of follow-up, and the variability in cephalometric reference points, planes and angles used for the analysis. The evaluation of stability following orthognathic surgery, with the SFA, requires further research, avoiding the previous limitations. A set of stable landmarks should be considered in future analyses. It is important to review the cases with CBCT scans at standard follow-up appointments. A homogenous sample and unified pre- and post-operative surgical and orthodontic criteria are necessary for future studies for the assessment of the stability of SFA.

4.4 RELATIONSHIP BETWEEN RELAPSE AND MAXILLARY ADVANCEMENT

In this study, a weak correlation was noted between relapse and magnitude of maxillary advancement in SFA (r=0.204) and OFA (r=0.578). The systematic review by Guijarro et al. (2016), which included 295 SFA patients, reported that relapse greater than 3mm was detected in 40% of the SFA cases in comparison to 16% of the OFA cases. However, surgical relapse below 1.5mm was more common in OFA cases (Peiro-Guijarro et al, 2016). On the other hand, we noted relapse below 1.5mm in 96% of SFA cases and all the OFA patients. In our study, the 3D method of assessment and the fact that our study group was limited to Le Fort I maxillary advancement only, may have contributed to this difference.

The study by Fahradyan et al. (2018) included 35 skeletal class III OFA cases, who underwent Le Fort I osteotomy in 46% of cases and bi-maxillary osteotomy in 54% of the cases. The study reported a positive correlation between the amount of maxillary horizontal advancement (mean=6.3mm) and relapse (mean=2.0mm). The authors reported that it is expected that 6 to 7mm of maxillary advancement will relapse by 2mm (28.6%). Hence, overcorrection should be considered. Furthermore, they suggested that bi-maxillary surgery might be considered when more than 6 to 7mm of maxillary advancement is required (Fahradyan et al, 2018). However, most of the landmarks that were used for the 2D cephalometric measurements were altered as a result of the surgical procedure, and this may have increased the risk of measurement errors.

The findings of our study showed excellent stability of Le Fort I maxillary advancement with both SFA and OFA. The magnitude of horizontal advancement was 6.79±2.3mm in the SFA cases and 6.75±1.56mm in the OFA cases. Nevertheless, the patients who underwent advancement with inferior repositioning (mean=1.31mm) showed slightly more relapse in the superior direction (mean=0.63mm) than those who had simultaneous maxillary impaction (mean=1.26mm), where mean relapse was 0.51mm.

The vertical relapse is likely to be related to the stretch of the soft tissues and musculature, which have been known as contributory factors that impact on maxillary stability (Akamatsu et al, 2016; Romero et al, 2020). In the majority of the cases the maxillary relapse was within 1mm and 1° following Le Fort I advancement, regardless of the direction of the vertical surgical movement. The small vertical surgical movement of the maxilla might have also contributed to the noted stability.

The absolute mean of the maxillary pitch rotation in SFA cases was $1.86\pm1.88°$ with total relapse of $1.56\pm1.42°$ (P=0.007). Fifty-six percent rotated in the downward (clockwise) direction (mean: 2.35°), which relapsed in the upward (counterclockwise) direction (mean: 1.49°). This could be related to the increase of the lower anterior facial height with the clockwise surgical rotation "Pitch" of the maxilla. This surgical movement stretches the soft tissues and creates an anterior gap between the anterior part of the maxilla and the base of the nose, which might have led to the detected relapse in the counterclockwise direction. However, there was a poor correlation (r=0.271) between pitch surgical rotation and the relapse.

Overall, the translational and rotational movements showed a clinically acceptable level of relapse and a poor correlation with magnitude of movements, further confirming that Le Fort I advancement is a stable procedure.

In contrast, Dowling et al. (2005) suggested overcorrection should be considered in large maxillary advancements. The authors reported on the relapse of Le Fort I maxillary advancement of 43 patients who followed the OFA with mean surgical movement of 4.9mm measured at point A. The study showed that surgical advancement of 4mm or more resulted in a horizontal relapse of 1.6mm, although this was limited to 0.2mm when the surgical advancement was less than 4mm. The result showed that maxillary advancement is generally stable, with the relapse primarily being influenced by the magnitude of the surgical advancement (Dowling et al, 2005). However, in our study 92% of OFA cases relapsed within 1mm, while they underwent maxillary advancement of 4 to10mm.

Similarly, Chen et al. (2018) reported a positive weak correlation (r=0.461) between relapse at point A and the surgical maxillary advancement. The findings were based on the analysis of 35 OFA patients who underwent bi-maxillary surgery. The mean maxillary advancement at point A was 3mm, and mandibular setback at Menton was 8.5mm. The authors reported on the correlation (r=0.388) between mandibular relapse (mean: 3.3mm) and the magnitude of mandibular setback (Chen et al, 2018). The 2D measurements utilizing landmarks that could be altered by surgery and orthodontic treatment may have impacted on their results. Furthermore, the magnitude of maxillary advancement was limited to 3mm, and it may be that larger movements might have produced a different outcome.

The study by Liao. (2022) showed that the magnitude of surgical maxillary yaw and roll were negatively correlated (r=-0.555, *P*=0.001) with their rotational relapse at 1-year postop follow-up. No correlation was detected between the magnitude of maxillo-mandibular relapse and the horizontal surgical movements. However, the horizontal maxillary advancement was 1.8±1.4mm, and mandibular setback of 7.3±4.5mm (Liao et al, 2022). Similarly, we noted a weak correlation (r=0.204) between the magnitude of maxillary advancement and the horizontal relapse at 6 months postoperatively. In our OFA cases, there was a moderate correlation (r=0.654, *P*=0.015) between magnitude of surgical maxillary pitch and its rotational relapse after 6 months. This might have been due to the small sample size.

In our study, the percentage of the relapse in relation to the surgical movement was calculated as: (T1-T2) x 100 / (T0-T1). The relapse ratio was less than 10% of the total maxillary advancement in 15 SFA cases and in 11 OFA patients. The 2 SFA patients who showed a relapse ratio greater than 20% of the total surgical movement, had a limited maxillary advancement of 4.50 and 4.75 mm respectively. This shows that there was no relationship between the magnitude of surgical advancement of the maxilla and the relapse measured at 6 months following surgery. Our findings do not support the concept of overcorrection of the maxilla to compensate for skeletal relapse in SFA maxillary advancement. We did not detect a relapse ratio greater than 20% in the OFA patients. We acknowledge these findings might be due to small sample size.

4.5 RELATIONSHIP BETWEEN RELAPSE AND THE QUALITY OF IMMEDIATE POSTOPERATIVE OCCLUSION

Several advantages of surgery-first approach have been reported in the literature(Akamatsu et al, 2016; Romero et al, 2020). The direction of the postsurgical orthodontic movement is in line with muscular forces from the lip and the tongue, thereby decreasing the time for orthodontic dental decompensation (Seifi et al, 2018) (Lee, 1994; Liao et al, 2010). According to the regional acceleratory phenomenon (RAP) immediately after correcting the skeletal discrepancy, the increase in bone turnover rate allows more rapid tooth movement (Zingler et al, 2017) . The worsening of the facial profile that inevitably occurs during the pre-surgical orthodontic treatment, especially in class III cases, is eliminated in the SFA (Anwar et al, 2022). However, the sub-optimal quality of the post-operative occlusion was reported as the main drawback of the SFA, and a potential cause of the skeletal relapse (Wei et al, 2018).

The review of the literature shows that the assessment of the relationship between occlusion and relapse was based on the planned or preoperative occlusion rather than the immediate occlusion following surgery (Cartwright et al, 2016; Ponduri et al, 2011). It was reported that the maxillary and mandibular stability was not related to the pre-operative overjet and overbite, nor the planned occlusion. The literature characterised the occlusal stability according to the incisal inclination, overjet, and overbite (Baek et al, 2010; Seifi et al, 2018). The occlusal contact was defined as an inter-occlusal distance of <0.2mm (Liao et al, 2022) which does not characterise the quality of occlusal contact.

In our study, the 3D analysis allowed the comprehensive description of the quality of the post-operative occlusion. The overjet and overbite, the number of teeth in occlusal contact, and the regions of occlusal contacts, have clearly described the quality of inter-digitation and occlusal contacts (Saghafi et al, 2024). The novel generation of the occlusal map has a broad clinical application in orthognathic surgery and other occlusion-based studies. This would not have been possible without the replacement of the defective dentition of the immediate postoperative CBCT scans with the images of the scanned dental models.

Cone Beam CT imaging has the drawback of being prone to distortions around the dentition (Wiranto et al, 2013). Metallic restorations and orthodontic appliances are the causes of streak artefacts seen around the dentition in the CBCT scans (Hirschinger et al, 2015). The replacement of the dentition using the IPS Case Designer® software package has proved to be of satisfactory accuracy (Baan et al, 2021a). In our study the excellent intra-examiner reproducibility (r=0.927) confirming the high reliability of the method.

4.5.1 The PAR index

The Peer Assessment Rating (PAR) has been used in several studies to assess occlusal outcomes in orthognathic surgery. However, the assessment was limited to OFA cases (Cartwright et al, 2016; Ponduri et al, 2011), with only three studies having assessed occlusal outcomes for SFA patients.

The study by Anwar et al. (2022) compared PAR scores between 20 SFA and 23 OFA Class III cases following completion of orthognathic treatment. They reported 90% and 88%, reductions of PAR score for the SFA and OFA respectively. The sample included Le Fort I maxillary advancement cases only. They recommended further assessments of other malocclusions and surgical procedures (Anwar et al, 2022).

Liao et al. (2010) measured the PAR score of 33 skeletal class III patients with AOB. They reported mean PAR score reductions of 88% for the 20 SFA cases and 92% for the 13 OFA cases (Liao et al, 2010). The baseline occlusion of the two groups was similar, in terms of overjet, overbite, and upper and lower incisor angles. In the study by Joh et al. (2013), there was no significant difference between the 16 SFA and 16 OFA cases regarding the quality of occlusion, before and after treatment, using the PAR index. However, in the SFA cases, 6 months of orthodontic treatment was carried out before surgery. This may have contributed to the similarity of the preoperative occlusal index between the groups (Joh et al, 2013).

Despite the reproducibility of the PAR index, it has a high weighting for overjet and low weighting for overbite. Therefore, its ability to comprehensively assess the occlusal characteristics is limited.

4.5.2 Measurements of overjet and overbite

In our study, we didn't detect differences in overjet and overbite between the OFA and the SFA group at 1 week following surgery. Similarly, in the study by Zhou et al. (2016), the 2D cephalometric measurements of 20 OFA and 20 SFA cases showed similar overjet and overbite at 1-week following surgery. However, their SFA cases received 3 months of pre-operative orthodontic treatment. At 12 months following surgery, the overjet was slightly higher in the OFA group (3.8mm in OFA versus 3.26mm in SFA), while the overbite was the same (2.08mm in OFA vs 1.79mm in SFA) (Zhou et al, 2016).

Likewise, the study by Park et al. (2015) showed similar overjet and overbite for 19 SFA and 19 OFA patients at 1 week postoperatively and at debonding. However, the SFA patients underwent 3 months of orthodontics treatment before surgery, which may have contributed to the recorded similarity in the overbite and the overjet corrections in the two groups (Park et al, 2015). Similarly, Akamatsu et al, 2016, reported that 14 SFA cases and 24 OFA cases, who underwent bi-maxillary surgery, had similar measurements of overjet (3.25mm vs 3.38mm, $P=0.732$) and overbite (1.60mm vs 1.65mm, $P=0.915$). The SFA patients underwent minimum pre-operative orthodontic treatment, which contributed to similar baseline occlusions in the 2 groups (Akamatsu et al, 2016).

In contrast, Ann et al. (2016) reported that at 1 month following surgery the overjet was significantly greater in the 12 SFA cases (4.83mm vs 2.63mm, $P<0.05$), whereas overbite was significantly greater in the 12 OFA patients (1.49mm vs 0.21mm, $P<0.01$). They noted a reduction of the overjet by 1.84mm and an increase in the overbite by 1.80mm at 1 year following the surgery in the SFA patients (Ann et al, 2016).

Liao et al. (2010) compared the overjet and overbite in 13 OFA and 20 SFA skeletal Class III patients who underwent bi-maxillary surgery. They reported that overjet was larger in the SFA group than in the OFA group (3.0 $\pm$ 1.2mm versus 2.2 $\pm$ 1.1mm; P=0.02) at the time of debonding, while the two groups had similar overjet (5.4mm vs 5.8mm) and overbite (3.5mm vs 3.4mm) measurements at the start of the treatment (Liao et al, 2010).

Joh et al. (2013) reported that overjet at debonding was greater in 16 SFA patients (3.46 mm) than in 16 OFA patients (2.82 mm), which was statistically significant (P=0.009). This was similar to the overjet at 1-month post-operatively (4.19 mm for OFA vs 5.20 mm for SFA, P=0.02). The increased labial inclination of the maxillary incisors from 1 month to debonding might have contributed to this finding. The two groups showed similar overbite measurements at 1 month (2.63mm vs 3.04mm) and at debonding (2.78mm vs 2.49mm), which might be due to minimum pre-operative orthodontic treatment in the SFA group (Joh et al, 2013).

Park et al., 2014 reported a larger overjet of 9.25 mm for 24 SFA cases in comparison to 3.27 mm in 36 OFA cases (P=0.001) at 1-month post-op. Likewise, the overbite was 2.09mm in SFA cases and 1.29mm in OFA cases (P=0.04). At debonding, the overbite was 1.60mm in OFA and 2.15mm in SFA , (P=0.01) while the overjet was similar (2.91mm vs 3.14mm) (Park et al, 2014). This showed the bimaxillary surgery was carried out with mandibular over correction to allow the decompensation of the retroclined lower incisors.

The analysis of occlusion is limited to 2D cephalometric measurements of overjet and overbite, which are subject to magnification and distortion. The results show variability among studies, and the inclusion of bi-maxillary cases, with post-operative counter-clockwise mandibular rotation, have impacted the overjet and overbite measurements. Furthermore, the relationship between the skeletal stability and the immediate post-operative occlusions was not studied.

4.5.3 Measurements of occlusal contacts

This study has provided the first comprehensive report on the relationship between the quality of the immediate postoperative occlusion and the stability of the surgical advancement of the maxilla at Le Fort I level in SFA cases. We considered three criteria to characterise the quality of the occlusion, which included the distance between the opposing occlusal surfaces, the number of occlusal/incisal contacts, and the distribution of occlusal contacts across the dental arches. Each of these parameters have provided an insight into the quality of the achieved occlusion immediately following surgery (Saghafi et al, 2024).

Zhao et al. (2023) compared the number of occlusal contacts recorded by T-scan (Dental Prescale II) and intraoral scanner (Trios 3 Shape). They reported no differences between the two methods (Zhao et al, 2023). However, the two methods are dependent on the biting force for recording the occlusal contacts. The thickness of the foil of the T-scan sensor and the articulating paper could have impacted on the results. The study by Ayuso-Montero et al. (2020) reported that T-Scan is more reliable when the patients apply maximum occlusal force. Furthermore, the sensor film does not always show uniform sensitivity and requires adjustment before each recording to eliminate the potential differences from individual bite forces (Ayuso-Montero et al, 2020).

In a study by Tammataratarn et al. (2022) the number of occlusal contacts in 30 OFA, and 30 SFA, skeletal class III patients who underwent bi-maxillary osteotomy, was compared with 30 skeletal and dental Class I patients, which were considered the gold standard. Preoperatively, the T-scan analysis showed the number of occlusal contacts in the OFA group to be significantly lower (9.70 ± 3.34) than in the control group (11.97 ± 1.67, P=0.006). At 1 month following surgery, the number of teeth in occlusal contact for both groups (OFA=9.57, SFA=9.53) was similar but less than in the control group (11.97, P<0.05). At 1 year following surgery, there was no difference between the control group and the two study groups.

The orthodontic treatment that usually starts at two weeks following surgery in the SFA cases might have contributed to the noted similarity of the occlusal contacts in the two study groups at the end of treatment (Tammataratarn et al, 2022).

There are few studies (Agbaje et al, 2017; Manikandhan et al, 2023; Wiechens et al, 2023) which have assessed the occlusal contacts of orthognathic patients using T-Scan. However, the analysis of occlusion was limited to before surgery and at the completion of the post-operative orthodontic treatment. Furthermore, none of the studies have reported on the relationship between stability and the recorded occlusal contacts by T-scan (Tammataratarn et al, 2022; Zhao et al, 2023).

The T-scan has its limitations for the assessment of the quality of occlusion immediately following orthognathic surgery. The limited access, swelling, and inability of patients to exert sufficient biting force, are among these limitations. The T-scan has high sensitivity; Imamura et al. (2015) reported 40% reduction in the number of occlusal contacts when the maximum bite force was reduced by half (Imamura et al, 2015). It is not possible to assess the static occlusion. The T-scan software only generates a 2D image of the occlusal contacts relative to the applied bite force during dynamic occlusion. **(Figure 45)**

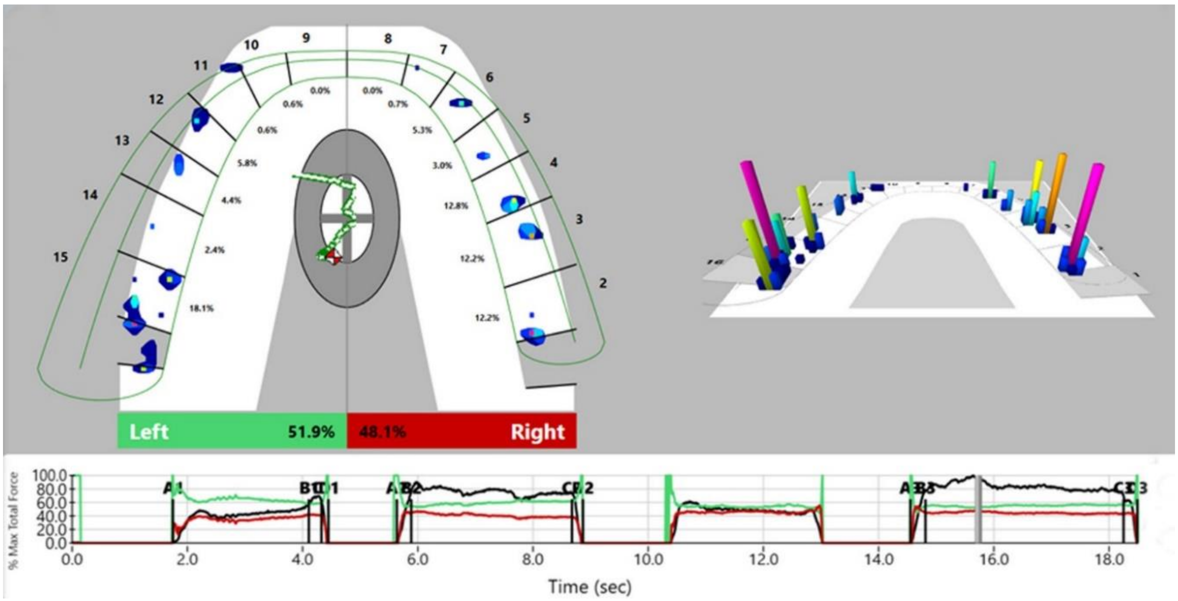

Figure 46. T-Scan desktop 2D Force View illustrating the left and right-side force percentage imbalance (51.9% left – 48.1% right).

Cao et al. (2023) reported that the sensor film of the T-scan did not show uniform sensitivity throughout the occlusal surfaces; it only records the distribution of biting pressure across the dental arches rather than accurate occlusal contacts. Furthermore, their patients reported that the discomfort of the bulky T-scan sensor had affected their occlusion (Cao et al, 2023).

In our study, the 3D analysis was based on the static occlusion obtained during CBCT scanning. The occlusal contacts were analysed more accurately, and objectively. In addition, it avoids the disadvantages of T-scan system to some extent, as it does not rely on the detection medium of sensor foil. By generating the 3D colour map based on the inter-occlusal distance of -0.5 to 0.5mm, the true occlusal contacts were assessed (Saghafi et al, 2024).

5 CHAPTER FIVE: CONCLUSIONS & SUGGESTIONS

This innovative study is based on the 3D analysis of the CBCT scans, which provided more comprehensive evaluation of skeletal stability. The 2D radiographs have several limitations including inaccuracy in superimpositions, distortion of images, and magnification. In the presented study the three selected landmarks allowed the quantification of the maxillary skeletal translational and rotational movements. These landmarks were not affected by orthodontic tooth movements or remodelling following the surgical procedure. The 3D landmark identification has been reported to show favourable validity and reliability (Park et al, 2019; Saghafi et al, 2024; Sam et al, 2019). Similarly, the intra-rater reliability of the 3D landmark identification in this study was excellent (ICC=0.99).

The generation of occlusal map and quantification of occlusal contacts provided a detailed analysis of immediate post-operative occlusion. This is the first time for this method to be reported in the English literature (Saghafi et al, 2024)

With recent developments in CBCT, virtual model surgery, and occlusal wafer fabrication for orthognathic surgery, the planning for SFA has become more accurate and predictable. It is our conclusion that SFA is stable following the correction of maxillary deficiency at Le Fort I level at 6 months postoperatively. There was a weak correlation between relapse and the magnitude of surgical movement. Likewise, we could not detect a strong correlation between the quality of occlusion and the relapse of maxillary advancement at 6 months following surgery. No significant statistical differences in the stability of the advanced maxilla were detected between OFA and SFA.

In this study, 48 class III patient who underwent Le fort I osteotomy were excluded from the study due defective or low quality CBCT images, scans taken beyond the 1 week or 6 months' time frame and missing CBCT scans due to Covid-19 Pandemic. The retrospective nature of the research sample and the policy of the Glasgow Dental Hospital regarding CBCT scans made it impossible to repeat the scan for any patient.

The sample size calculation showed a cohort of 20 subjects was required to detect at least 1mm of skeletal relapse. However, future studies with larger sample are required to further convince clinicians to shift to the Surgery-First approach for orthognathic treatment.

Future recommendations:

- The hierarchy of surgical stability needs to be revised based on the 3D method of skeletal assessment of different orthognathic procedures.
- The impact of different facial deformities, including class II and short-face syndrome, and surgical approaches, including bi-maxillary surgery and bilateral sagittal split osteotomy, on relapse should also be studied using the 3D method of assessment.
- Future studies should focus on assessing the skeletal movements and stability using the 3D methodology proposed in this thesis to reach a better understanding of the relapse associated with different surgical techniques.
- The evaluation of post-operative occlusions, using the variables defined in this thesis, provides a better understanding of the relationship between occlusion and stability in SFA orthognathic patients.
- Long-term stability, beyond 6 months following surgery, should be considered in future studies.

- Despite the fact that a prospective randomized trial would be considered as the “gold standard” for comparing OFA and SFA, we believe that there are ethical concerns around this type of research, since one approach is already deemed more efficient regarding the overall duration of treatment and patient satisfaction, without compromising facial aesthetics, occlusal quality, or skeletal stability.
- A multicentre study is needed to provide further evidence to change the approach of orthognathic treatments of dentofacial deformities. It is important to provide structured training for orthodontists to achieve this target. The availability of 3D software is essential to assess the skeletal stability and predict the occlusion immediately following surgery and at the completion of the treatment. The correction of postoperative occlusion of SFA, sometimes is referred to as ‘secondary malocclusion’ depends on the orthodontist judgement. Following surgery, orthodontic movements are faster due to surgical trauma which stimulates osteoclastic activity and the reduced resistance of the surrounding muscles and soft tissues. Careful planning and agreement between the surgeon and orthodontist are required to achieve the skeletal, and occlusal goals. SFA may not be suitable for some cases where the predicted postoperative occlusion interferes with the required surgical movement which includes narrow inter-canine distance. It is important to emphasise the steep learning curve in selecting the appropriate cases for the SFA and planning the orthodontic treatment of the secondary malocclusion after surgery.
- Meta-analysis should be considered to augment the sample size for the assessment of the skeletal stability and evaluation of the quality of occlusion using objective 3D methods of analysis.

6 CHAPTER SIX: REFERENCES

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