TMJ loads during biting in long and short facial types: Changes pre- and post-orthognathic surgery

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

TMJ loads during biting in long and short facial types: Changes pre- and post-orthognathic surgery

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1) Abstract

Title: TMJ loads during biting in long and short facial types: Changes pre- and post-orthognathic surgery.

Objective: The specific aim of the study was to compare predicted temporomandibular mandibular joint (TMJ) loads during biting in dolichofacial, mesofacial, and brachyfacial types before and after orthognathic surgery. Secondary aims were to determine the effects of gender, age, and occlusal plane angle on TMJ loads for the same biting task.

Materials and Methods: CBCT images from November 2015 to January 2018 were collected pre- and post-orthognathic surgery at one private oral surgery office from patients aged 15 years and older with no history of temporomandibular disorder (TMD), syndromes, craniofacial deformities, or TMJ procedures. Facial type was determined using a cephalometric analysis. Three-dimensional anatomical data were derived from CBCT images and used in numerical models to predict TMJ loads for a range of mandibular canine biting angles.

Results: Out of 148 surgical cases available, 46 met the inclusion criteria and represented 21 males and 25 females with average (± standard deviation) age at time of surgery of 32.0 (± 15.2) years. Subjects were divided into three groups based on Frankfort-Mandibular Plane Angle (FHMPA), including 10 dolichofacial (FHMPA >30°), 17 brachycephalic (FHMPA<22°), and 19 mesofacial (FHMPA 23-29°) subjects. Statistically significant differences in FHMPA, at both time points, were found amongst facial types. No significant differences, at both timepoints, in TMJ loads were found between facial groups. A positive correlation was found between surgical changes in occlusal plane angle and TMJ loads (Figure 7). Regression analyses showed that the

occlusal plane angle explained 45 – 61% of the variability shown in predicted ipsilateral and contralateral TMJ loads for canine biting pre- and post-surgery (Figure 6), with the ipsilateral approximately 30% larger than the contralateral TMJ loads for the same increase in occlusal plane angle. Larger changes in occlusal plane angle following orthognathic surgery resulted in higher ipsilateral TMJ loads (R^2 = .46) (Figure 7B).

Conclusions: TMJ loads were not statistically significantly different in dolichofacial, mesofacial, and/or brachyfacial subjects before and after orthognathic surgery. Gender and age had no significant effects on TMJ loads for canine biting. However, facial phenotype was related to occlusal plane angle, with higher occlusal plane angles found in dolichofacial subjects compared to lower occlusal plane angles found in brachyfacial subjects. The occlusal plane angle was positively associated with TMJ loads (R^2 = 0.45 – 0.61) with higher TMJ loads for the ipsilateral joint than the contralateral joint. Using a definition of changes of ≥20% in TMJ loads were clinically important, this study showed that when occlusal plane angles were increased ≥7 degrees, clinically important increases in TMJ loads were predicted and thus, possibly increase the risk of Degenerative Joint Disorder (DJD) following orthognathic surgery.

2) Introduction

2.1 Temporomandibular Disorder (TMD) and Degenerative Joint Disorder (DJD)

Temporomandibular disorder (TMD) is defined by the American Academy of Orofacial Pain as "a collective term that embraces a number of clinical problems that involve the masticatory muscles, the temporomandibular joint (TMJ) and the associated structures." Jaw clenching increases pain and can lead to TMD and persons diagnosed with TMD typically engage in more frequent and higher levels of non-functional tooth contact than healthy controls.[1-3] These findings support how jaw use can affect the TMJ. Mechanical loading of the TMJ and activation of the masticatory (jaw) muscles that produce the loading are important to understand. This is because the magnitude and frequency of joint loading, known collectively as "mechanobehavior"[4] are thought to be important etiological factors leading to pain and degenerative joint disease (DJD).[5-8] DJD is a common intra-articular disorder of TMD. While mechanobehaviour is a candidate contributor to DJD, the etiology of DJD is multifactorial.

2.2 Facial Type

Facial dimensions include three aspects: the transverse, anteroposterior, and vertical. The vertical dimension is often used to categorize persons into long (dolichofacial), short (brachyfacial), or average (mesofacial) facial types. Dolichofacial and brachyfacial individuals can be distinguished by the ratios of facial width to height that are relatively small and large, respectively. However, a commonly used parameter to determine these facial types is the orientation of the lower border of the jaw (mandibular plane, MP) relative to the anatomical reference plane called Frankfort Horizontal (FH), which passes through the inferior margin of the orbits and the upper margin of each ear canal or external auditory meatus. The angle between MP and FH (FHMPA) in long faces, or dolichofacial, individuals, is large, whereas in short faces, or brachyfacial, individuals the angle is small. Facial type can influence orthodontic and orthognathic surgical treatment planning.[9-13]

2.3 Facial Type & Orthognathic Surgery

The human jaws can be thought of as a classic lever system. The musculature is positioned between the fulcrum at the jaw joint and the point of force application between the teeth. The geometry of this lever system can affect the biting force due to the varying mechanical advantages of the muscles. Mechanical advantage is the ratio of force produced by a machine (the jaw complex of muscles and bones) to the force applied to it. Mechanical and biological levers have three elements: a fulcrum, force arm, resistance arm. Different facial types have variations in the length of the force arm and the muscles involved in chewing allowing different magnitudes of bite force.[14] Marques et al. conducted a study to evaluate the length of the force and resistance arms to calculate the mechanical advantage and muscular work of the temporalis muscle in brachyfacial and dolichofacial subjects. They concluded that the mechanical advantage of the temporalis muscle in short facial types is significantly greater than in dolichofacial types.[14] The authors discussed how anterior and posterior facial heights are strongly correlated with maximum bite force and often reflected in the assignment of orthognathic surgical procedures. Orthognathic surgery can alter the size and relative positions of the maxilla and mandible and, thus, change the facial type and geometric relationships of the anatomical structures important to jaw use, like the teeth, TMJs and masticatory muscles. Surgical procedures therefore have potential to an effect the mechanical advantage of the mandibular muscles.

Proffit et al. stated that due to the differences in the geometries of the jaw system, dolichofacial individuals are expected to exert less biting force than brachyfacial individuals.[11] This study found that dolichofacial individuals had significantly less occlusal forces during maximum effort bite force, simulated chewing, and swallowing when compared the average facial types. In a later study, Proffit et al. studied the effect of orthognathic (jaw) surgery on occlusal force and completed the same tests. [15] The expectation was the change from a dolichofacial to a more normal facial type via surgery would increase the bite force. The results were not what the authors expected and no true conclusions on the change in mechanical advantage could be made. There were short-comings in the study design, for example, maximum bite force may not be a reliable indicator following surgery as people may bite more cautiously, and therefore more research is needed to further explore the functional changes following jaw surgery.

2.4 Bite Force versus Joint Loading Forces

Bite force has often been used as an indicator of the functional status of the masticatory system. It is related to the facial morphology, occlusion, neuromuscular mechanism, and other factors including gender, age, and body type.[16] Variance in bite force may be explained by differences in muscle sizes, craniofacial morphology, vertical jaw relation, facial height and inclination, and occlusion. Quiudini et al. conducted a study to characterize bite force in brachyfacial and dolichofacial individuals. They evaluated 190 subjects (90 long faces, 100 short faces) and assessed their maximum bite force. Bite force measurements are dependent on the cooperation of the individual and their motivation. Some subjects may be concerned with potential damage to dentition with maximum bite force, discomfort to their teeth, or other psychological factors. These factors can be uncontrolled variables into the study. The authors discussed these limitations and tried to minimize them. From their study, they found that bite force was significantly higher in brachyfacial individuals than dolichofacial individuals. Bite force was also influenced by gender, weight, and height with males having a higher bite force compared to females in both groups.[16]

Another consideration with bite force studies is the effect of orthodontics. Thomas et al. conducted a study to evaluate the effects of orthodontic treatment on oral motor function, changes in mandibular motion and maximum bite forces. This study evaluated 15 orthodontic and orthognathic surgery subjects and found that there was a reduction in bite force during orthodontic treatment. They concluded this change was most likely due to the discomfort that occurs during orthodontic treatment.[17] In addition, when using bite force as a measure of masticatory function for persons following orthognathic surgery, many individuals are cautious following surgeries when biting due to soreness, fear of injury, or loss of proprioception. Furthermore, maximum bite force may not be important to normal masticatory function.[15]

2.5 3-D modeling of Jaw Mechanics

Measuring human joints is challenging due to the invasive nature of the measuring modalities. While other modalities have been used in animals to directly measure these forces, it is not translatable directly to humans.[2,18-22] Computer models are used as a non-invasive technique to study joint systems, such as wrist, knee, shoulder, hip, spine, and the TMJ.[2,23-29] Typically, computer models of the craniomandibular apparatus represent the mandible as a 3-dimensional rigid body with unknown joint and muscle forces. The locations of either an applied bite force or external force are known. A unique static solution is not possible because there are several combinations of joint and muscle forces that can produce a static equilibrium.[30-42] This is known as mechanical indeterminacy.

Numerical models are a specific form of computer model that provide solutions to indeterminate mechanical problems by using optimization strategy.[2] The optimization strategy represents an objective function, a theory of neuromuscular control.[37,43] Using this objective function, the model determines which joint and muscle force combination produces static equilibrium and meets the requirements of this objective function.[2] TMJ numerical models have shown that the articular eminence develops to optimize the direction of condylar loading and therefore facilitates the minimization of joint loads.[28,44-46] The TMJ numerical models also consider the neuromuscular control of the muscles of mastication. The modeling suggests that the neuromuscular control of these muscles is organized to minimize joint loads, minimize muscle effort, or both, depending on biting position.[45,46]

2.6 Relevant Research

Nickel et al. conducted a study using validated numerical models to evaluate the effects of combined orthodontic and orthognathic surgical treatment on TMJ loads and muscle forces. The stated goals of their study were to validate the numerical model predictions of the TMJ sagittal eminence morphology and muscle forces produced during molar biting and use those models to calculate the changes in TMJ and muscle forces following orthognathic surgery.[2] Ten subjects who underwent orthodontic and orthognathic surgery treatments participated. Consistent with the objectives of minimization of joint loads and minimization of muscle effort, three-dimensional anatomical data from each subject were used to predict the TMJ eminence morphology and joint and muscle forces during biting for each subject, using computer models. Using jaw tracking, the actual sagittal shape of the eminence in each subject was measured in order to validate the numerical model. Additionally, surface electromyographic recordings were used to measure muscle forces involved in the same static biting tasks as modeled for each subject. The results showed a R^2= 0.96 for predicted versus measured eminence shape and R^2= 0.98 for predicted versus measured muscle forces. This validated the models and suggested they could be used to calculate joint forces. When the validated numerical models were applied to study TMJ loads during biting, the results showed that TMJ loads increased in 8 subjects, with the average increase being 4% relative to the applied bite forces. One case showed an increase up to 20% relative to the applied bite force, indicating some persons may experience clinically important increases in TMJ loads as a result of combined orthodontic and orthognathic surgical treatment.[2]

A retrospective study conducted by Iwasaki et al. evaluated jaw mechanics during biting between dolichofacial and brachyfacial subjects at three ages using cephalometric analysis and computer-assisted numerical modeling.[3] The authors evaluated ten dolichofacial and ten brachyfacial facial type individuals and derived three-dimensional anatomical data from x-ray images of the head in two standardized, perpendicular views (lateral and posteroanterior cephalograms) made at average ages of 6, 12, and 18 years. These data were used in numerical models to predict TMJ loads for a comprehensive range of biting angles relative to applied bite-forces of 100 units. This approach addressed the problems associated with use of maximum bite force as study outcome. They defined brachyfacial subjects as having FHMPA ≤22° and dolichofacial subjects with FHMPA ≥30°. The results from the study showed that dolichofacial subjects had significantly larger TMJ loads for the same biting tasks at a larger range of biting angles than brachyfacial subjects and that these loads increased in magnitude with age. Correlation analysis demonstrated that with increased age, higher TMJ loads were associated with shorter ramal heights in the dolichofacial subjects whereas lower TMJ loads were associated with longer ramal heights in the brachyfacial subjects.[3] Ramal height is the vertical distance between the most super anterior point on the mandibular condyle (Condylion) and the lowest posterior and outward point of the angle of the mandible (Gonion). Notably, without other compensations, short and long ramal heights were associated with large and small FHMPA, respectively. These findings are important in considering the TMJ loads and facial type. While studies have illustrated that brachyfacial individuals have increase in bite force compared to dolichofacial individuals, Iwasaki et al. found the TMJ loads are higher in dolichofacial subjects. The increase in TMJ loads could be an important finding when considering TMD risk factors.

In a prospective study, Nickel et al. examined magnitudes and frequencies of jaw loading (mechanobehavior) and ramus height in groups of ten subjects with long and short facial types.[4]

The authors used numerical models to calculate the TMJ loads for a range of static biting based on the subjects' three-dimensional anatomy. To determine frequencies of jaw loading, called "duty factors," subjects used portable equipment at home to record jaw muscle activities via electromyography (EMG) during the day and night. Subjects also had jaw muscle EMG and bite forces recorded in the laboratory. These laboratory data were used to calibrate at-home recordings and calculate duty factor (%, jaw muscle activity divided by the total recording time) for each muscle for a range of jaw loading magnitudes and durations. The results showed that dolichofacial subjects had higher TMJ loads but lower jaw muscle duty factors than brachyfacial subjects.[4]

2.7 Orthognathic Surgery

Orthognathic surgery may alter the facial type and the physiological system by changing the sensory and proprioceptive inputs. To investigate this, Throckmorton et al. studied the changes of maximum occlusal forces after orthognathic surgery.[47] These authors evaluated bite forces pre- and post- orthognathic surgery for up to 2 years after surgery in 117 adult subjects and 43 control subjects. They concluded that there was a temporary reduction in maximum voluntary bite force for the first six months following surgery but there was an overall gradual increase in bite force following orthognathic surgery compared to pre-surgical levels but not greater than control levels. This study also showed that male subjects had higher bite forces than female subjects (Male: 16.9 ± 7.9 Kilopond (Kp) vs Female: 12.5 ± 5.6 Kp for control maximum bite forces). The authors suggested that these sex-related differences were due to larger body and muscle size on average in males compared to females.[47] In a later study, Throckmorton and Ellis evaluated the relationship between surgical changes in facial type morphology and changes in the maximum bite force. Morphology was evaluated using standard lateral cephalograms. Many of the cephalometric measurements used to diagnose craniofacial deformities for jaw surgery were not correlated with maximum bite forces or jaw muscle strength. However, they did find strong correlations of anterior and posterior facial height measurements with maximum bite force. Anterior and posterior facial heights are also used to classify facial type. For example, dolichofacial subjects often have a long anterior face height and a short posterior face height, which would result in a large FHMPA.[48] Throckmorton et al. conducted another study that used factor analysis to determine which craniofacial morphology features are most important in determining the orthognathic surgery procedure. The second best factor used to determine the surgical procedure was a factor labeled: DIVERGE. This factor is based primarily on the difference between anterior and posterior facial heights.[49] This result indicates that facial type is important when discussing treatment planning for both surgeons and orthodontists. Therefore, it is important to understand each facial type pre- and post-treatment to improve treatment outcomes.

In addition to orthognathic surgery altering facial type and TMJ loads, it is important to discuss the literature concerning orthognathic surgery and its effects on the TMJ and oral function. Bailey et al. discussed long-term stability and condylar changes associated with orthognathic surgery. They found that the risk of condylar changes ranges from 5-10% in patients who have surgery to advance the mandible. Their findings also stated that temporomandibular disorder (TMD) occurs in the minority of surgery patients and may be dependent on how much the condyles have been displaced. Some of the risk factors for TMD following surgery include transverse displacement of the condyles during surgery and rigid internal fixation, due to the torque necessary for screwing in the plates.[50] Te Veldhuis et al. conducted a systematic review to examine the effect of orthognathic surgery on the TMJ. The outcomes measured in the review included: joint noises, mandibular movements, maximum mouth opening, and pain on palpation, bite force, and patient satisfaction. Majority of patients showed a decrease in post-surgery pain on palpation, reduction in joint noises, and general improvement in functional and psychosocial benefits. However, there were many limitations to this review. The heterogeneity of the studies caused the level of evidence to be low. In addition, many of the included studies did not use the recommended TMD diagnosis protocol or a standardized method to diagnose TMD or TMD symptoms. With limited evidence the authors concluded that orthognathic surgery seems to have little or no harm on the TMJ and oral function.[51] Another systematic review worked to examine orthognathic surgery patients longitudinally for signs and symptoms of TMD.[52,53] The findings were similar to Te Veldhuis et al. with the conclusion that orthognathic surgery should not be advocated for the sole purpose of treating TMD but that for the majority of patients, TMD signs and symptoms improved according to these reviews.[52,53] A systematic review and meta-analysis, by Al-Moraissi et al., researched the question if orthognathic surgery causes or cures TMD. The authors evaluated articles with subjects who underwent various orthognathic surgeries and were categorized into nine sub diagnoses of TMD. The authors found a significant reduction in TMD in subjects with a retrognathic mandible after bilateral split osteotomies (BSSO) but no significant difference after BSSO and Le Fort I procedures. Subjects with prognathism showed significant differences in TMD symptoms after isolated BSSO or intraoral vertical ramus osteotomy (IVRO) and combined BSSO and Le Fort I, however no difference in TMD symptoms after BSSO of bimaxillary surgery (IVRO and Le Fort I). Overall, the authors concluded there was a reduction in TMD symptoms following surgery, however; surgery created TMD symptoms in a small group of subjects. The authors discussed potential reasons for a decrease in TMD following surgery which included a change in condyle-disc relationship, decrease in clenching, resolution of muscle disorders, however; definite evidence to support these reasons were not provided. There were multiple limitations of this study, as well as biases. For example, TMD was not well defined for each study used and was based on questionnaires rather than examination.[54] In addition, during orthognathic surgery, the mandibular osteotomies created a proximal segment, the segment of the condyle and ramus, and the position may have been altered, potentially introducing factors that could lead to TMD. Control of the proximal segment during orthognathic surgery has been emphasized for successful orthognathic surgical procedures.[55,56] Researchers have studied the effects of different surgeries, the management of the proximal segments, and the effects on the TMJ. For example, IVRO is a common procedure for prognathic mandibles and have a lower complication rate[57]; the procedure consists of a full thickness vertical osteotomy through the mandibular ramus posterior to the mandibular foramen, creating a proximal segment consisting of the condyle and posterior ramus and a distal segment containing the anterior ramus coronoid process, inferior alveolar nerve, and tooth-bearing mandible.[58] During the osteotomy, the displacement of the condyle moves it away from the disc and posterior attachment, decompressing the TMJ apparatus.[56,59-62] Studies have shown an improvement in the disc-condyle relationship in patients with jaw deformities following surgery.[59] A complication of the IVRO is medial displacement of the proximal segment, which occurs about 3-8% of cases.[57] The main complications of medial displacement are damage to the neurovascular bundle, necrosis of the distal tip of the proximal segment, and Eagle-like syndrome (flattened face and asymmetry).[57,63] Ueki et al. evaluated the changes in position and angle of the proximal segment, including the condyle, after an IVRO and the effect on postoperative complications in 29 subjects with mandibular prognathism. The authors measured the changes in condylar angle, ramus angle, and displacement of the proximal segment pre- and postoperatively. The position of the TMJ disc was also examined via MRI assessment. The postoperative complications evaluated included TMJ symptoms, defined by anterior disc displacement with or without reduction. The authors found that TMJ symptoms were improved in 97% of the patients who underwent IVRO on both sides.[56] Overall, better controlled studies are needed to evaluate the effects of orthognathic surgery on the TMJ, TMJ/disc relationship, and oral function.

2.8 Statement of the problem

The specific aim of the study was to compare predicted temporomandibular mandibular joint (TMJ) loads during biting in dolichofacial, mesofacial, and/or brachyfacial subjects before and after jaw (orthognathic) surgery. Secondary aims of this study include evaluate the effects of gender, age, and occlusal plane angle (Oc-FH) on TMJ loads during canine biting. The importance of this study is to understand fully the changes following orthognathic surgery in regard to TMJ loads during biting for each facial type. Due to the potential increased risk in developing TMD following orthognathic surgery, determining if TMD loads change post-surgery is important in understanding risk. TMJ loads and muscle forces could increase following orthognathic surgery due to the changes in the dentofacial complex. In addition, understanding facial type can influence treatment planning for orthodontic and orthognathic surgery patients.

2.9 Hypotheses

The null hypotheses are TMJ loads for the same canine biting tasks are not significantly different in dolichofacial, mesofacial, and/or brachyfacial subjects: 1. before orthognathic surgery, and 2. after orthognathic surgery. Gender, age, and occlusal plane angle (OP-FH) have no significant effect on TMJ loads for the same canine biting tasks.

3) Materials & Methods

3.1 Description of sample

The study was a retrospective study using case records of individuals who underwent orthognathic surgery, with and without orthodontic treatment, by various surgeon providers that were gathered from a private oral surgery office in Portland, OR. All individuals signed a clinical consent allowing their records to be used for research purposes. Oregon Health & Science (OHSU) Institutional Review Board (IRB) approval was obtained (Appendix 1). Inclusion criteria were: ≥15 years of age at the pre-orthognathic surgery stage and subjects with available pre- and post-orthognathic surgery cone beam computed tomography (CBCT) images of the head and jaws. Exclusion criteria were: any evidence of DJD in the case history, syndromes, or stated craniofacial deformities, TMJ replacement prostheses or TMJ procedures completed at surgical date. Data collection included: pre- and post- surgery CBCT images, age at time of surgery, gender, surgery location (maxilla, mandible, both). The CBCT images were de-identified and assigned a random case number using a software application that segmented three dimensional medical images (ITKSnap, GNU General Public License, Pennsylvania). De-identified CBCT images were analyzed using specialized cephalometric analysis software (Dolphin, Dolphin Imaging & Management Solutions Chatsworth, California). Facial type was determined by analyzing a generated lateral cephalogram (Figure 1) from the CBCT using a custom cephalometric analysis (See Appendix 1). The analysis included Frankfort Horizontal to Mandibular Plane angle (FHMPA), posterior face height (Sella –Gonion, S-Go, mm), anterior face height (Nasion-Menton, Na-Me), mm), Posterior (P)/Anterior (A) face height (S-Go/Na-Me, %), Occlusal plane to Frankfort Horizontal (OP-FH, °) (see Figure 1). The occlusal plane was was determined by a line connecting the midpoint between the upper (U6) and lower first molars (L6) to the midpoint between the upper (U1) and lower incisors (L1). The same person traced the images using the cephalometric analysis software. Facial type was determined using FHMPA for each subject based on the pre-treatment lateral cephalogram. Subjects were divided into three groups based on FHMPA, dolichofacial (FHMPA ≥ 30°**)**, mesofacial (FHMPA = 23-29°), or brachyfacial (FHMPA ≤ 22°). If the subject's maxillary and mandibular posterior teeth were not in contact in the image, for example if a bite-stick was used when the CBCT image was made, a simulation was done using the cephalometric-software program to mimic maximum intercuspation of the posterior teeth.

3.2 Landmarks and measurements

From the CBCT-derived lateral cephalogram, the following cephalometric landmarks and measurements were used: Porion, orbitale, sella, nasion, basion, bridge of nose, tip of nose, menton, gonion, ramus point, articulare, constructed gonion, condylion, A-point, B-point, anterior nasal spine (ANS), posterior nasal spine (PNS), maxillary first molar (U6), mandibular first molar (L6), mandibular central incisor (L1), internal symphysis superior, internal symphysis inferior, maxillary central incisor (U1) (Figure 1, Appendix 2). The important landmarks for the study included porion and orbitale to establish Frankfort Horizontal (FH), a line connecting the landmarks gonion and menton created an angle with FH to create FHMPA (°). The landmarks sella and gonion established posterior face height (mm) and nasion and menton established anterior face height (mm). A best fitting line bisecting the molar (U6, L6) and incisor (U1, L1) tracings established the occlusal plane line, which created an angle with FH to create occlusal plane to FH (OP-FH, °). The soft tissues landmarks, bridge of nose, tip of nose, soft tissue A-point and B-point, soft tissue menton, gnathion, pogonion, allowed for virtual treatment planning. All bilateral anatomic landmarks were represented by a mid-point between right and left landmarks. The results of this custom cephalometric analysis were used to categorize cases into the three facial type groups as described above.

Using the CBCT images uploaded to the cephalometric software “3D” section, “Edit” was selected (Appendix 3). First, the orientation of the CBCT was completed to define the X, Y, Z axes by selecting “Orientation” in the software program and using the toggle controls to adjust the pitch, yaw and roll of the CBCT image in three dimensions. By definition, the origin of the orthogonal axis system was the mid-point between right and left condylion points, where condylion was the supero-anteriormost mediolateral midpoint on the condyle (Figure 2A). In the frontal view, the mid-sagittal (X-Y) plane was defined between the orbits, approximately through nasion, and best estimate for facial midline. In the lateral view (Figure 2B), the axial plane was defined through the best-estimated occlusal plane and the coronal (Y-Z) plane was perpendicular to this. The axial (X-Z) plane (Figure 2C) was set to best estimate the occlusal plane perpendicular to the mid-sagittal plane from the frontal view. The mid-sagittal plane and coronal plane were also verified in the axial view. The resulting orientation of the CBCT image was saved.

Next, in order to identify landmarks that represent the craniomandibular anatomy of each case, then measure these in 3D relative to the X-Y-Z axis system to create a “geometry file” (Figure 3) for use in the numerical models, “Digitize / Measure” was selected in the cephalometric software program (Appendix 3). A scale line was set at 90 mm using the 2D line tool and provided mm-calibration within the geometry file and between geometry files for different cases. Based on previously described numerical models[43] the muscle centroids were defined as the center of the muscle attachment area. The “insertion” was defined as the centroid of the muscle attachment on the mandible and the “origin” was defined as the centroid of the muscle attachment located on the skull or hyoid bone and not located on the mandible. Landmarks were identified in one view and then cross-checked in the two other views, using the clipping slice to increase accuracy and ultimately verify that each landmark was correct in frontal, lateral and axial views. The following landmarks were then identified on the CBCT images for the geometry file, by identifying bilateral landmarks on one side and assuming symmetry:

Condyles: (1) Right and (2) left superoanterior most point

(3) Left central incisor (midpoint of incisal edge)

(4) Left mandibular canine cusp tip

(5) Left mandibular first molar mesiobuccal groove

(6) Left masseter muscle “insertion” on mandible

(7) Left masseter muscle “origin” on skull

(8) Left medial pterygoid muscle “insertion” on mandible

(9) Left medial pterygoid muscle “origin” on skull

(10) Left lateral pterygoid muscle “insertion” on mandible

(11) Left lateral pterygoid muscle “origin” on skull

(12) Left anterior temporalis muscle “insertion” on mandible

(13) Left anterior digastric muscle “origin” on hyoid bone

(14) Left anterior digastric muscle “insertion” on mandible

Three images, 2D screenshots of the identified landmarks, were saved in a frontal view, axial view, and lateral view, for each time point. These images were used to create the geometry files.

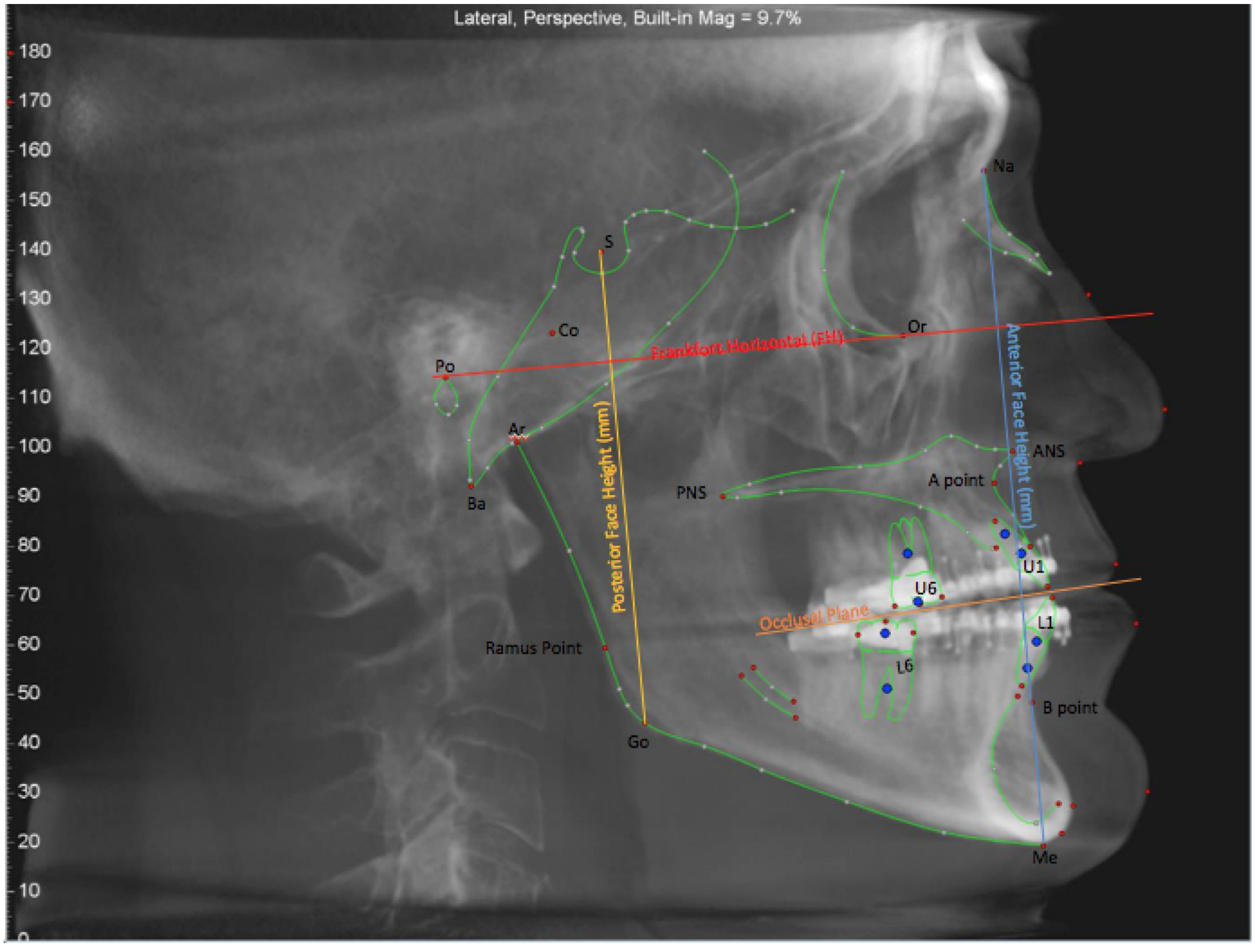


Figure 1: Traced Lateral Cephalogram Example – showing reference planes, angular and linear measurements.

Lateral cephalogram derived from CBCT image traced with custom cephalometric analysis (see Appendix 2). The analysis included Frankfort Horizontal (Po-Or) to Mandibular Plane (Go-Me) angle (FHMPA), posterior face height (S-Go), mm), anterior face height (Na-Me, mm), Posterior (P)/Anterior (A) face height (S-Go/Na-Me, %), Occlusal Plane to Frankfort Horizontal (OP-FH, °).

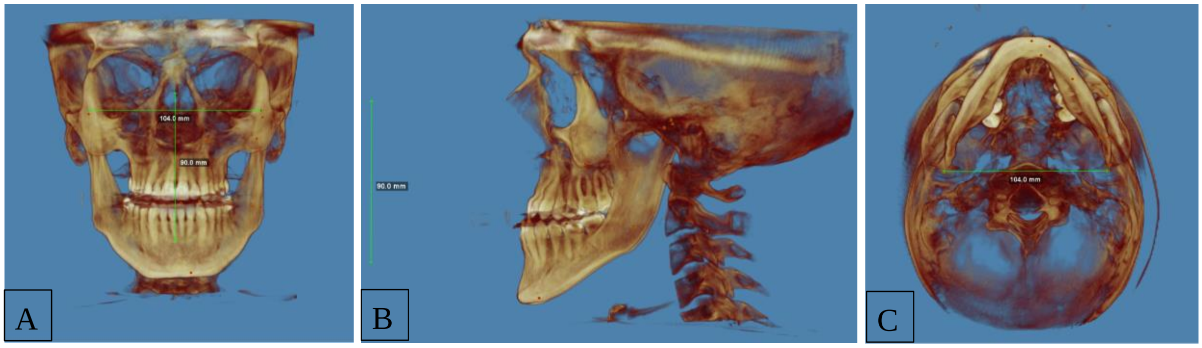


Figure 2: 2D images of identified landmarks used to create geometry files. Example of 2D images of the identified landmarks from the CBCT. **A.** Frontal, **B.** Lateral, and **C.** Axial views

3.3 Craniofacial geometry files

Individual geometry files represented the three-dimensional position coordinates of the TMJ, incisor, canine, molar, and five masticatory muscle pairs on one side and symmetry were assumed (Figure 3). From the CBCT images for each case and time-point, following landmark identification, lateral, posteroanterior, and axial images were exported and used to create craniofacial geometry files using a customized software program (MatLab, version R2019a #41, Massachusetts). That is, the X, Y, and Z coordinates were determined for the centroids of the muscles of mastication, the most superoanterior point on the mandibular condyle, and the mandibular incisor, canine, and first molar landmarks.

Some of the CBCTs were made when subjects were biting onto a bite stick or while wearing a post-surgical splint, which prevented positioning of the mandible to a maximum intercuspal position (MIP). Therefore, before creating the post-surgical geometry files, it was necessary to reposition the mandible to a position of maximum intercuspation. This involved a two-step process. The first step was accomplished by using the virtual treatment planning feature of the cephalometric analysis software (Dolphin, Dolphin Imaging & Management Solutions Chatsworth, California). The virtual treatment planning tool facilitated autorotation of the mandible into maximum intercuspation (MIP), and created a numerical value for the anterior (X) and superior (Y) millimeter displacement of the mandible to achieve MIP. These anterior and vertical measurements were then used in the second step of the process, where a customized computer program (MatLab, version R2019a #41, Massachusetts) used the anterior and vertical measurements to reposition the mandible prior to proceeding with digitizing the coordinates required to produce the post-surgical geometry file.

3.4 Numerical modeling to predict effective eminence shape

The numerical models used each subject's specific geometry file and an objective function to predict the effective sagittal TMJ eminence shape, which was defined as the sagittal view shape of the hard and soft tissue structures articulating with the mandibular condyle as it moved from most retruded to most protruded position with the jaw in a centered position. The eminence shape was expected to remain the same pre- and post- orthognathic surgery for the subjects included in this study because the surgery did not include the eminence and the timeframe between pre- and post-surgery was too short for much remodeling to occur. Therefore, only the pre-surgical eminence was predicted and used with the geometry file to calculate TMJ loads for both pre- and post- surgery time points. The effective sagittal eminence shape was represented as a polynomial equation and determined by the numerical model with the objective function of minimization of joint loads based on previous studies that demonstrate eminence shapes may develop to minimize joint loads.[28,64,65]

3.5 Numerical modeling of TMJ loads

The case-specific predicted effective sagittal eminence morphologies and the geometry files were then used in another numerical model, with the objective function of minimization of muscle effort (MME), to predict TMJ forces during biting. Predicted joint loads were expressed as a percentage of the applied bite force. This model was used based on previous validation studies.[2,66] The model calculated the ipsilateral and contralateral TMJ loads per unit of applied bite force (%) during biting on the mandibular canine for a range of biting angles from 0-350° in the occlusal plane (θ_{xz}) in 10-degree increments; and perpendicular to the occlusal plane, defined as θ_y = 0 degrees, and a range of θ_y from 0-40° in 5 degree increments.

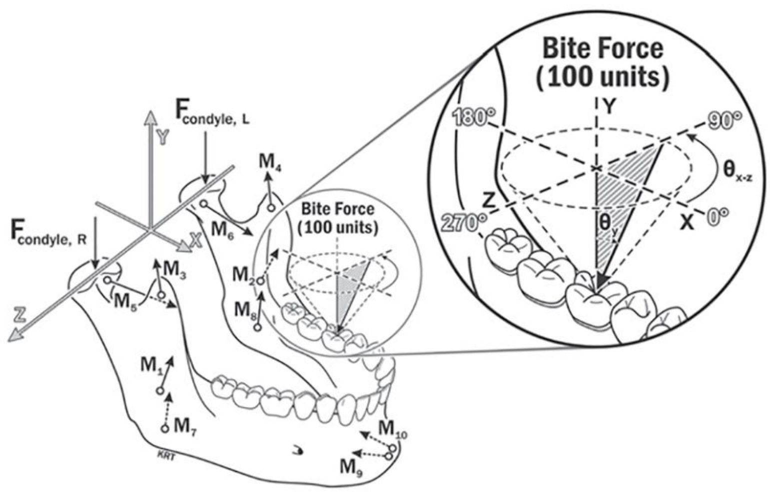


Figure 3: Three-dimensional anatomy (geometry file) for the numerical modeling of TMJ loads. The left image demonstrates individual anatomy including TMJs ($F_{condyle}$, R=right, L=left), and the five masticatory muscle pairs ($M_{1, 2}$ = masseter, $M_{3, 4}$ = anterior temporalis, $M_{5, 6}$ = lateral pterygoid, $M_{7, 8}$ = medial pterygoid, $M_{9, 10}$ = anterior digastric muscles). The enlarged image

illustrates the axis and bite force vectors involved for first molar biting on the left. The numerical models mimicked a full range of in vivo biting conditions. The measured bite forces were in the occlusal plane (θ_{xz}, 0-350°) and relative to vertical (θ_y, 0-40° where 0° is perpendicular to the occlusal plane). (Modified from [67]).

3.6 Data analysis

Using the geometry file data from the CBCT images input into the numerical models, TMJ loads for the same comprehensive range of mandibular canine biting tasks were predicted for each case and time-point and the results were averaged. That is, average TMJ loads for the joint ipsilateral and for the joint contralateral to the applied canine biting force were calculated from the results of the comprehensive range of canine biting angles tested. Such results were then assessed for each group by averaging TMJ loads at pre- and post-surgery time-points and averages compared between groups for each time point. Change in occlusal plane angle (OP-FH) and mandibular plane angle (FHMPA) were determined by post-surgical values (T2) minus pre-surgery values (T1). The cases were also categorized by occlusal plane angle (OH-MP, °), gender (female, male) and age (years). The same person traced one subject's cephalogram, created geometry files, and determined TMJ loads in ten trials separated by one week to determine reliability.

Independent Variables	Dependent Variables
Facial type pre-surgery - Categorical: dolichofacial, mesofacial, brachyfacial - Continuous: FHMPA, °	Pre-surgery TMJ load (% of applied bite-force)
	Ipsilateral TMJ Load (FcIpsilat)
	Contralateral TMJ Load (FcContra)
Occlusal plane angle (OP-FH, °)	Post-surgery TMJ loads (% of applied bite-force)
Gender (female, male)	Post-surgery (T2)-pre-surgery (T1) change in mandibular plane angle (ΔFHMPA, °)
Age (years)	Post-surgery (T2)-pre-surgery (T1) change in occlusal plane, (ΔOP-FH, °)

Table 1: Independent and Dependent Variables

3.7 Statistical Tests

Data analyses were performed with statistical software (SAS version 9.4, SAS Inc. Cary, NC. USA). Coefficient of variation (CV %) was used to measure the dispersion of the data, which reflects the repeatability and/or reliability. CV were set as: <10 very good, 10-20 good, 20-30 acceptable, and CV>30 not acceptable. Normalized data were expressed relative to maximum values for both groups combined.

Descriptive statistics including means and standard deviations of variables (Table 1) at each time points were calculated as well change in FHMPA, OP-FH, and TMJ loads between post-surgery (T2) and pre-surgery (T1) (Δ=T2-T1). An ANOVA was Two-group t-tests were used to assess differences in mean TMJ loads and change in FHMPA due to surgery between phenotypes. Two-group t-tests were used to compare between two facial types. Regression analyses were completed to test associations between continuous variables: TMJ loads versus occlusal plane angle and change in occlusal plane angle. Analysis of variance (ANOVA) and multivariate analysis of variance (MANOVA) tested effects of independent variables on dependent variables separately and together, respectively. Where significant differences were revealed, post hoc tests were applied. Significant differences were defined by P-value <.05. Additionally, since statistically significant differences in relatively low joint loads may not be relevant to the physiology of the TMJs, differences, which were +/- 20% or more, were designated as clinically important.

4) Results

4.1 Sample Description

Of the 148 cases available, a total of 46 cases representing 21 males and 25 females, met the inclusion criteria. Common reasons for exclusion of cases were lack of pre- and post-surgery CBCT images, history of DJD, syndromes, or TMJ procedures completed in addition to orthognathic surgery. Included cases were divided into three diagnostic groups (Table 2), including seventeen brachyfacial (10 males, 7 female), ten dolichofacial (8 females, 2 males), and nineteen mesofacial (10 females, 9 males) cases.

Serial tracing of cephalograms indicated the maximum CV of 3.6% for FHMPA, 1.6% for Anterior Face Height, and 1.8% for Posterior Face Height, which indicated very good repeatability and reliability for the methods of tracing, landmark identification and cephalometric measurement. Some CBCT images did not include nasion, affecting the anterior facial height measurement and the facial proportions data only, but facial proportions were not analyzed in the statistical analysis. The CV for Occlusal Plane to FH was 14.5%, which indicated good repeatability and reliability (Table 3).

The overall mean age ± standard deviation (SD) of subjects at time of surgery was 32.0 ± 15.2 years. The average ± SD ages for each phenotype prior to surgery were 32 ± 13.3, 34.4 ± 16.6, and 29.8 ± 15 years and not significantly different (Table 4). The average ± SD FHMPA for each phenotype pre-surgery was 35.8° ± 4.3°**,** 18.6° ± 3.1,° and 25.9° ± 2.5° for dolichofacial, brachyfacial, and mesofacial facial types, respectively and significantly different ($P<.00001$; Table 4). Similarly, average ± SD FHMPA for each phenotype post-surgery was 31.3° ± 6.3°**,** 17.9° ± 3.6°, and 23.7° ± 3.7° for dolichofacial, brachyfacial, and mesofacial facial types, respectively and significantly different ($P<.00001$; Table 4). The difference in T2-T1 FHMPA between the groups were -4.5° ± 4.6°**,** -0.7° ± 2.2°, and -2.2° ± 3.3° for dolichofacial, brachyfacial, and mesofacial facial types, respectively and statistically significant between the groups ($P=.03$; Table 4). On average, the T2-T1 change in FHMPA decreased for all groups by -2.2° (± 3.6°). The FHMPA at T1 was 25.9° ± 2.5 ° and was significantly higher than FHMPA at T2 which was 23.7° ± 3.7 ° for mesofacial cases (Figure 4). There were no statistically significant findings within groups for T2-T1change in occlusal plane angle (Δ OP-FH, °), however, for each group, the occlusal plane angle decreased post-surgery (Figure 5). Based on gender, the only statistically significant finding was the change in FHMPA in the dolichofacial facial group ($P=.042$). The average Δ FHMPA (°) for males was -9.8° ± 0.9° and -3.2° ± 4.5°

(Table 6). For mesofacial facial types, the change in occlusal plane angle (Δ OP-FH, °) was statistically significant (p=0.00063) between males (-1.4°± 2.5°) and females (2.9°± 2.3°).

Table 2: Numbers of cases by facial type and gender

	Dolichofacial (FHMPA ≥30°)	**Brachyfacial (FHMPA ≤22°)**	**Mesofacial (FHMPA 23-29)**
Males	2	10	9
Females	8	7	10
Total	10	17	19

Table 3: Coefficient of variation (CV %) used to measure dispersion of the data, reflecting the repeatability and/or reliability of the following variables: Frankfort horizontal mandibular plane angle (FHMPA), Posterior (P) Face Height, Anterior (A) Face Height, Posterior/Anterior Face Height (P-A Face Height, %) Occlusal plane angle (OP-FH), Pre-surgery (T1) Ipsilateral TMJ Load (FcIpsilat), and Pre-surgery (T1) Contralateral TMJ Load (FcContra)

	Mean	**STD**	**CV (100%)**
FHMPA	18.1	0.7	3.6
Posterior (P) Face Height	92.7	1.6	1.8
Anterior (A) Face Height	136.2	2.1	1.6
P-A Face Height	68.1	0.6	0.9
OP-FH	-5.6	0.8	14.5
T1-FcIpsilat	60.4	4.4	7.3
T1- FcContra	46.8	3.9	8.4

CV<10 = very good, CV 10-20 = good, CV 20-30 = acceptable, and CV>30 = not acceptable

Table 4: Average ages and standard deviations (SD) at surgery, Frankfort horizontal mandibular plane angles (FHMPA), pre-surgery (T1), post-surgery (T2), Occlusal plane angle (OP-FH) T1 and T2 for facial type groups

	Dolichofacial (n=10)		**Brachyfacial (n=17)**		**Mesofacial (n=19)**		
	Average	**SD**	**Average**	**SD**	**Average**	**SD**	**P-Value**
Age (years)	32.1	13.3	34.4	16.6	29.8	15.0	ns
T1 FHMPA (°)	35.8	4.3	18.6	3.1	25.9	2.5	< 0.00001*
T2 FHMPA (°)	31.3	6.3	17.9	3.6	23.7	3.7	< 0.00001*
∆T2-T1 FHMPA (°)	-4.5	4.6	-0.7	2.2	-2.2	3.3	<0.03*
T1 OP-FH (°)	9.8	4.3	2.5	4.4	5.1	3.6	<0.001*

T2 OP-FH (°)	6.8	5.1	1.2	4.3	4.8	3.1	<0.01*
ΔT2-T1 OP-FH(°)	-3.0	4.2	-1.3	2.6	-0.3	3.6	ns

Significant (*P<.05) differences in FHMPA, Δ FHMPA (°), and OP-FH (°) were found at both time points across all groups. No significant difference in age, where ns = not significant

Table 5: Male and female mesofacial cases, average ages and standard deviations (SD) at surgery, Frankfort horizontal mandibular plane angles (FHMPA) (T1: pre-surgery, T2: post-surgery), Occlusal plane angle (OP-FH) T1 and T2

Mesofacial Group (FHMPA 23-29°)					
	Male (n=10)		**Female (n=9)**		
	Average	**SD**	**Average**	**SD**	**P-value**
Age (years)	25.3	7.6	33.9	18.9	ns
T1 FHMPA (°)	25.5	2.5	26.4	2.5	ns
T2 FHMPA (°)	24.1	3.1	23.4	4.3	ns
ΔT2-T1 FHMPA (°)	-1.4	3.2	-2.9	3.4	ns
T1 OP-FH (°)	5.5	3.3	4.7	4.0	ns
T2 OP-FH (°)	4.6	2.9	4.9	3.4	ns
ΔT2-T1 OP-FH (°)	-0.9	2.7	0.2	4.3	ns

Significant (*P<.05) differences in Δ OP-FH (°) between males and females between the mesofacial group, where ns = not significant

Table 6: Male vs. Female dolichofacial, average ages and standard deviations (SD) at surgery, Frankfort horizontal mandibular plane angles (FHMPA) (T1: pre-surgery, T2: post-surgery), Occlusal plane angle (OP-FH) T1 and T2

Dolichofacial Group (FHMPA ≥30°)					
	Male (n=2)		**Female (n=8)**		
	Average	**SD**	**Average**	**SD**	**P-value**
Age (years)	44.8	16.3	28.9	12.6	ns
T1 FHMPA (°)	36.2	3.2	35.7	5.0	ns
T2 FHMPA (°)	26.4	4.1	32.5	6.7	ns
ΔT2-T1 FHMPA (°)	-9.8	0.92	-3.2	4.5	<0.05*
T1 OP-FH (°)	12.3	0.49	9.1	4.9	ns
T2 OP-FH (°)	3.8	2.2	7.5	5.8	ns
ΔT2-T1 OP-FH (°)	-8.5	1.7	-1.6	3.4	<0.02*

Significant (*P<.05) differences in Δ FHMPA (°) between males and females within the dolichofacial facial type group, where ns = not significant

Table 7: Male vs. Female Brachyfacial, average ages and standard deviations (SD) at surgery, Frankfort horizontal mandibular plane angles (FHMPA) (T1: pre-surgery, T2: post-surgery), Occlusal plane angle (OP-FH) T1 and T2

Brachyfacial Group (FHMPA ≤22°)					
	Male (n=10)		**Female (n=7)**		
	Average	**SD**	**Average**	**SD**	**P-value**
Age (years)	34.6	16.6	34.1	15.4	ns
T1 FHMPA (°)	18.8	3.3	18.2	2.4	ns
T2 FHMPA (°)	18.2	2.3	17.4	4.7	ns
ΔT2-T1 FHMPA (°)	-0.6	1.7	-0.8	2.6	ns
T1 OP-FH (°)	1.7	4.5	3.6	3.6	ns
T2 OP-FH (°)	0.6	4.9	1.9	2.6	ns
ΔT2-T1 OP-FH (°)	-1.1	1.9	-1.6	3.5	ns

No significant difference between male and female within the brachyfacial facial type group, where ns = not significant.

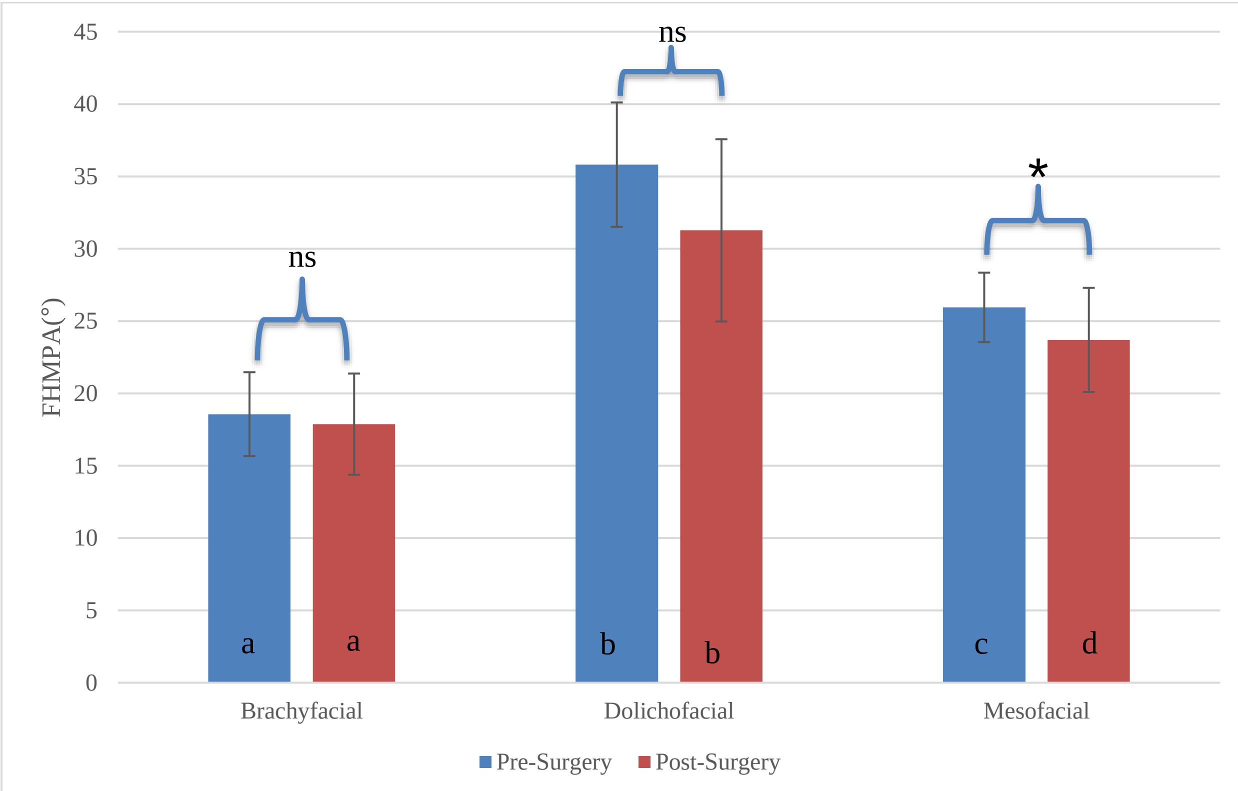


Figure 4: FHMPA pre- and post-surgery for facial groups

Results show statistically significant differences between all facial groups for the pre-surgery and post-surgery time points (indicated by different letters) and significant change in FHMPA within the mesofacial group between pre- and post-surgery. The average change in FHMPA for mesofacial subjects was (-2.2° ± 3.3°).

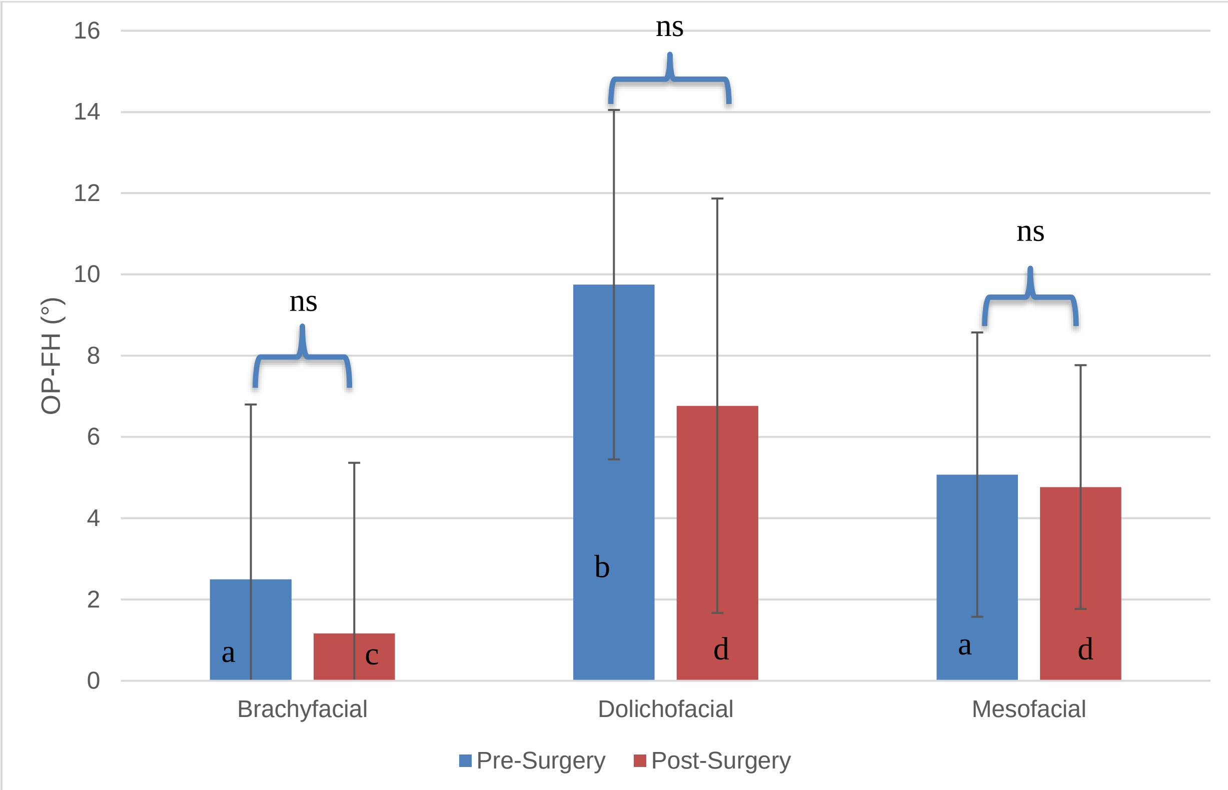


Figure 5: Occlusal Plane Angle Pre- and Post-surgery for facial groups. For all facial groups the occlusal plane angle decreased on average from pre-surgery to post-surgery, but these changes were not statistically significant (ns) within the groups. Significant differences in occlusal plane angle between groups for the same time-point are indicated by different letter, where a versus b and c versus d indicates a significant differences between pre-surgery and post-surgery measurements, respectively (all $P<0.05$).

4.2 TMJ Loads

The average TMJ loads for the ipsilateral joint during canine biting pre-surgery for brachyfacial, mesofacial, and dolichofacial facial types were 50.6% ± 8.4%, 48.6% ± 9.8%, and 45.4% ± 8.3% of the applied bite force, respectively. These results were not significantly different. The average TMJ loads for the contralateral joint during canine biting pre-surgery for brachyfacial, mesofacial, and dolichofacial facial types were 59.2% ± 10%, 56.3% ± 7%, and 60.2% ± 7.9%, respectively. These findings were not significantly different between groups (Tables 11-13). Post-surgery, the TMJ loads were not significantly different between groups or within groups (Table 11-13) for either the ipsilateral or contralateral condyle. Reliability tests from 10 repeated trials demonstrated that the CV for TMJ loads were 7.3% and 8.4%, for pre-surgical ipsilateral and contralateral TMJs, respectively.

Plots of ipsilateral and contralateral TMJ loads during canine biting versus occlusal plane angle for the overall sample showed that larger TMJ loads were associated with steeper occlusal plane angles pre-surgery and post-surgery (Figure 6). That is, the occlusal plane angle explained 45 – 61% of the variability shown in predicted ipsilateral and contralateral TMJ loads for canine biting pre- and post-surgery (Figure 6). The ipsilateral TMJ loads were larger relative to the occlusal plane angle than the contralateral TMJ loads, as seen in the slope of regression relations (Figure 6). That is, the ipsilateral TMJ loads increased more per unit increase in occlusal plane angle compared to the contralateral TMJ loads by a factor of 1.3. This was seen in the slopes of the regression plots for the pre-surgical ipsilateral TMJ loads (y=1.6x+42.8) versus the pre-surgical contralateral TMJ loads (y=1.3x+52) (Figure 6a, 6c). An increase in TMJ loads was seen for both the contralateral and ipsilateral TMJs as the occlusal plane angle increased (Figure 7AB). Focusing on the ipsilateral side, when occlusal plane angles were ≥7 degrees larger, TMJ loads during canine biting were ≥ 20% of the applied bite force larger, and these differences were defined as clinically important (Figure 7B).

Table 8: Dolichofacial vs. Brachyfacial groups, average ages and standard deviations (SD) at surgery, TMJ loads (T1 FcIpsilat, T2 FcIpsilat, T1 FcContra, T2 FcContra), and changes in TMJ loads (T1: pre-surgery, T2: post-surgery), (T2-T1 FcIpsilat and T2-T1 FcContra)

Brachyfacial vs. Dolichofacial Groups					
	Brachyfacial (n=17)		Dolichofacial (n=10)		
	Average	SD	Average	SD	P-value
Age (years)	34.4	16.6	32.1	13.3	ns
T1 FcIpsilat	50.6	8.4	45.4	8.3	ns
T2 FcIpsilat	50.5	8.8	43.3	8.4	ns
T2-T1 FcIpsilat	-0.1	4.6	-2.1	8.1	ns
T1 FcContra	59.2	10.0	60.2	7.9	ns
T2 FcContra	59.5	9.1	61.3	3.9	ns
T2-T1 FcContra	0.3	8.1	1.0	6.7	ns

FcIpsilat = TMJ Loads Ipsilateral. FcContra = TMJ Loads Contralateral. No significant difference in TMJ loads between brachyfacial and dolichofacial groups, where ns = not significant

Table 9: Brachyfacial vs. Mesofacial groups, average ages and standard deviations (SD) at surgery, TMJ loads (T1 FcIpsilat, T2 FcIpsilat, T1 FcContra, T2 FcContra), and changes in TMJ loads (T1: pre-surgery, T2: post-surgery), (T2-T1 FcIpsilat and T2-T1 FcContra)

Brachyfacial vs. Mesofacial Groups					
	Brachyfacial (n=17)		**Mesofacial (n=19)**		
	Average	**SD**	**Average**	**SD**	**P-value**
Age (years)	34.4	16.6	29.8	15.0	ns
T1 FcIpsilat	50.6	8.4	48.6	9.8	ns
T2 FcIpsilat	50.5	8.8	45.9	15.9	ns
T2-T1 FcIpsilat	-0.1	4.6	-2.5	14.5	ns
T1 FcContra	59.2	10.0	56.3	7.0	ns
T2 FcContra	59.5	9.1	54.1	18.1	ns
T2-T1 FcContra	0.3	8.1	-2.6	16.4	ns

FcIpsilat = TMJ Loads Ipsilateral. FcContra = TMJ Loads Contralateral. No significant difference in TMJ loads between brachyfacial and mesofacial facial type groups, where ns = not significant

Table 10: Mesofacial vs. Dolichofacial groups, average ages and standard deviations (SD) at surgery, TMJ loads (T1 FcIpsilat, T2 FcIpsilat, T1 FcContra, T2 FcContra), and changes in TMJ loads (T1: pre-surgery, T2: post-surgery), (T2-T1 FcIpsilat and T2-T1 FcContra)

Mesofacial vs. Dolichofacial Groups					
	Mesofacial (n=19)		**Dolichofacial (n=10)**		
	Average	**SD**	**Average**	**SD**	**P-value**
Age (years)	29.8	15.0	32.1	13.3	ns
T1 FcIpsilat	48.6	9.8	45.4	8.3	ns
T2 FcIpsilat	45.9	15.9	43.3	8.4	ns
T2-T1 FcIpsilat	-2.5	14.5	-2.1	8.1	ns
T1 FcContra	56.3	7.0	60.2	7.9	ns
T2 FcContra	54.1	18.1	61.3	3.9	ns
T2-T1 FcContra	-2.6	16.4	1.0	6.7	ns

FcIpsilat = TMJ Loads Ipsilateral. FcContra = TMJ Loads Contralateral. No significant difference in TMJ loads between dolichofacial and mesofacial groups, where ns = not significant

Table 11: Pre-surgery and post-surgery ipsilateral and contralateral TMJ loads (% of applied bite force) during canine biting for brachyfacial subjects

TMJ Loads – Brachyfacial Group (n=17)					
	Pre-Surgical		**Post-Surgical**		
	Average	**Standard Deviation**	**Average**	**Standard Deviation**	**P-Value**
Ipsilateral	50.6	8.4	50.5	8.8	ns
Contralateral	59.2	10.0	59.5	9.1	ns

No significant difference in TMJ loads between pre-and post-surgical TMJ loads in brachyfacial subjects, where ns = not significant

Table 12: Pre-surgery and post-surgery ipsilateral and contralateral TMJs (% of applied bite force) during canine biting for mesofacial subjects

TMJ Loads – Mesofacial Group (n=19)					
	Pre-Surgical (T1)		**Post-Surgical (T2)**		
	Average	**Standard Deviation**	**Average**	**Standard Deviation**	**P-Value**
Ipsilateral	48.6	9.8	45.9	15.9	ns
Contralateral	56.3	7.0	54.1	18.1	ns

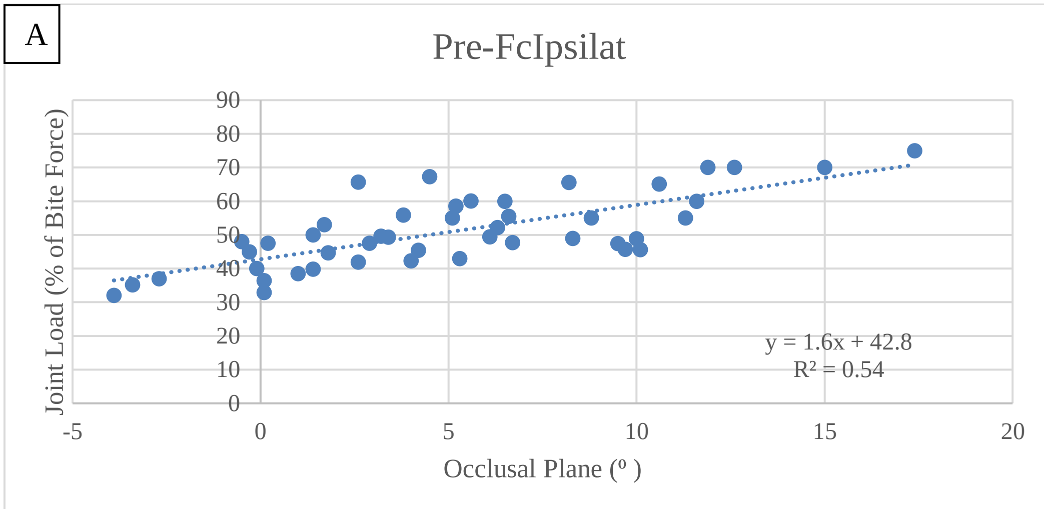
No significant difference in TMJ loads between pre-and post-surgical TMJ loads in mesofacial subjects, where ns = not significant

Table 13: Pre-surgery and post-surgery ipsilateral and contralateral TMJ loads (% of applied bite force) during canine biting for dolichofacial subjects

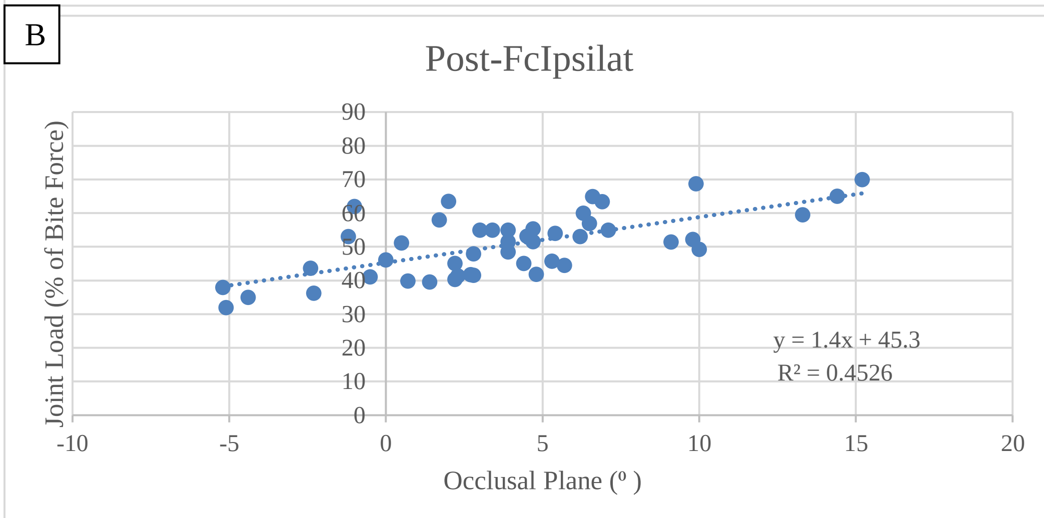
TMJ Loads – Dolichofacial Group (n=10)					
	Pre-Surgical (T1)		**Post-Surgical (T2)**		
	Average	**Standard Deviation**	**Average**	**Standard Deviation**	**P-Value**
Ipsilateral	45.4	8.3	43.3	8.4	ns
Contralateral	60.2	7.9	61.3	3.9	ns

No significant difference in TMJ loads between pre-and post-surgical TMJ loads in dolichofacial subjects, where ns = not significant

A


Pre-FcIpsilat
Joint Load (% of Bite Force)
90
80
70
60
50
40
30
20
10
0
-5
0
5
10
15
20
Occlusal Plane (º)
y = 1.6x + 42.8
R² = 0.54

B


Post-FcIpsilat
Joint Load (% of Bite Force)
90
80
70
60
50
40
30
20
10
0
-10
-5
0
5
10
15
20
Occlusal Plane (º)
y = 1.4x + 45.3
R² = 0.4526

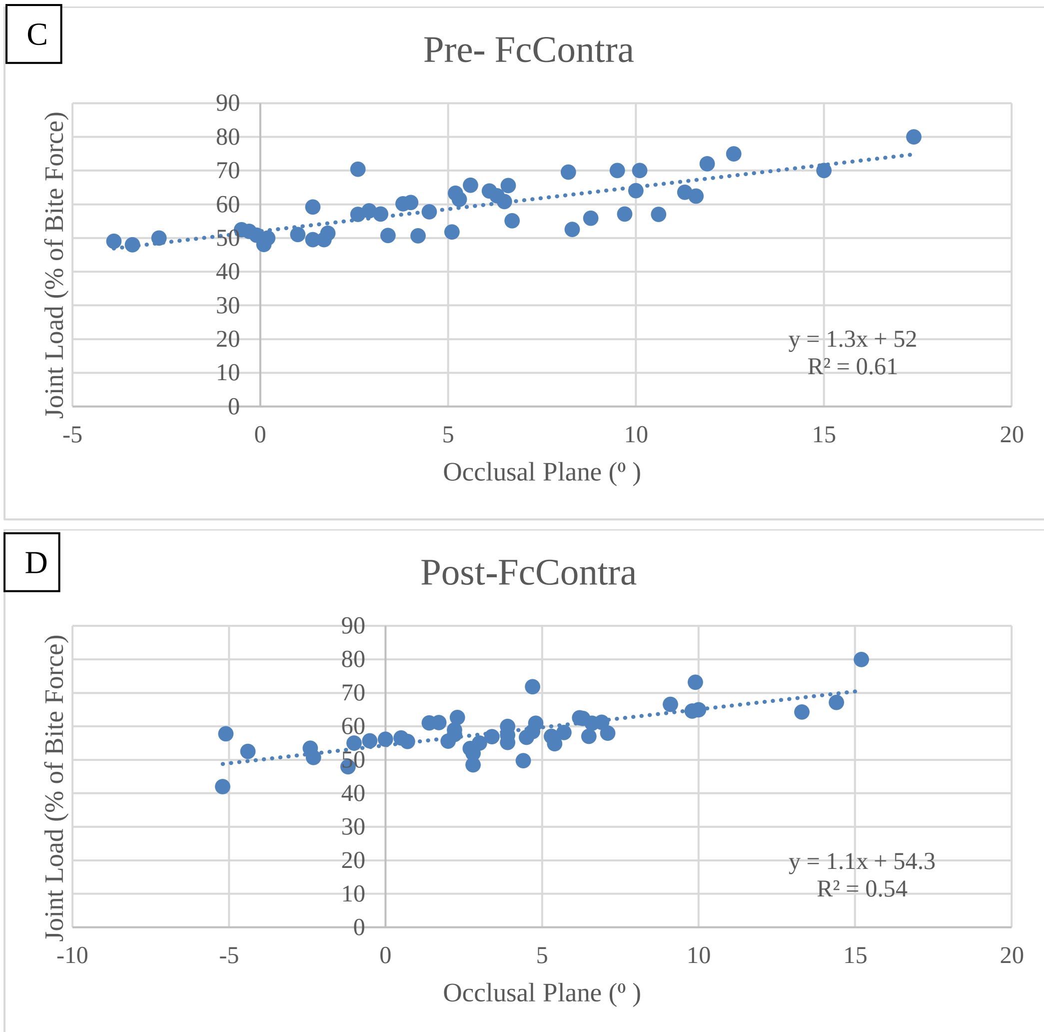


Figure 6: Ipsilateral (FcIpsilat) and contralateral (FcContra) TMJ loads (% of applied bite force) during canine biting versus occlusal plane angle (º) for all cases pre-surgery (A and C respectively) and post-surgery (B and D, respectively).

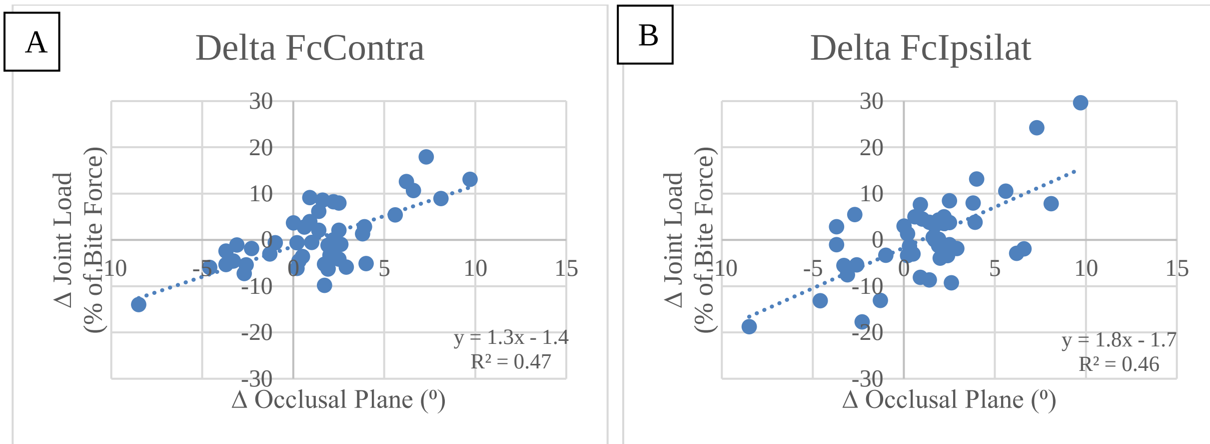


Figure 7: Change in Contralateral (FcContra) (A) and Ipsilateral (FcIpsilat) (B) TMJ loads (% of applied bite force) during canine biting versus change in occlusal plane angle (post-surgery OP-FHº – pre-surgery OP-FHº) for all cases.

5) Discussion

5.1 Craniofacial form and TMJ loads

The study evaluated ipsilateral and contralateral TMJ load force differences, for the same static canine biting conditions, between brachyfacial, dolichofacial, and mesofacial phenotypes before and after orthognathic surgery. The descriptive statistics for FHMPA and OP-FH affirmed the significant differences in these measurements between the pre-surgical dolichofacial, mesofacial, and brachyfacial subjects (Table 4).

The results showed no significant difference between or within facial types for ipsilateral and contralateral TMJ loads. This affirms the null hypothesis, that there are no differences between facial type and TMJ loads before or after orthognathic surgery. This does not support the findings of Nickel et al. that following orthodontic and orthognathic surgical treatments, small increases in TMJ loads occur.[2] The results also do not support the findings by Iwasaki et al. that ipsilateral and contralateral TMJ loads were significantly different and ≥20% larger in dolichofacial than brachyfacial phenotypes.[3] Previous research found that different θ_{xz} biting angles produced jaw-distalizing bite forces and significant differences in joint loads, with >20% difference between facial groups. [3] The loads for this study were averaged over all angles, eliminating the ability to distinguish group difference if loads were dependent on specific biting angles. Averaging the biting angles potentially explains the difference in findings from previous research. The relationship to facial type and occlusal plane angle showed that dolichofacial subjects had a steeper occlusal plane, on average, than mesofacial and brachyfacial subjects. While the facial phenotype did not show a significant relationship to TMJ loads during average canine biting, the occlusal plane angle was highly associated (R^2=0.45-0.61, Figure 6) to TMJ loads. This indirect relationship does relate to the results found by Iwasaki et al in 2017.[3] The current results demonstrated larger TMJ loads as the occlusal plane angle increased. The largest, and potentially the most clinically important result, was for the ipsilateral joint TMJ loads as the occlusal plane angle increased following surgery. The slope of this regression indicates a larger change in occlusal plane angle is associated with a larger increase in TMJ loads and that a ≥7 degree increase in occlusal plane angle could result in ≥20% increase in TMJ loads. These results indicated the importance of managing the occlusal plane angle during orthognathic surgical planning and treatment. The current study demonstrated that minimizing the change in the occlusal plane to less than 10 degrees minimized increases in TMJ loads. The occlusal plane orientation to muscle and bite force vectors may explain the group differences. Park et al. evaluated the effects of the occlusal plane on masticatory function, using bite force, masticatory muscle activity, and biting efficiency as measurements, after orthognathic surgery.[68] These authors found a significant negative correlation with postoperative occlusal plane and masticatory efficiency, meaning the steeper occlusal planes were less efficient, however, the differences were not significant.[68] Sato et al. evaluated the inclination of the occlusal plane and the direction of the masticatory movement path.[69] The masticatory axis was defined as the axis passing the opening and closing turning point on the sagittal masticatory path. These authors found a positive correlation between the Frankfort-horizontal plane-masticatory axis, occlusal plane, and mandibular plane angles and concluded that the masticatory movement path was closely associated with the occlusal plane.[69] These findings support the concept of facial phenotypes, including occlusal plane differences, influencing masticatory function. Wolford et al. discussed the importance of the occlusal plane alteration in orthognathic surgery.[13,70] Surgical alteration of the occlusal plane may provide benefits to the patient relative to functional and esthetic results. These authors stated that as the occlusal plane increased in steepness, it approached the slope of the TMJ articular eminence, which could produce functional problems, and potentially increase risk for TMD.[12,13,70] Wolford et al. emphasized that with proper planning and rigid fixation, increasing or decreasing the occlusal plane with healthy TMJs are stable procedures.[13] However, this claim was not followed up long-tem. In addition, research showed the development of the TMJ eminence to be consistent with the objective minimization of joint loads.[71] Therefore, by altering the mechanics with the change in occlusal plane angle, the eminence is no longer consistent with this biologic objective; that is, the eminence shape becomes inconsistent with the minimization of the loads. [2,5,28,29,71] Since effective eminences may have developed into shapes associated with the objective of minimizing TMJ loads, the association could work to maintain mechanical integrity of joint tissues while high loads could cause fatigue failure.[71] Therefore the inconsistency with joint load minimization following the altered occlusal plane could cause increased joint loading magnitudes, fatigue-failure and increased risk for degenerative TMJ changes. Since surgeons have the ability to plan for the final occlusal plane angle, careful planning will help to control occlusal plane angle and avoid increasing its steepness with treatment to avoiding the expected concomitant increase in TMJ loads, and therefore minimizing one risk factor for developing DJD following surgery. Since DJD is complex, it is essential to minimize all risks clinicians are able to control.

5.2 Gender

Within the groups, there were two significant findings between males and females. In the dolichofacial phenotype, males had a significantly larger average ΔT2-T1 FHMPA (°) (-9.8° ± 0.9°) than females (-3.2° ± 4.5°) (Table 6). This may be indicative of preferred facial esthetics for each gender. Another significant difference ($P<.02$) seen between genders found in the dolichofacial group was Δ OP-FH (°), post-surgery OP-FH (T2) – pre-surgery OP-FH (T1), the change was larger in males (-8.5° ± 1.7°) than females (-1.6° ± 3.4°). The dolichofacial group had an uneven distribution of males (n = 2) versus females (n = 8); hence, a more balance sample is needed to evaluate the gender differences within the dolichofacial group. Reports in the literature indicate women have a higher risk and incidence, reported, for TMD.[72-75] Therefore, reducing TMD risk factors for women following surgery is especially important. While the occlusal plane angle was reduced, it was, on average, less of a decrease for dolichofacial females than for dolichofacial males following orthognathic surgery. It may be a consideration to reduce the occlusal plane more for dolichofacial females than dolichofacial men, if possible, when surgical treatment planning.

5.3 Limitations of the study

This study has several limitations. This was a retrospective study, so the numerical model that predicted TMJ loads was not tested for accuracy by comparing data recorded from subjects with model predictions. Since it is not possible to measure in vivo TMJ loads in humans, testing of accuracy of modeling could be accomplished by comparing model predicted muscle activities for a given jaw-loading task with data of muscle activities recorded in subjects performing the same jaw-loading task. This was not possible given the retrospective nature of the study.

As a retrospective study from a private office, the sample size was limited by the data available. The office had incomplete records available prior to 2011 due to switching from paper to digital records. Therefore, data for mesofacial subjects were included due to limited number of subjects for both dolichofacial and brachyfacial facial types.

The study was limited by focusing on canine biting. Future follow up studies could evaluate incisor, canine, and molar biting. In addition, future studies could evaluate specific biting angles, where, rather than averaging biting angles as was done in the current study, further analysis could include testing biting angle effects on dolichofacial and brachyfacial joint loads. Another limitation of the study was that skeletal symmetry was assumed. Future studies could evaluate the same CBCTs, using both lateral views, to evaluate potential asymmetries and the effects on TMJ loads. The focus of the study on TMJ loads fails to consider the importance of compressive stress on the longevity of the TMJ tissues. The TMJ complex is repeatedly subjected to mechanical loading producing various levels of stresses on it. Stress is measured by the amount of force over a given area. In this study, the areas of TMJ loading were unknown for the given canine biting tasks in each case at each time-point. Future work, which brings together the 3D anatomy of the TMJ and finite element modeling of stress distribution over the articulating surfaces, may be a fruitful area of future research to explore the effects of orthognathic surgery. Additionally, dynamic mechanics, and the mechanical work imposed on the TMJ cartilages as a result of tractional forces, remains open for new research endeavors. Static and dynamic mechanics could affect the shape and/or volume of the cartilage, and be a critical factor in the development of osteoarthritis.[2,5,6,28,76,77]Along this line, the current study did not look at the change in the proximal segment, as it would rotate around the X, Y, or Z-axes. The rotation of the proximal segment could alter the joint congruency, changing the contact areas within the TMJ in different functional positions. The change in position of the proximal segment could be a factor in developing DJD. Many surgeons work to control the proximal segment to try to maintain the same joint relations pre- and post-surgery.

New developments in finite element modeling indicate that future research should examine the pathophysiology of nutrient supply to the TMJ disc cartilage, as it is an important factor in TMJ longevity. Cisewki et al. conducted a study to determine the combined effect of oxygen level and glucose concentration on cell viability, ATP production, and matrix synthesis of TMJ disc cells.[78] The study used pig TMJ disc cells and cultured them with different glucose concentrations at various oxygen levels and measured cell viability. Cell viability was significantly decreased without glucose. When glucose was present and oxygen levels were low, cell viability increased significantly, however, as the oxygen levels decreased with glucose present, production of ATP, collagen, and proteoglycan were decreased. The authors concluded that while both glucose and oxygen are important in cell viability, glucose is the limiting nutrient for the TMJ disc cell survival.[78] Furthermore, Wu et al. evaluated the region and strain-dependent diffusivities of glucose and lactate in healthy human cartilage endplate (CEP) and found that mechanical strains impeded solute diffusion in the CEP, significantly.[79] The CEP is implicated as the main pathway for nutrient supply to the disc. The authors emphasized the importance of maintaining the balance of nutritional environment in healthy human disc under mechanical loading to reduce the risk of disc degeneration.[79] In a later study, Wu et al. discovered sustained mechanical loading of TMJ discs significantly reduced nutrient levels, using experimental and computational modeling approaches.[80] With the critical interaction of mechanical loading and nutrient supply and metabolism of the TMJ disc, managing loads is critical. Increasing TMJ loads has potential to alter the nutrient supply to the TMJ disc. Finite element modeling of oxygen and glucose gradients in the TMJ cartilages before and after surgery may be a beneficial research endeavor.

As clinicians, it is important to create an informed and evidence based treatment plan. Understanding the changes made during orthognathic surgery better helps the planning stages. This study highlighted the importance of the occlusal plane in relation to TMJ loads during canine biting. More research needs to be completed to further understand the changes in TMJ loads following orthognathic surgery for all facial types. In addition, more research is needed to understand the joint changes and risks for DJD following orthognathic surgery.

6) Conclusions

TMJ loads were not statistically significantly different in dolichofacial, mesofacial, and/or brachyfacial subjects before and after orthognathic surgery. Gender and age had no significant effects on TMJ loads for canine biting. However, facial phenotype was related to occlusal plane angle, with higher occlusal plane angles found in dolichofacial subjects compared to lower occlusal plane angles found in brachyfacial subjects. The occlusal plane angle was positively associated with TMJ loads ($R^2 = 0.45 – 0.61$) with higher TMJ loads for the ipsilateral joint than the contralateral joint. Using a definition of changes of ≥20% in TMJ loads were clinically important, this study showed that when occlusal plane angles were increased ≥7 degrees, clinically important increases in TMJ loads were predicted and thus, possibly increase the risk of Degenerative Joint Disorder (DJD) following orthognathic surgery.

Appendix1: IRB approval Letter

OREGON HEALTH & SCIENCE UNIVERSITY

IRB MEMO

Research Integrity Office
3181 SW Sam Jackson Park Road - L106RI
Portland, OR 97239-3098
(503)494-7887 irb@ohsu.edu

APPROVAL OF SUBMISSION

February 15, 2019

Dear Investigator:

On 2-15-2019, the IRB reviewed the following submission:

IRB ID:	STUDY00019428	MOD or CR ID:	MOD00018174
Type of Review:	Modification		
Title of Study:	TMJ loads during biting in long and short facial types: Changes pre- and post-orthognathic surgery		
Title of modification	TMJ loads during biting in long and short facial types: Changes pre- and post-orthognathic surgery		
Principal Investigator:	Laura Iwasaki		
Funding:	None		
IND, IDE, or HDE:	None		
Documents Reviewed:	• Protocol		

The IRB granted final approval on 2/15/2019. The study is approved until 1/26/2022.

Review Category: Expedited-Minor Modification

Copies of all approved documents are available in the study's **Final** Documents (far right column under the documents tab) list in the eIRB. Any additional documents that require an IRB signature (e.g. IIAs and IAAs) will be posted when signed. If this applies to your study, you will receive a notification when these additional signed documents are available.

Ongoing IRB submission requirements:

- Six to ten weeks before the expiration date, you are to submit a continuing review to request continuing approval.
- Any changes to the project must be submitted for IRB approval prior to implementation.
- Reportable New Information must be submitted per OHSU policy.
- You must submit a continuing review to close the study when your research is completed.

Version Date: 06/30/2016 Page 1 of 2

Guidelines for Study Conduct

In conducting this study, you are required to follow the guidelines in the document entitled, "Roles and Responsibilities in the Conduct of Research and Administration of Sponsored Projects," as well as all other applicable OHSU IRB Policies and Procedures.

Requirements under HIPAA

If your study involves the collection, use, or disclosure of Protected Health Information (PHI), you must comply with all applicable requirements under HIPAA. See the HIPAA and Research website and the Information Privacy and Security website for more information.

IRB Compliance

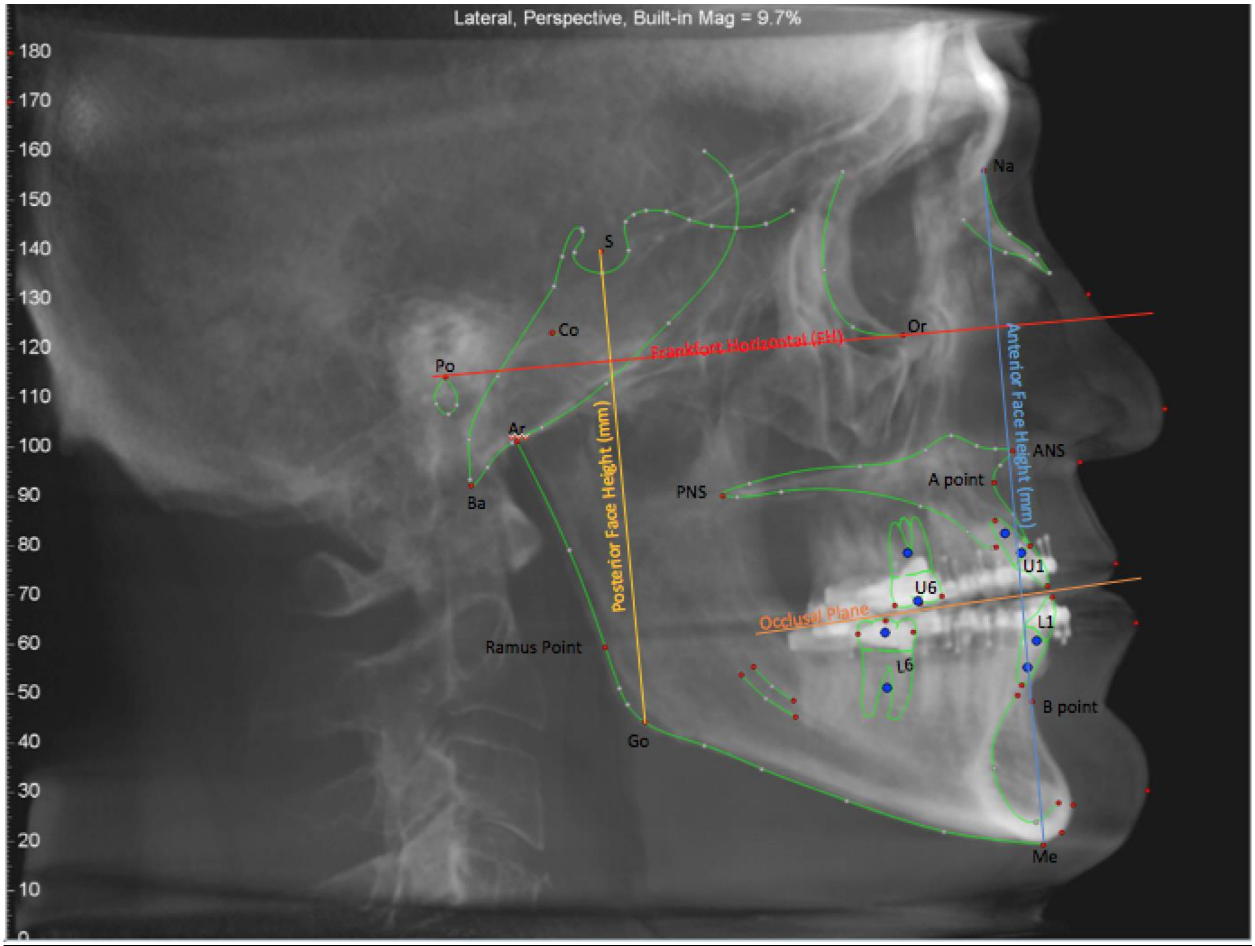
The OHSU IRB (FWA00000161; IRB00000471) complies with 45 CFR Part 46, 21 CFR Parts 50 and 56, and other federal and Oregon laws and regulations, as applicable, as well as ICH-GCP codes 3.1-3.4, which outline Responsibilities, Composition, Functions, and Operations, Procedures, and Records of the IRB.

Sincerely,

The OHSU IRB Office

Version Date: 06/30/2016 Page 2 of 2

Appendix 2: Custom Cephalometric Analysis



Appendix Figure 1: Traced Lateral Cephalogram Example – showing landmarks as listed below.

From the CBCT-derived lateral cephalogram, the following cephalometric landmarks (Appendix Figure 1):

- Porion (Po)
- Orbitale (Or)
- Sella (S)
- Nasion (Na)
- Basion (Ba)
- Bridge of nose
- Tip of nose
- Menton (Me)
- Gonion (Go)
- Ramus point

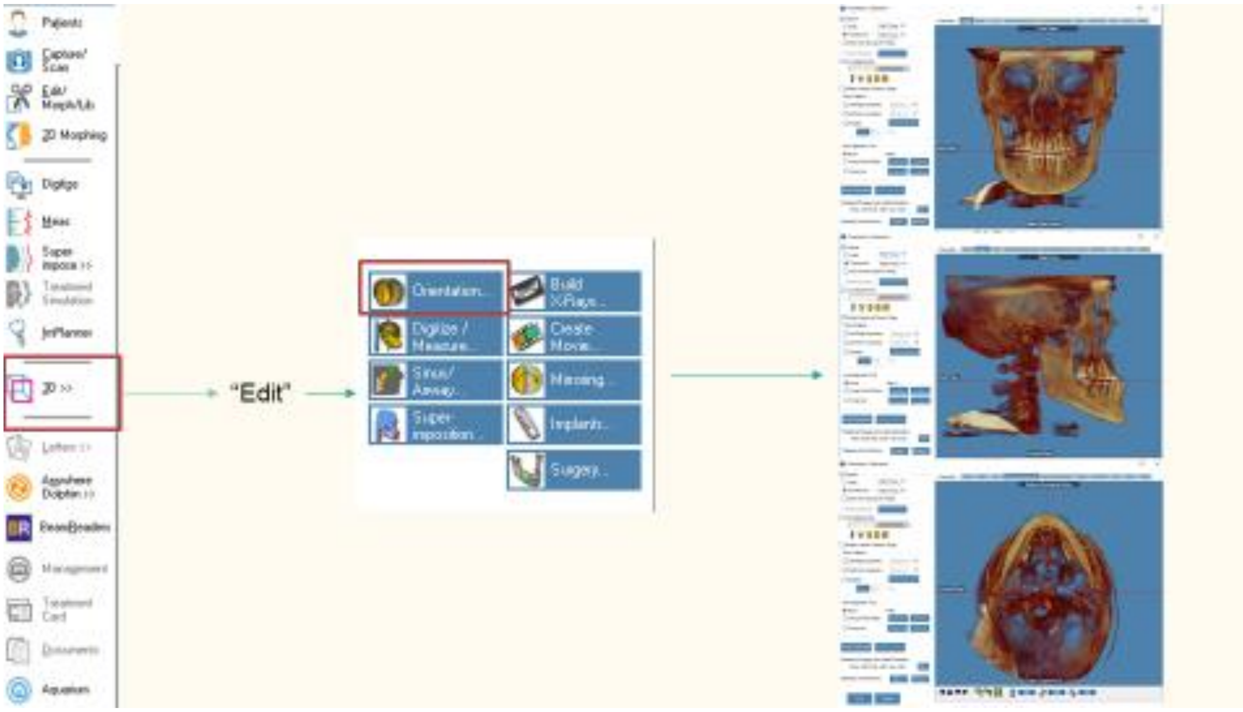
- Articulare (Ar)
- Constructed gonion
- Condylion (Co)
- A-point
- B-point
- Anterior nasal spine (ANS)
- Posterior nasal spine (PNS)
- Maxillary first molar (U6)
- Mandibular first molar (L6)
- Mandibular central incisor (L1)
- Internal symphysis superior
- Internal symphysis inferior
- Maxillary central incisor (U1)

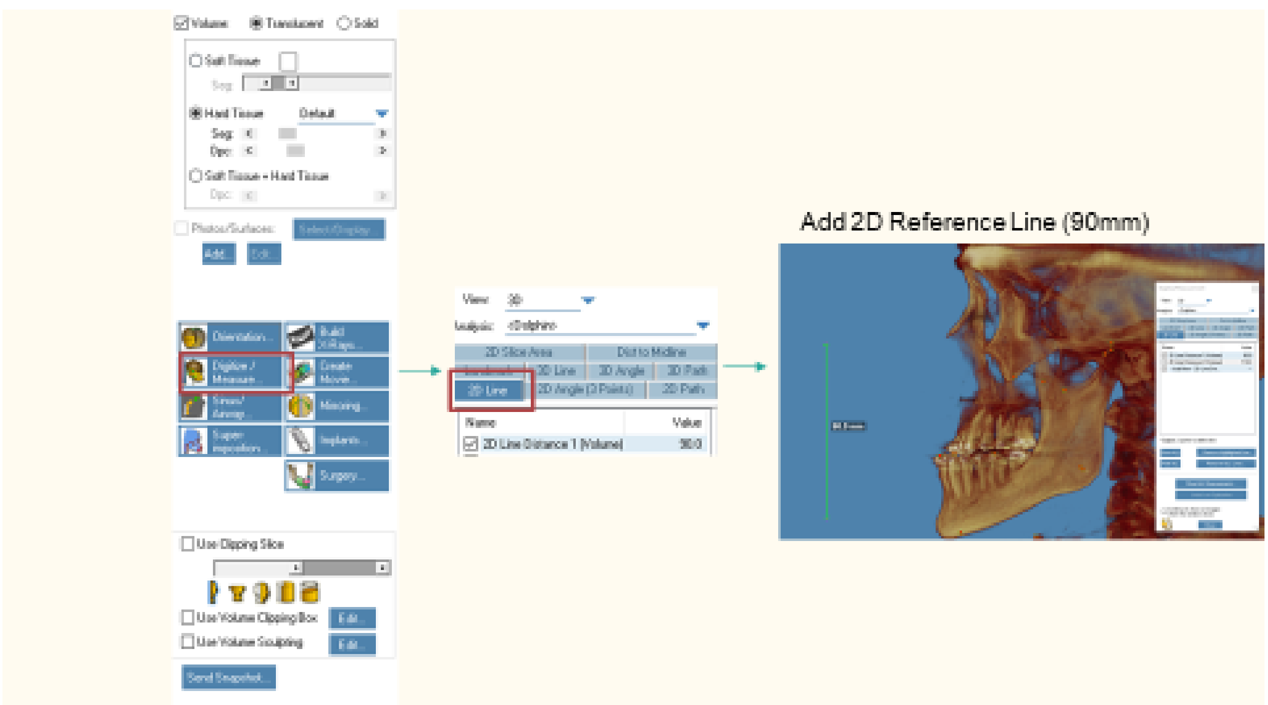
Using the listed landmarks, the following measurements, references lines, angles were used:

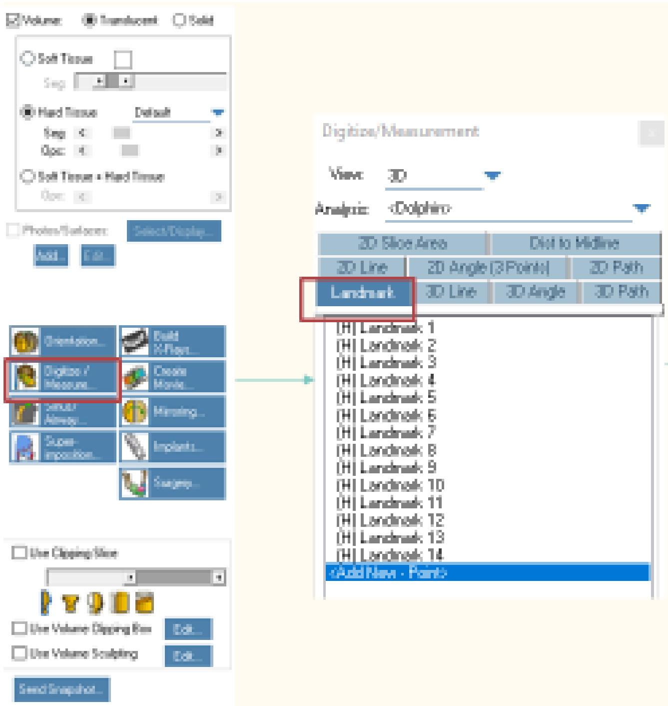
- Frankfort Horizontal (FH): Porion to orbitale
- Mandibular Plane (MP): Gonion to menton
- FHMPA (°): Angle between FH and MP
- Posterior Face Height (mm) – Sella – Gonion (S-Go)
- Anterior Face Height (mm) – Nasion – Menton (Na-Me)
- Posterior/Anterior face height (S-Go/Na-Me, %)
- Occlusal Plane – Line bisecting molars (U6/L6) and incisors (U1/L1)
- Occlusal Plane Angle – Angle between occlusal plane and FH (OP-FH, °)

The soft tissues landmarks, bridge of nose, tip of nose, soft tissue A-point and B-point, soft tissue menton, gnathion, pogonion, allowed for virtual treatment planning. All bilateral anatomic landmarks were represented by a mid-point between right and left landmarks. The same person traced the images using the cephalometric analysis software. If the subject's maxillary and mandibular posterior teeth were not in contact in the image, for example if a bite-stick was used when the CBCT image was made, a simulation was done using the cephalometric-software program to mimic maximum intercuspation of the posterior teeth.

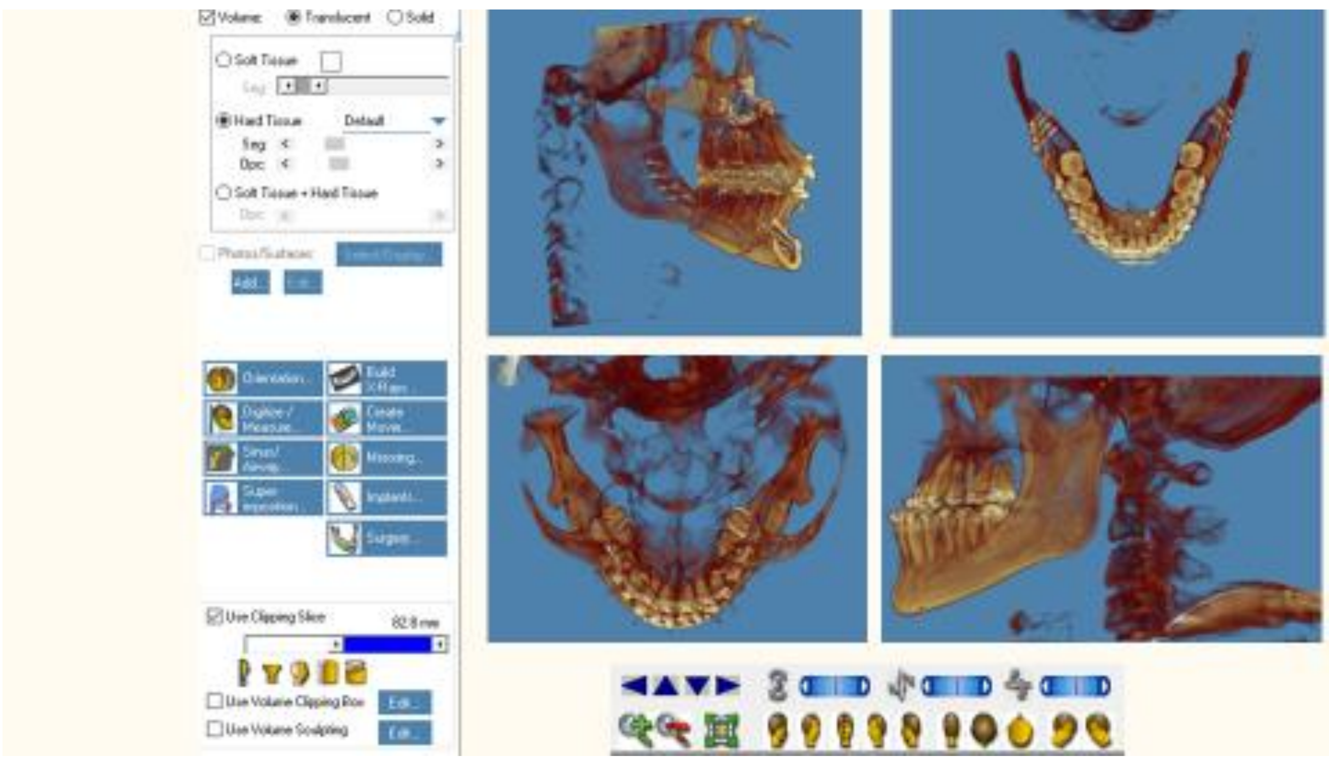
Appendix 3: Geometry file landmarks – additional guides to software application

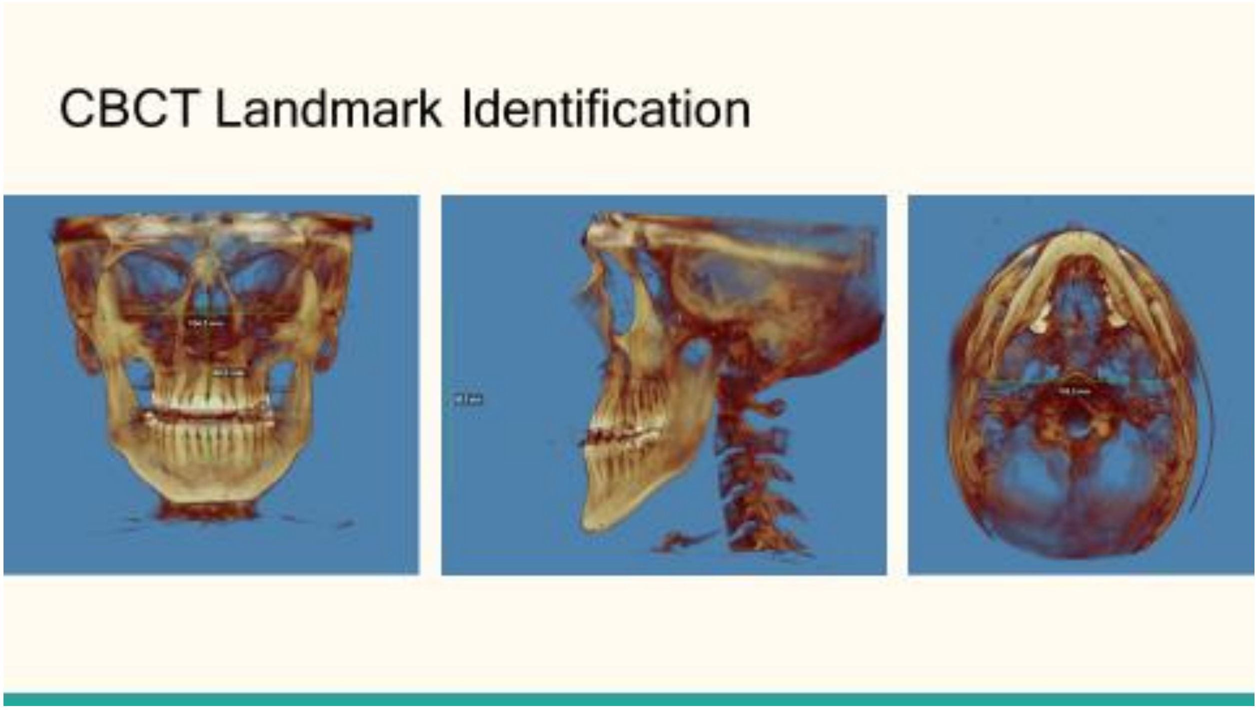






Landmarks Identified:
(1) Right and (2) left superoanterior most point of the condyles
(3) Left central incisor (midpoint of incisal edge)
(4) Left mandibular canine cusp tip
(5) Left mandibular first molar mesiobuccal groove
(6) Left masseter muscle "insertion" on mandible
(7) Left masseter muscle "origin" on skull
(8) Left medial pterygoid muscle "insertion" on mandible
(9) Left medial pterygoid muscle "origin" on skull
(10) Left lateral pterygoid muscle "insertion" on mandible
(11) Left lateral pterygoid muscle "origin" on skull
(12) Left anterior temporalis muscle "insertion" on mandible
(13) Left anterior digastric muscle "origin" on hyoid bone
(14) Left anterior digastric muscle "insertion" on mandible





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