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Three-dimensional Hard and Soft Tissue Change in the Treatment of Bimaxillary Protrusion

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Three-dimensional Hard and Soft Tissue Change in the Treatment of Bimaxillary Protrusion

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Three-dimensional Soft and Hard Tissue Change in the Treatment of Bimaxillary Protrusion

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ABSTRACT

Introduction: Lower facial convexity related to bimaxillary protrusion is prevalent in Asian and African populations. Underlying skeletal protrusion combined with increased dentoalveolar protrusion and incisor proclination influence facial muscle balance, contributing to lip incompetence, mentalis strain, and excessivegingival display. The relationship between dentoalveolar movement and soft tissue change is determined by facial anatomy and muscle activity. This study evaluates the relationship between soft and hard tissue movement resulting from orthodontic treatment in an Asian population. Three-dimensional (3D) correlations between lip and incisor movements are quantified to identify components of soft tissue adaptation. **Methods:** 24 consecutive non-growing Asian patients (n=20 female, n=4 male, mean age=24) diagnosed with severe bimaxillary dentoalveolar protrusion were evaluated using pre- and post-treatment cone beam CT (CBCT). Patients were treated with four first premolar extractions and anterior retraction using either skeletal or non-skeletal anchorage. Longitudinal CBCT radiographs were registered on the anterior cranial base using an automated, voxel-wise mutual information based algorithm. Soft and hard tissue changes were determined from vector displacements and visualized using color mapping. **Results:** Upper lip retraction was concentrated mainly between the nasolabial folds and commissures. Lower lip retraction was accompanied by significant redistribution of soft tissue at the pogonion. Soft tissue changes were variable and related to the initial resting lip posture. 3D upper lip retraction was correlated with vertical and A-P movement (p=0.03) of the upper incisor. Lower lip retraction was more variable, and correlated with lower incisor A-P movement (p=0.016). Use of skeletal anchorage resulted in 1.5 mm greater lower lip retraction than intraoral anchorage and with greater retraction of the upper and lower incisor root apices (p=0.02). **Conclusions:** Soft tissue adaptation resulting from anterior dental retraction correlated with regional facial muscle activity near the nasolabial fold, mentolabial sulcus, and pogonion. Significant retraction (2–4 mm) of soft tissue occured outside of the mid-sagital region.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Bimaxillary protrusion is a common dentofacial deformity particularly prevalent in Asian and African populations, and present in almost every ethnic group.[1-6] Underlying skeletal prognathism and dentoalveolar protrusion produce a convex lower-facial profile, procumbent lips and a protrusive anterior dentition, often resulting in lip incompetence, mentalis strain and excessive gingival display. This situation is often esthetically unacceptable to the patients and they seek treatment by the orthodontist or the oral surgeon. Both orthodontic and surgical treatments can be utilized to improve facial balance. Orthodontic treatment can correct dentoalveolar protrusion by uprighting and retracting the anterior teeth typically following extraction of four premolars. Surgical treatment reduces protrusion through repositioning of segments of the jaws. Both treatment approaches can reduce facial convexity and improve lip posture significantly.

Improvement of the soft tissue profile depends on many variables related to the anatomy of the face including lip thickness, facial muscle activity, and ethnicity.[7-12] The relationship between dentoalveolar movement and soft tissue change is complex and contingent on soft tissue relationships functioning in all three planes of space.[13-21] Previous studies have focused on lip changes occurring only in the mid-sagittal plane, using superimposed lateral cephalograms and facial photos.[6] However, the 2D approach fails to consider the complex three-dimensional (3D) geometry of the human face.[13,22] In particular, soft tissue changes in the frontal view are judged more heavily by patients and are often overlooked in clinical studies.[23] Computer simulations that predict soft tissue change from orthodontic and surgical movement rely on relationships derived from the mid-sagittal plane. Accurate treatment predictions require data on the three-dimensional relationship between hard and soft tissue change. Advances in (3D) imaging utilizing cone beam computed tomography (CBCT) and 3D photography can be utilized for global evaluation of these changes.[13,14,22,24-27]

This study was designed to evaluate the 3D changes in soft tissues resulting from hard tissue changes produced by orthodontic treatment of bimaxillary protrusion. The goals were to: (1) characterize 3D changes to the face and skeleton resulting from retraction of the anterior teeth, (2) identify and quantify relationships between incisor and lip movement occurring outside of the mid-sagittal plane, and (3) test differences in results using skeletal and non-skeletal anchorage mechanics in the treatment of bimaxillary protrusion.

MATERIAL AND METHODS

The study population consisted of 24 consecutive non-growing Asian patients with bimaxillary dentoalveloar protrusion treated in the orthodontic clinic at the University of California, San Francisco. All patients were treated via extraction of four first premolars, and retraction of the anterior dentition using controlled maxillary anchorage. Institutional review board approval for the study was obtained from the University of California, San Francisco prior to treatment.

The inclusion criteria for patients were: a Class I molar and canine relationship, mild or no crowding, severe dentoalveolar protrusion, and complete pre- and post-treatment CBCT radiographs and photos. Only non-growing Asian patients were included. The group was mostly female (n=20), with ages ranging from 20-29. Initial protrusion was quantified by measuring the distance between the most anterior point on the maxillary and mandibular incisors to the A point–Pogonion along a line parallel to Frankfurt Horizontal (**Fig. 1A**). Lip thickness was measured from the cervical aspect of the maxillary and mandibular incisors to the most anterior point on the upper and lower lips (*labrale superius* and *labrale inferius*) respectively **(Fig. 1A**). All patients had greater than two standard deviations of protrusion of the upper and lower incisors relative to Asian means (**Table I**). The degree of upper and lower incisor protrusion, skeletal protrusion (defined by SNA, SNB), sagittal jaw relationship (defined by ANB), lip thickness, and maxillary and mandibular crowding were similar between treatment groups (**Table I**). The differences were not statistically significant (P>0.05).

Patients meeting the inclusion criteria were divided into two treatment groups based on the type of anchorage utilized. Both groups were treated via extraction of four first premolars and full fixed appliances using 0.018” slot and twin brackets (Unitech™ or Ensignia™). Following resolution of anterior crowding, the mandibular anterior teeth were retracted *en masse* in both groups as shown (**Fig. 2**). In the skeletal anchorage group (n=11), bilateral C-tube temporary skeletal anchorage mini-plates[28] (C-plates) were placed mesial to the maxillary first molar (**Fig. 2**). The maxillary anterior teeth were then retracted *en masse* on a 0.016”x0.022” stainless steel archwire using elastomeric chain ligated from the c-tube to a canine retraction arm placed close to the height of the center of resistance. In the non-skeletal anchorage group (n=13), the maxillary canines were first retracted segmentally on a 0.016”x0.022” stainless steel archwire using a soldered stainless steel trans-palatal bar or arch between the maxillary first molars for anchorage (**Fig. 2**). Following retraction of the canines, the maxillary incisors were retracted *en-masse* using intrusion-retraction loops placed distal to the lateral incisors. Finishing was performed on a 0.0175” square stainless steel archwire.

Cone-beam computed tomography (CBCT) scans were taken at T1 (pre-treatment) and T2 (post-treatment) using the Hitachi CB MercuRay machine (Tokyo, Japan). Both scans were taken with the patient in maximum intercuspidation with lips and face in repose, as instructed by the technician. A scan captured 512 images with a 12-inch diameter spherical volume encompassing the face, jaws and entire cranial base. The voxel dimension was 0.376 mm^3. DICOM data sets were converted into Amira™ mesh files and manipulated using Amira™ 5.4.2 software (Visage Imaging, San Diego).

The T1 and T2 scans were registered on stable structures in the cranial base. Regions of the scan volumes were individually defined as a reference, masking structures outside the volume. This region included the entire cranial base, zygomatic arches, maxillary sinuses, frontal bone, and posterior cranial fossa (**Fig. 3**). These structures are stable in non-growing patients.[29-32] The masked T2 volume was then reoriented via isometric rigid translation and rotation onto the cranial base of the T1 scan using an automated, voxel-based algorithm which maximizes mutual information between the volumes.[25,27]

After the T1 and T2 volumes were registered on the cranial base, the hard tissue skeleton and exterior soft tissue surface were isolated using voxel-value based segmentation. The segmentation values were selected for optimal rendering, and kept constant for all time points and patients. Triangle-mesh surfaces were then generated representing the skeleton, teeth, and exterior facial soft tissue. To quantify the relative change between the T1 and T2 surfaces, vectors were calculated from each vertex on the T1 surface to the nearest point on the T2 surface, with a length equal to the Euclidean distance between the points. To determine the degree of change relative to the surface, the component of the vector perpendicular to the T1 surface was calculated, representing either outward (positive) or inward (negative) displacement of the surface. Surface distances were converted into a color scale, with longer wavelength colors (red), representing inward displacement, and shorter wavelength colors (blue) representing outward displacement (**Fig. 3**). A green color indicates zero displacement. The color maps represent a global approximation of actual surface displacements.

The accuracy of the cranial base registration was verified by visualizing the surface displacement map of the interior surface of the cranial fossa. The only deviation occurs at the boundary of the scans, which are not identical due to differences in patient orientation. Based on the color scale, differences between the surfaces is less than 0.5 mm over the region of the cranial fossa. CBCT registrations were repeated by two independent observers to verify consistency. 2D Slices were taken through the maxillary and ethmoid sinuses to confirm superimposition of trabeculae and finer structures within the sinus.

To quantify absolute changes to the dentition and soft tissue, landmark points were defined on the teeth and lips using InVivo™ (San Jose, CA) software. A coordinate system was constructed using an adjusted Frankfurt horizontal plane passing through sella prime, right porion, and right orbitale. Orthogonal vertical planes passing through nasion were defined relative to the horizontal. Twelve hard tissue landmarks were selected on segmented surfaces of the skull and teeth. These landmarks consisted of: the right and left maxillary and mandibular central incisor edges and root apices, and the maxillary and mandibular first molar crowns and mesial-buccal root apices. Ten soft tissue landmarks were defined by dividing the lips into five equally spaced slices spanning the inter-commissure length (**Fig. 1B**). The most anterior point on the upper and lower lips was landmarked in each sagittal section (**Fig. 1B**). Vectors were then determined at each landmark between the T1 and T2 surfaces, representing movement at each location between time-points. A separate mandibular superimposition using established stable structures[31] was performed to measure movement of the mandibular incisors.

Digital 2D cephalometric tracings were generated and superimposed on the cranial base using TIOPS™ software (Roskilde, Denmark; www.tiops.com). Lateral cephalograms were generated from the CBCT data using Dolphin™ 11.7 software (Chatworth, CA).

Statistical analysis

Displacement vectors for landmarks on the central incisors and lips were determined between timepoint T1 and T2 on the CBCT radiographs. The inclination change of the incisors was measured as the change in axial inclination between T1 and T2. The vertical and A-P (anterior-posterior) components of each vector were averaged between right and left incisors. The A-P components of lip movement were averaged across five planes spanning the inter-commissure length for the upper and lower lip to determine the average A-P movement for each lip.

The validity of superimposition and landmark placement was determined using two independent observers performing multiple observations on records of ten randomly selected patients from the combined groups. The calibrated independent observers repeated superimposition and landmark placement at two week intervals to determine inter- and intra-observer error. The variability in the A-P and vertical components of the displacement vectors between observations were used to calculate ICC coefficients to test reliability. The ICC values for intra-observer and inter-observer correlation were all greater than 0.85. In addition, Bland-Altman plots[33] were made to analyze the inter-observer differences. Histograms were constructed for all variables to assess for normality. Due to the small sample size and lack of normality, non-parametric methods were used. Inter-group differences were compared using a Wilcoxon rank sum test. Interactions between variables were mostly linear, as determined from testing in linear and quadratic models. A non-parametric Spearman rank correlation coefficient was calculated for each comparison, and adjusted for multiple comparisons using a Holm-Sidak correction. The STATA™ software package was used for statistical calculations.

RESULTS

Treatment group characteristics

The facial profiles of the patients in this study were all characterized by convexity of the lower facial 1/3rd . The typical lip profile was protrusive, demonstrating either mentalis strain or an inter-labial gap at rest. The variability in lip thickness was relatively low within the population (mean standard deviation=1.94 mm). Crowding was mild (<4 mm) in each arch, and was not significantly different between groups (**Table I**). The skeletal sagittal jaw relationship was within normal limits in both groups. There were no statistically significant ($p>0.05$) differences in the dental or skeletal parameters between groups.

Quantified Dental and Soft Tissue Movements

Dental Displacement

The maxillary incisor edges were retracted 1.47 mm more posteriorly on average in the skeletal anchorage group than in the non-skeletal group (p=0.13; **Table II**). The root apices of the maxillary incisors in the skeletal anchorage group were retracted approximately 0.9 mm on average, with little apical root retraction in the non-skeletal anchorage group (p=0.053; **Table II**). This movement was accompanied by 3.36° greater reduction on average in maxillary incisor proclination in the non-skeletal anchorage group. These differences, however, were not statistically significant with the available sample size. Movement of the maxillary incisor edge followed a consistent inferior and posterior vector, with a high degree of correlation between A-P and vertical movement (p=0.0005; **Table III**). The sagittal and vertical movements of the maxillary incisors were highly correlated with the degree of retroclination (p=0.0002; **Table III**), indicating primarily an apex-centered tipping movement, especially in the non-skeletal anchorage group.

The reduction in lower incisor proclination was not significantly different between treatment groups. Movement of the mandibular incisor was more variable in both groups. Coordination between vertical and horizontal movement was low (ρ=-0.10; **Table III**), indicating significant variability in the vector of movement. Retraction of the anterior teeth was accompanied by significant remodeling of the supporting alveolar bone. In both groups, remodeling of alveolar bone was measured around the roots of the maxillary and mandibular anterior teeth, approximately 1-2 mm in magnitude (**Fig. 4A2-C2** and **5A2-C2**).

The maxillary first molars moved significantly more mesial (2.40 mm) in the non-skeletal anchorage group (p=0.008; **Table II**). No significant difference was detected in the vertical movement of the maxillary molars. However, there was considerable variability in vertical movement between individuals. This vertical movement produced measurable degrees of forward (**Fig. 4A1**) or backward (**Fig. 5C1**) rotation of the mandible.

Soft Tissue Displacement

Three-dimensional soft tissue displacement varied considerably between patients and treatment groups (**Fig. 4A3-C3** and **Fig. 5A3-C3**). Significant redistribution of soft tissue was measured at the submental sulcus and soft tissue pogonion. The lip change extended to the nasolabial folds laterally, the columella superiorly, and mentolabial sulcus inferiorly. Patients beginning with a resting inter-labial gap showed the greatest change to the lower lip position in response to maxillary incisor retraction, bringing the lips come together (**Fig. 4A3, C3** and **Fig. C3**). Changes outside of the lip region were noted in the lateral view in several patients, notably in the masseter region and cheeks where inward soft tissue movements were detected (**Fig. 4C3** and **Fig. 5C3**). It should be noted that some patients experienced significant changes in weight during the treatment period, as noted in facial photographs, consistent with generalized retraction of soft tissue in the cheeks. In patients in which the mandibular plane angle decreased due to maxillary molar intrusion, the chin moved anteriorly, as noted in the skeletal and soft tissue projections (**Fig. 4A1,A3**).

Mean lower lip retraction was greater in the skeletal anchorage group by 1.49 mm, but was not statistically significant ($p=0.051$; **Table II**). Retraction of the lower lip was significantly correlated with A-P movement of the lower incisors ($\rho=0.71$; **Table III**), with little ($\rho=0.52$; **Table III**) correlation with upper incisor A-P movement. Retraction of the upper lip was highly correlated with A-P movement of the maxillary incisors ($\rho=0.74$; **Table III**), and slightly correlated with A-P movement of the mandibular incisors ($\rho=0.63$; **Table III**). Correlation with vertical movement of the maxillary incisors was observed, but not statistically significant ($\rho=-0.60$; **Table III**). Significant lip retraction occurred in vertical sections away from the midline, diminishing only slightly toward the nasolabial fold (**Fig. 4A3-C3** and **Fig. 5A3-C3**). The retraction vector progressed from an A-P direction at the mid-sagittal plane, to a more laterally oriented vector near the commissures. The lower lip retraction zone was narrower, bounded by the submental sulcus inferiorly, and commissures laterally (**Fig. 4A3-C3** and **Fig. 5A3-C3**).

DISCUSSION

Three-dimensional soft tissue changes

Interpretation of the true soft tissue displacement is complicated by confounders such as weight change, variations in head posture and facial muscle activity.[9,34] We observed significant retraction of the upper and lower lips during treatment, which correspond with values reported in previous studies.[5,6,21,35-38] There was considerable individual variability in lip retraction. 3D studies of soft tissue change following surgical midface Le Fort I advancement show a similar pattern of change, bounded by the nose medially, and the nasolabial fold laterally.[13] The soft tissue change following surgical advancement of the maxillary alveolar process was concentrated in a triangular area spanning the nasolabial folds, similar to our measurements.[13]

The shape of the nasolabial fold is specifically influenced by muscle activity and age, and disappears in the paralyzed face.[39] It is made up of dense fibrous tissue and striated muscle bundles, with insertions for the levator muscles of the upper lip. This connective tissue plane may function as a boundary to upper lip retraction, accompanied by changes in resting muscle activity in the *lip levator* and *orbicularis oris* musculature. Other studies[40] have noted significant changes at the soft tissue pogonion level from orthodontic retraction or anterior segmental osteotomy. These changes may be related to a relaxation of the mentalis muscle and redistribution of the soft tissue in response to dental retraction.[40] 3D evaluation of lower lip change following surgical mandibular setback followed a similar pattern, with change concentrated over the central portion of the lower lip and chin.[22] Orthodontic retraction in this study produced lower lip changes which diminished toward the commissures, in proportion to the degree of retraction. However, in patients demonstrating significant lower lip eversion, the extent and zone of retraction was significantly greater, extending beyond the commissures to the buccal regions.

Correlations between hard and soft tissue changes

The relationship between lip retraction and anterior incisor movement relies on complex, multifactorial relationships that depend on lip strain and thickness[12], dentofacial morphology[21], and ethnicity and gender.[5,6,16,41] Soft tissue changes can be predicted using linear approximations of these relationships. Studies of lip movement following retraction of anterior teeth in Japanese populations[6,35] show upper lip retraction correlated strongest with horizontal retraction of the maxillary incisor, followed by vertical movement of the mandibular incisor. Our measurements yielded similar results, indicating a strong correlation of upper lip retraction with maxillary incisor A-P retraction. In addition, we observed upper lip retraction slightly correlated with mandibular incisor A-P retraction, and maxillary incisor vertical movement, consistent with the results of previous studies.[5,6,38] These studies also showed a strong correlation between lower lip retraction and both upper and lower incisor A-P retraction. In contrast, our population showed lower lip retraction strongly correlated only with A-P retraction of the lower incisors. Brock et al[38] showed strong correlation of upper lip movement with displacement of landmarks on the facial and cervical aspect of the upper incisor, consistent with our observations.

The ratio of maxillary incisor retraction to the mean upper lip retraction was 1.73:1 (**Table IV**), which is midway between reported ratios ranging from 1.5:1[42] to 2.5:1[37] in bimaxillary dentoalveolar protrusive Asian populations.[5,6,35,37,40-42] The ratio of mandibular incisor retraction to mean lower lip retraction in this study was 0.83:1 (**Table IV**), correspondingly lower than ratios of 1.12[42] to 1.32:1[35] reported in previous studies. However, these correlation coefficients only consider the A-P component of incisor movement, when in fact both the upper and lower incisors are also moving vertically. Significant intrusion and reduction of overbite were measured in both groups in this study, which also contributes to A-P lip retraction. In fact, upper lip retraction was more sensitive to vertical incisor movement than A-P movement, with a ratio of -0.61 maxillary incisor vertical movement to upper lip A-P retraction. Measurements of lip retraction lateral to the midline were also greater in many cases, contributing to a greater average lip retraction than seen with conventional 2D measurements. A similar effect was observed in 3D mid-facial soft tissue changes resulting from surgical mandibular setback, with greater retraction detected away from the midline.[22]

The difference could also be related to severe pre-treatment lip strain in this population. Many patients in this study exhibited a resting inter-labial gap or everted lower lip in repose, indicative of high lip strain when the lips are closed. Previous studies[9,12] demonstrate greater lip sensitivity in patients with either high lip strain or thin lips. Patients with a large resting inter-labial gap demonstrated the greatest lip retraction response per mm of incisor retraction. Retraction of the incisors in our study population may have induced changes in lip posture and facial muscle balance which could have amplified lip changes, resulting in lower ratios of incisor to lip retraction. One could conclude that the lip response resulting from treatment follows a non-linear relationship with respect to initial lip protrusion.

Anchorage Effects

The difference in lower lip retraction between anchorage types was consistent with results from previous studies showing significantly greater lower lip retraction in the skeletal anchorage group, with no detectable difference in upper lip retraction.[36] However, this difference represents only 35% of the total A-P lower lip retraction, which is not likely to be clinically significant. In contrast, studies in a dentally protrusive Chinese population showed the reverse, with greater upper lip retraction and no significant difference in the lower lip retraction.[43] The inter-group difference in retraction of the maxillary incisor edges was measurable (1.47 mm), but not statistically significant with the available sample size. Similarly, Liu et al.[43] reported a 2.27 mm difference in maxillary incisor retraction in a similar study comparing anchorage types in a bimaxillary protrusive Asian population. The inter-group difference in maxillary molar anchorage loss in the current study (2.4 mm) was less than observed values in other studies (3.3-4.0

mm).[36,43] This difference could be related to variation in the type of non-skeletal anchorage utilized in the treatment, with previous studies utilizing either transpalatal arches[43], or transpalatal bars occasionally including second molar ligation and headgear.

CONCLUSIONS

- 3D soft tissue changes resulting from retraction of the anterior teeth in patients with bimaxillary protrusion are variable, but correlated with initial resting lip posture. Upper lip retraction is concentrated between the nasolabial folds and commissures laterally. Lower lip retraction is concentrated at the midline, diminishing toward the commissures. Significant redistribution of soft tissue near pogonion can occur.
- A-P and transverse lip retraction is correlated with both A-P and vertical movement of the maxillary and mandibular incisors.
- Clinical soft tissue changes in bimaxillary protrusive patients treated with first premolar extraction are similar when using either skeletal or non-skeletal forms of anchorage. Treatment using maxillary skeletal anchorage results in 2.4 mm less maxillary molar anchorage loss.

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Table I. Population Characteristics

	Non-Skeletal Anchorage mean (s.d.)	Skeletal Anchorage mean (s.d.)	*P* value
U1i– A Pg (mm)	10.67 (2.38)	11.58 (2.57)	0.68
L1i– A Pg (mm)	6.43 (3.19)	6.81 (3.26)	0.91
SN/MP°	34.02 (5.84)	36.22 (5.64)	0.40
U1/PP°	122.10 (6.70)	119.58 (5.74)	0.45
L1/MP°	99.40 (5.35)	98.23 (4.98)	0.62
SNA°	83.79° (3.81)	83.29° (4.10)	0.45
SNB°	80.35° (4.42)	80.34° (3.45)	0.91
Mx Crowding (mm)	-3.90 (2.02)	-3.85 (0.84)	0.94
Mn Crowding (mm)	-2.60 (0.75)	-2.85 (0.57)	0.99
UL thickness	11.59 (1.45)	10.65 (2.59)	0.33
LL thickness	12.62 (1.64)	12.88 (2.08)	0.71
Age	21.6 (7.1)	27.4 (7.9)	0.10
Gender (% female)	91%	70%	0.22

UL, upper lip, *LL*, lower lip. U1i, maxillary incisal edge. L1i, mandibular incisal edge. *A Pg*, hard tissue A point to Pogonion line.

Table II. Inter-group Differences

Mean Movement (*T1* – *T2*)	Non-Skeletal Anchorage mean (s.d.)	Skeletal Anchorage mean (s.d.)	Difference	*P* value
Upper Lip retraction (mm)	2.26 (0.33)	2.67 (0.36)	-0.49	*NS*
Lower lip retraction (mm)	2.63 (0.40)	4.12 (0.73)	-1.49	0.051
U1i retraction (mm)	4.16 (0.74)	5.63 (0.66)	-1.47	0.13
U1i extrusion (mm)	1.79 (0.37)	1.84 (0.37)	-0.04	*NS*
U1 root retraction (mm)	-0.081 (0.33)	0.89 (0.47)	-0.97	0.053
L1i retraction (mm)	3.39 (0.74)	3.14 (0.71)	-0.25	*NS*
L1i intrusion (mm)	0.40 (0.23)	0.54 (0.37)	-0.13	*NS*
U1 retroclination (deg.)	13.18° (2.60)	9.82° (1.59)	-3.36	*NS*
L1 retroclination (deg.)	8.75° (1.45)	9.89° (1.72)	-1.14	*NS*
U6 crown A– P (mm)	1.95 (0.40)	-0.45 (0.55)	2.40	0.008*
U6 root A– P (mm)	1.81 (0.33)	-0.53 (0.32)	2.34	0.0004*
U6 crown Extrusion (mm)	0.02 (0.23)	0.83 (0.46)	-0.81	0.17

*Indicates $P < 0.05$. *NS* indicates $P > 0.2$. Lip retraction is measured as the mean anterior– posterior retraction measured at five landmarks spanning the inter-commissure distance.

Table III. Soft and Hard tissue Variable Correlation: Both Groups Combined

	UL ret	LL ret	U1i y	U1i z	U1 retro	L1 retro	L1i y	L1i z
UL ret.	-	0.69	0.74*	-0.60	0.53	0.26	0.63	-0.27
LL ret.	0.08	-	0.52	-0.24	0.26	0.30	0.71*	-0.14
U1i y	0.02*	0.50	-	-0.81*	0.83*	0.25	0.51	-0.36
U1i z	0.16	*NS*	0.0005*	-	-0.89*	-0.05	-0.30	0.44
U1 retro	*NS*	*NS*	0.0002*	<0.0001*	-	0.13	0.25	-0.36
L1 retro	*NS*	*NS*	*NS*	*NS*	*NS*	-	0.23	-0.14
L1i y	0.10	0.016*	*NS*	*NS*	*NS*	*NS*	-	-0.10
L1i z	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	-

Both groups combined (n=24). Spearman rank correlation coefficients (ρ) are in the upper right corner, P significance levels are in the lower left corner. *retro*, indicates retroclination. *y*, indicates anterior-posterior incisal edge movement. *z*, indicates vertical incisal edge movement. *UL* ret, and *LL* ret, indicate mean anterior– posterior retraction of the upper and lower lips respectively. * indicates $P < 0.05$, *NS* indicates $P > 0.5$

Table IV. Soft and Hard tissue Variable Interactions: Linear Regression Slopes

	UL ret.	LL ret.	U1i y	U1i z	U1 retro	L1 retro	L1i y	L1i z
UL ret.	-	0.69	0.74*	-0.60	0.53	0.26	0.63	-0.27
LL ret.	1.18 (0.51– 1.84)	-	0.52	-0.24	0.26	0.30	0.71*	-0.14
U1i y	1.73* (1.07– 2.40)	0.71 (0.22– 1.20)	-	-0.81*	0.83*	0.25	0.51	-0.36
U1i z	-0.61 (-0.98– -0.24)	*NS*	-0.35* (-0.51– -0.19)	-	-0.89*	-0.05	-0.30	0.44
U1 retro	4.00 (1.27-6.71) °/mm	*NS*	2.72* (1.76– 3.68) °/mm	-6.35* (-7.86– -4.84) °/mm	-	0.13	0.25	-0.36
L1 retro	*NS*	*NS*	*NS*	*NS*	*NS*	-	0.23	-0.14
L1i y	1.07 (-1.84– -0.29)	0.83* (0.45-1.22)	0.56 (0.19-0.93)	*NS*	*NS*	*NS*	-	-0.10
L1i z	*NS*	*NS*	*NS*	0.84 (0.17-1.52)	*NS*	*NS*	*NS*	-

Values of the slope of linear regression. Spearman rank correlation coefficients (ρ) are in the upper right corner, linear regression slopes are in the lower left corner. Dependent variables are indicated in the left column heading, independent variables are indicated in the upper row heading. *y*, indicates anterior-posterior incisal edge movement with posterior being positive. *z*, indicates vertical incisal edge movement with superior being positive. Values in parentheses are the 95% confidence interval. *indicates a P <0.05, *NS* P >0.5.

Figure 1. Soft Tissue Cephalometric Measurements

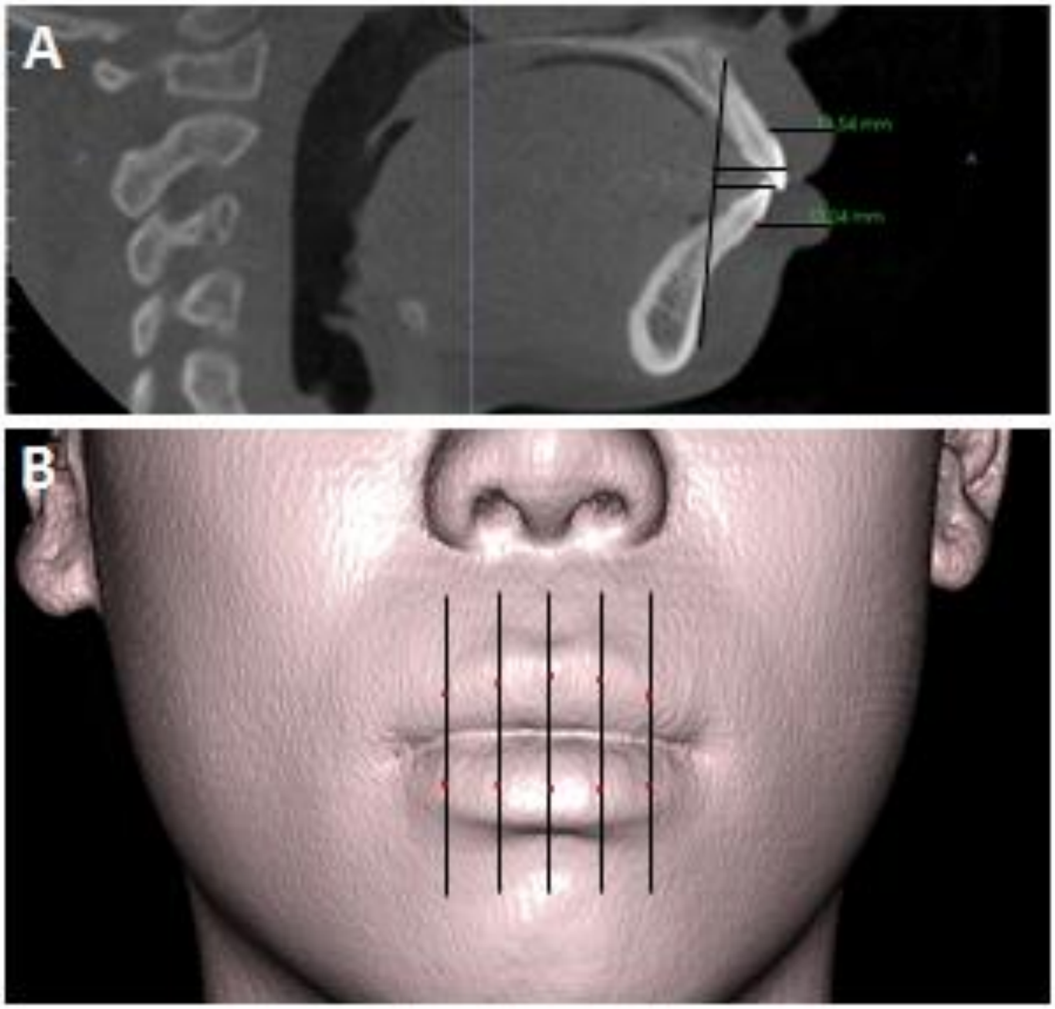

Figure 1. (**A**) Initial cephalometric measurements were made using a section centered at the mid-sagittal plane and aligned to the Frankfurt horizontal plane. Dentoalveolar protrusion was quantified by measuring the horizontal distance from the most anterior point on the maxillary and mandibular incisors to the hard tissue A point–Pogonion line. Lip thickness was measured from the most anterior point on the upper and lower lips to the cervical aspect of the maxillary and mandibular incisors respectively. (**B**) Changes to the lips between T1 and T2 were measured by

dividing the inter-commissure distance into five sagittal planes and placing landmarks at the most anterior point on the upper and lower lips in each plane.

Figure 2. Clinical photos illustrating the space closing mechanics used in the two treatment groups. The mandibular arch was treated the same in both groups. Following alignment and resolution of crowding, the mandibular anterior dentition from canine to canine was retracted *en-masse* on 0.016”x0.022” stainless steel wire in 0.018” slot brackets using elastomeric chains ligated from the first molar to the canine. In the skeletal anchorage group, the maxillary anterior dentition was retracted *en-masse* using a 0.016”x0.022” stainless steel archwire passing through labial c-tube temporary skeletal anchorage mini-plates placed mesial to the maxillary first molar. Elastomeric chains were ligated from hooks on the archwire to the c-tube for retraction. In the non-skeletal anchorage group, the maxillary canines were retracted segmentally on a 0.016”x0.022” stainless steel archwire using a trans-palatal bar or arch between the maxillary first molars for anchorage.

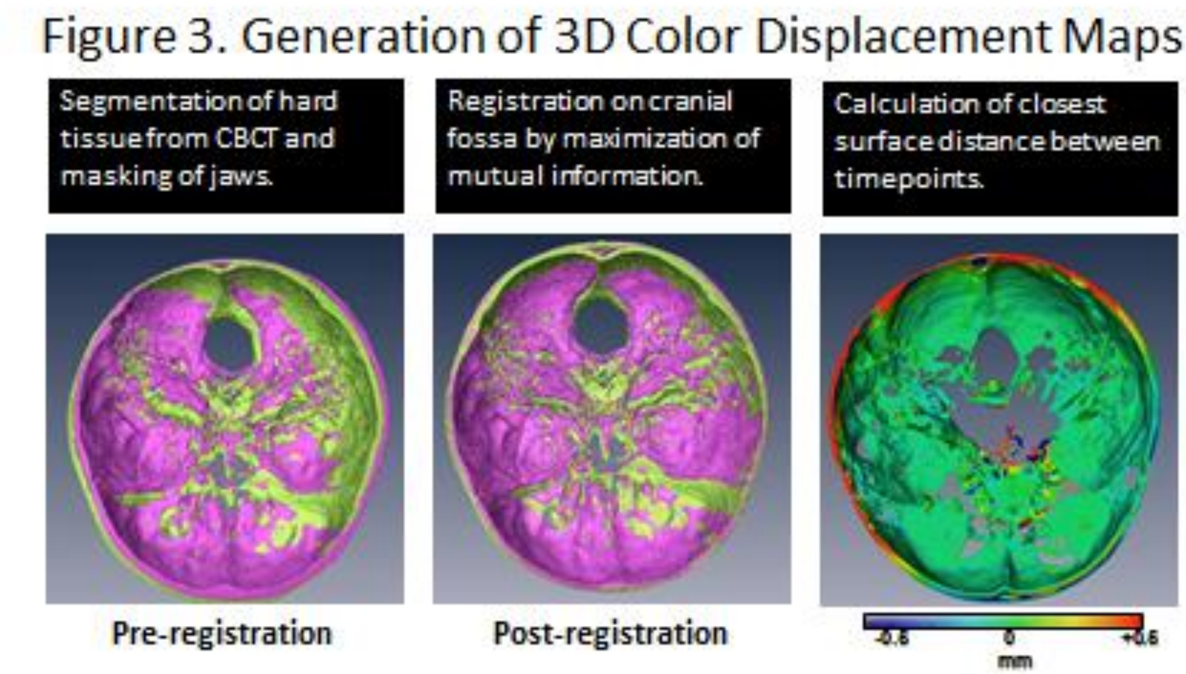

Figure 3. Registration method for the T1 and T2 CBCTs. Hard tissue was segmented, and the cranial fossa was separated from the skull. The CBCTs were registered using a rigid, automated, voxel-wise registration algorithm maximizing mutual information. Surface discrepancies between registered hard tissue surfaces at T1 and T2 are shown at 0.5 mm resolution. Green indicates no difference, blue= -0.5 mm, red= +0.5 mm difference.

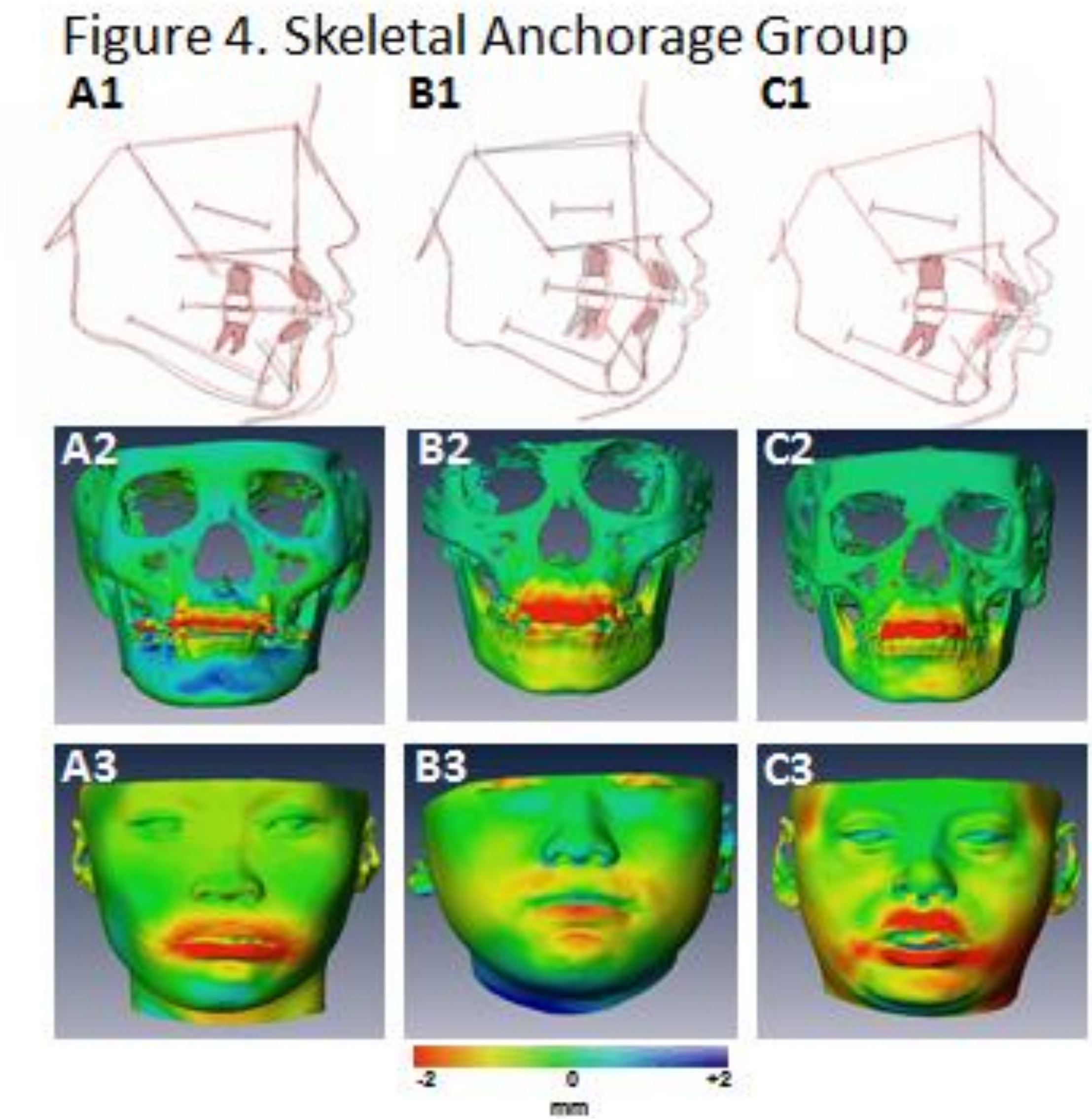

Figure 4. 2D Cephalometric tracings (**A1-C1**), 3D hard (**A2-C2**), and soft tissue (**A3-C3**) superimpositions of three patients (**A-C**) representing variation in the skeletal anchorage group. 2D tracings are superimposed on the cranial base. Black indicates T1, red indicates T2. Hard and soft tissue colored displacement maps are projected onto the T1 pre-treatment CBCT scan. Color scale ranges from -2 mm (red=subtractive change) indicating inward displacement, to +2 mm (blue=additive change) indicating outward displacement. Green indicates zero change.

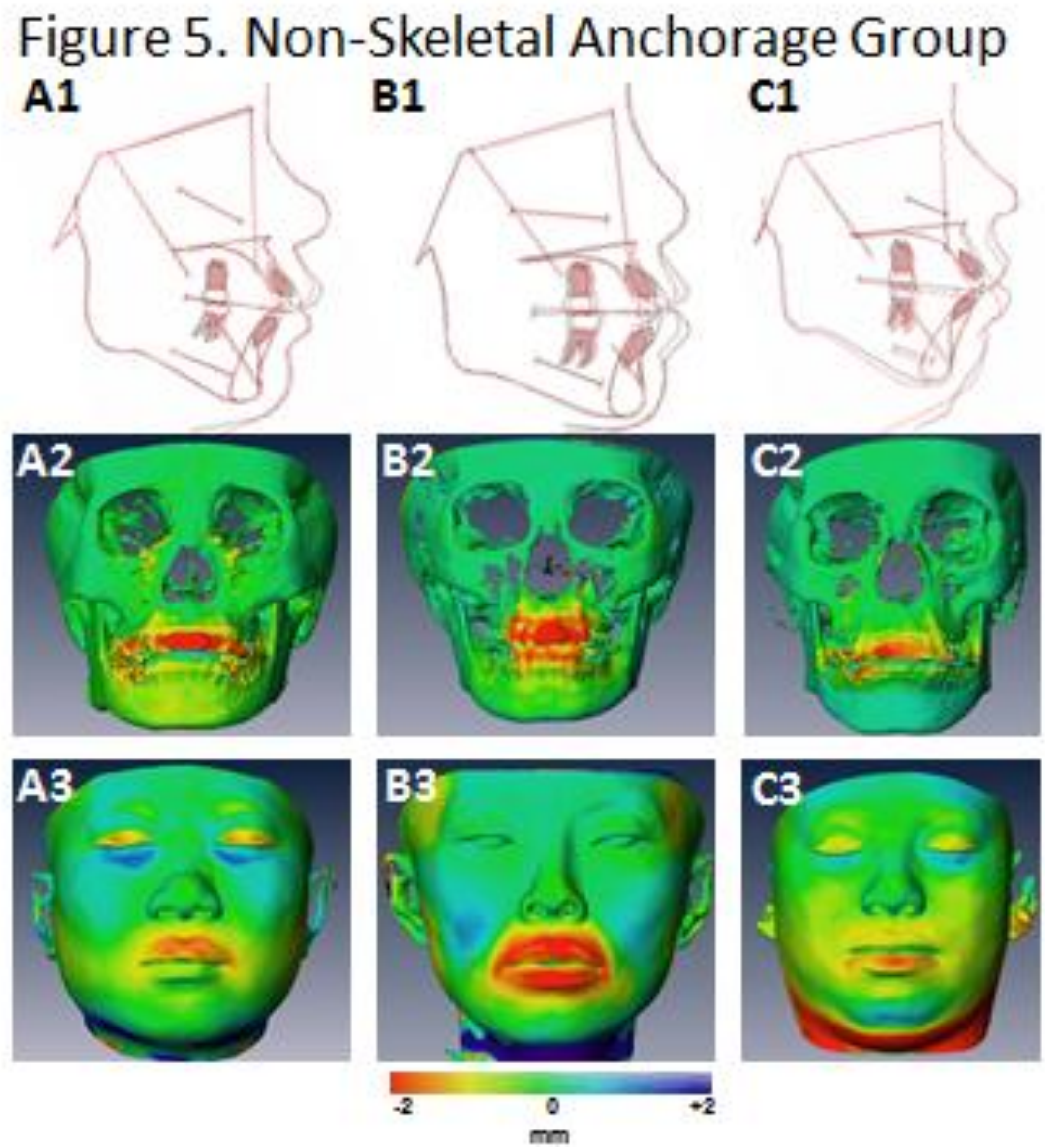

Figure 5. 2D Cephalometric tracings (**A1-C1**), 3D hard (**A2-C2**), and soft tissue (**A3-C3**) superimpositions of three patients representing variation in the non-skeletal anchorage group. Hard and soft tissue colored displacement maps are projected onto the T1 pre-treatment CBCT scan.

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