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The Relationship of Impacted Maxillary Canines And Maxillary Skeletal and Dental Size and Shape: A Cone Beam Computed Tomography Study

by
Jonathan Gao

THESIS
Submitted in partial satisfaction of the requirements for degree of
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in

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in the

GRADUATE DIVISION
of the
UNIVERSITY OF CALIFORNIA, SAN FRANCISCO

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Evaluation of the Relationship of Maxillary Impacted Canines and Maxillary Skeletal and Dental Shape and Size: A Cone Beam Computed Tomography Study

Jonathan Gao

Abstract

The purpose of this study was to compare skeletal and dentoalveolar shape and size differences in patients with maxillary impacted canines versus unaffected patients using landmarked CBCT images and geometric morphometrics.

104 cone-beam computed tomography scans from patients presenting with palatal or buccal impacted maxillary canines and 40 control patients with no impacted dentition were landmarked. 146 landmarks were plotted in Stratovan Checkpoint. Cone-beam computed tomography images including the nasal cavity, palate, sinus, alveolar crest, maxillary lateral walls, and dentition were landmarked by five examiners. No patient had undergone any type of orthodontic treatment in the past. Landmarked CBCT images were evaluated for shape and symmetry using geometric morphometric analysis by performing Procrustes superimposition, principal component analysis, and canonical variates analysis. Shape differences were further investigated by using linear regression analyses. Size differences were then investigated by looking at centroid size based on ratios between dentition and the entire landmarked maxilla.

To analyze shape differences, we utilized a principal components analysis and found impaction location of the canine contributed to the primary and secondary principal component of the variance in the shape. Removing the variance of tooth location, a principal component analysis was conduct on the asymmetric component. We found patients with maxillary canine impactions had a constriction of the arch on the side of the impaction as well as lowering of the

sinus floor on the side of the maxillary canine impaction compared to the control. The shape differences found were not statistically significant and we found no difference in shape between palatal versus buccal impactions.

Looking at size with differences of the dentition, the centroid size of the maxillary canine, central incisor and first molar were statistically different between the impacted and nonimpacted groups with a reduction in centroid size of the canine in the impacted versus nonimpacted groups. There were no statistically significant size differences between the impacted maxillary canine groups however there was a reduction in size in the palatal size versus the buccal side. The centroid sizes of the maxilla without teeth, arch width, and palate size in the impacted versus the nonimpacted group were all statistically different from the control group with the impacted group being smaller while there was no difference between the palatal versus buccal groups.

When looking at the size of the maxilla between males versus females, it was found that males consistently had large centroid sizes in their overall maxilla compared to females. We isolating for gender, there was no statistically significant difference in maxilla size between maxillary impaction palatal or buccal impactions.

Patients with impacted maxillary canines have both shape and size differences in the overall maxillary structure as well as the maxillary canine compared to patients without impacted maxillary canines. Amongst the dentition there was a general size reduction between the impacted versus nonimpacted tooth sizes. The impacted canines and first incisors and first molars on the side of the impaction had a statistically significant reduction in size compared to the nonimpacted canine patients. We also found a reduction in overall maxillary size in patients with impacted canines. There was also no statistically significant difference in centroid size of teeth or maxillary structures between palatal and buccal groups. These findings reflect that perhaps the etiology of canine impaction location is in line with the genetic theory rather than a lack of guidance from an undersized lateral incisor.

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Introduction

The maxillary permanent canines are the most frequently impacted teeth, with exception of the third molars. Impacted maxillary canines have a prevalence of 1–2.5% in the population with 85% of impactions being palatal and 15% buccal occurring twice as often in females as males. (Ericson et al, 1988) Additionally, unilateral impacted maxillary canines are more common than bilateral impacted canines. (Herrera)

The consequences from the impaction of maxillary canines can include increased treatment time and complexity, damage and or loss of the canine or neighboring teeth, and periodontal defects. (Ali Alqerban et al, 2015) Cone beam computer tomography (CBCT) analysis has allowed researchers to evaluate tooth size, shape, and position in individuals with impacted canine. Through shape and size analysis by geometric morphometrics, the relationship of impacted canines and the surrounding maxillary structures can be better understood. This research dissects the intricate interplay between dental development, root formation, and the eruption process. The incorporation of advanced imaging techniques enables a more accurate assessment of developmental stages and anatomical relationships, offering valuable information for unraveling the complexities of canine impaction.

The exact etiology of impacted maxillary canines is unknown however the main rationales are the guidance theory or genetic theory. (Becker et al, 2015) It has been found that environmental factors, such as dental anomalies, crowding, and the spatial relationships of neighboring teeth, contribute significantly to the etiology of impacted maxillary canines (Bishara, 1992).

The guidance theory attributes impaction to surrounding dental anomalies that have a genetic background relative to the canine such as undersized laterals leading to impaction. (Baccetti, 1994) Additionally, the guidance theory states that the direction and eruption of the canine is highly dependent on environmental factors especially in the absence of a lateral with a fully developed root that coincides with timing of the eruption of the maxillary canines. (Becker et al, 1981) Becker et al found that in males with palatally impacted canines the buccal-lingual dimension of all teeth was statistically smaller than in patients without palatally impacted canines while in females only the laterals were smaller in the buccal-lingual dimension (Becker et al, 2002).

The genetic theory attributes impactions to a hereditary link causing a developmental disturbance to the canine itself. (Becker et al, 2015) Family-based studies have revealed a hereditary component, indicating a heightened prevalence of impacted canines among individuals with a positive family history (Ali Alquerban et al, 2015). Recent studies have shown the presence of certain single nucleotide polymorphisms in the *PAX9* gene to increase risk of having a palatally impacted canine. (Vitria et al, 2019)

Developmental influences on maxillary canine eruption are integral to our understanding of impaction mechanisms (Baccetti et al., 2010; Ericson and Kurol, 1988). This research aims to augment the existing knowledge base and advocate for the integration of CBCT measurements in studying impacted maxillary canines. With increased compute power and the advancement of artificial intelligence in healthcare and orthodontics, by better understanding the relationship of pathology and the surrounding structures we may better create diagnostic tools to predict and treat maxillary canine impaction.

Canine Development

The maxillary permanent canines are crucial in maintaining oral function, stability, and aesthetics (Yang et al, 2019). The maxillary permanent canine has the longest root in the mouth and also provides canine guidance so that there is posterior disocclusion during lateral excursive movements. (Thorton et al, 1990)

Calcification of the maxillary canine starts at 4-5 months of age, the crown is completely formed by 6-7 years of age, eruption occurs at 11-12 years of age, and root formation is complete by 12-15 years of age (Ristaniemi et al, 2022). The maxillary canine migrates more than 22mm in a downward and forward direction to erupt adjacent to the distal aspect of the lateral incisor (Coulter et al, 1997). Coulter found that the maxillary canine travels on average 11.8mm in the anterior-posterior direction, 18.56mm in the vertical direction, and 2.67mm in the lateral direction during its migration pathway. Many factors can prevent the proper eruption of the canine during its 22mm long and tortuous eruption pathway, and the canine can become impacted and remain embedded within soft or hard tissue (Dadgar et al, 2021).

Treatment

Early diagnosis of canine displacement and impaction is important because interceptive treatment of maxillary canine impaction can reduce treatment costs and time, decreases risks of complications and adverse outcomes, and facilitates orthodontic mechanics (Alqerban et al, 2015). Thus, early detection is often the first approach in growing individuals so that the canine can be guided into its normal erupted position. It is suggested that patients be examined as early as the ages of eight or nine to assess the displacement of canines from their normal position. Radiographic and clinical evaluations (palpation and visual inspection) can be used to investigate the possibility of canine impaction (Shapira et al, 1980). If early canine impaction is suspected, treatment often consists of removal of the deciduous canines or is combined with creating spaces in the dental arch (Zuccati).

Extraction of the primary canine is supported on the basis of the assumption that the primary canine would present as an obstacle in the eruption pathway of the permanent canine. In a study by Ericson and Kurol, they found that "if the crown of the permanent canine were distal to the midline of the later incisor root, the primary canine extraction normalized the erupting position of the permanent canine in 91% of the cases. In contrast, the success rate decreased to 64% if the permanent canine crown were mesial to the midline of the lateral incisor root" (Ericson).

Maxillary expansion is another treatment option in the early mixed dentition period. In a study conducted by Baccetti, "rapid maxillary expansion protocol was applied and according to their results the prevalence rate of successful eruption (65.7%) in the treatment group was significantly higher ($p<0.001$) than the control group (13.6%). Space for the maxillary permanent canine can also be created by distalization, with devices such as headgear, or by extraction of maxillary deciduous first molars (Nieri). If these different interceptive treatments fail, or if early detection of an impacted canine fails, surgical exposure of the impacted canine is essential, usually requiring a combination of surgical and orthodontic interventions to bring the canine successfully into the dental arch. Therefore, older patients with impacted canines require more time and are more difficult to treat than younger patients (Becker).

Current Diagnosis

To be able to properly provide interceptive treatment and avoid more arduous treatment such as surgery, the clinician must be able to proper predict and diagnose impaction early in a patient's development. In a literature review published by Listas et al., surveyed from 1996 to May of 2010, it was found that current models used to predict canine impaction are based on two dimensional radiographs (panoramic and AP Cephalometric radiographs) and clinical measurements. Clinically, several studies have investigated the relationship between a maxillary transverse discrepancy and palatally impacted maxillary canines, however the findings of these studies have been conflicting. In one study by Langberg and Peck, they compared the pre-treatment arch widths (measured clinically) of 10 males and 21 females in the permanent dentition with palatally displaced canines to the arch widths of an unaffected group of orthodontic patients with the same age and sex distribution. They did not find any statistical differences between the two groups both in the anterior and the posterior maxillary width (Langberg). Conversely, in a study by McConnell *et al.,* they found that a transverse maxillary deficiency in the anterior portion of the dental arch as a local cause for palatal canine displacement. In their study "Inter-molar and inter-canine widths were recorded in 57 patients with 81 impacted maxillary canines and in 103 patients with normally erupted canines that served as a control group. Their results demonstrated statistically significant differences ($p<0.05$) in the maxillary width between the two groups, particularly in the anterior portion of the maxilla" (McConnell).

Radiographically, two dimensional radiographs including panoramic imaging and AP cephalograms have been used to assess and predict displaced canines in the mixed dentition period. "Three variables visible on panoramic radiographs have been proposed (to predict canine impaction): I) angle measured between the long axis of the impacted canine and the midline. II) distance between the canine cusp tip and the occlusal plane (from the first molar to the incisal edge of the central incisor) and III) the sector where the cusp of the impacted canine is located" (Ericson). In one retrospective study of 554 maxillary canines of children between 4 and 12 years old, investigators discovered that when the lateral incisor is not yet fully developed, panoramic radiographs show 67% overlapping of the canine and lateral incisor. However, when lateral incisor development is complete, only 11% of the subjects show some degree of overlapping. "According to the authors, the overlapping of the canine and lateral incisor can be considered as a sign of early canine displacement after the incisor has completed its root development" (Fernandez). On PA radiographs, one study suggested that, "At the age of 8, the maxillary canines should have medial inclination with crowns below the lateral border of the nasal cavity and the roots lateral to the border of the nasal cavity. Some parameters such as intercanine width, size of the follicle, symmetry and width of the nasal cavity might be associated with increased probability of upper canine impaction" (Sambataro). These two-dimensional radiographic methods and the aforementioned clinical measurements have served as the gold standard for years for assessing and predicting maxillary canine impaction.

Cone-Beam Computed Tomography

While the use of two-dimensional radiographs for diagnosis has proven useful, panoramic radiographs are inherently technique sensitive and prone to distortion. In particular, panoramic image mesiodistal angles have been proven to be significantly different from true angle measurements (Mckee). In one study by Haney, they compared traditional two-dimensional images to CBCT images in patients with maxillary impacted canines. They found that there was a 21% disagreement in the mesio-distal location and a 16% disagreement in the labial-palatal position of the impaction. Therefore, while useful, previous models using two-dimensional radiographs are inherently flawed. CBCT imaging provides a much more precise tool to locate impacted canines and factors associated with impacted canines. Current maxillary canine impaction models, which use panoramic imaging, could greatly benefit from CBCT imaging. Creating a prediction model using CBCT imaging would increase accuracy in early diagnosis and interceptive treatment of maxillary canine impaction.

While CBCT imaging has been around for over two decades, only until recently has the use of this imaging modality become more affordable and common amongst the common orthodontic practice. With the widespread use of CBCT imaging and its added benefits, it is becoming increasingly important to conduct more studies using three dimensions. In the last few years studies using CBCT imaging to evaluate the etiology of maxillary canine impaction have emerged. While these studies have evaluated factors associated with maxillary canine impaction, such as lateral incisor root resorption and position of adjacent teeth, no three-dimensional study exists that provides a comprehensive evaluation of factors associated with maxillary canine impaction. Therefore, this study will aim to evaluate both skeletal and dental factors associated with palatally impacted maxillary canines using CBCT imaging.

Geometric Morphometric Analysis

The three-dimensionality of CBCT imaging provides the unique opportunity to not only evaluate where objects are in relation to one another in a 3D sphere, but also allows for the evaluation of shape and size. In the literature, geometric morphometrics (GMM) has been proposed as an effective method of visualization of shape changes (Papagiannis). "This method can show three-dimensional (3D) morphological changes in their complexity much more effectively than coefficients resulted from traditional morphometric analysis" (Klienberg). The geometric morphometrics method (GMM) is a technique to study scale and shape relationships of structures using Cartesian geometric coordinates rather than linear, areal (of area), or volumetric variables (Liuti). In GMM the centroid size is the preferred method to measure size as it is “the square root of the sum of squared distances of all the landmarks of an object from their centroid.” (Klingenberg) Therefore to gain a deeper understanding of the shape and structures surrounding maxillary canine impaction, geometric morphometric analysis can be used with CBCT imaging. A study by Sobhani et al. looked at the palatal structure size and shape utilizing GMM and found statistically significant difference in the shape of the midpalate but not size.

Central Hypothesis

We hypothesize there is a difference in the size and shape of maxillary dentition and surrounding maxillary structures in patients with maxillary impacted canines compared to patients with no impactions.

Specific Aims

1. Evaluate the maxillary dentition size and shape in impacted maxillary canine group versus control group.
2. Evaluate the maxillary nasal cavity, palate, and arch size and shape
3. Evaluate the differences in female versus male subjects
4. Compare the above studied variables between palatally displaced maxillary canines, buccally displaced maxillary canines, and nondisplaced canines.
5. Determine the relationship of studied variables on the position of canine displacement.

Materials and Methods

This cross-sectional study evaluates the factors associated with impacted maxillary canines compared to subjects that have non-displaced maxillary canines using CBCT images. This study was conducted at the University of California, San Francisco in conjunction with a radiology center in Sacramento, California. CBCT images were obtained from both the radiology center and the University of California, San Francisco Orthodontic Clinic. All images taken between March 2021 and November 2022. The CBCT images were screened for the presence of palatally and buccally impacted maxillary canines, with inclusion criteria including aged greater than 12 years (The maxillary canine is on average fully erupted by ages 11-12) and a clinically diagnosed unilateral or bilateral maxillary canine impaction. Exclusion criteria were poor image quality, syndromic and cleft patients, prior orthodontic treatment or early extractions, root canal treatment, and presence of cysts or other pathologies.

This cross-sectional study consisted of 106 total subjects (59 females and 65 males), 40 “palatal impaction” subjects (22 females, 18 males, mean age 15.1 years) with palatally impacted canines 26 “buccal impaction” subjects (15 females, 11 males, mean age 14.6) and 40 “control” subjects (22 females, 18 males, mean age 14.6 years) with nondisplaced canines. All subjects were between the ages of 12 and 29 years old. All CBCT data (DICOM files) were assigned new names by using randomly generated codes that removed patient identification information. After de-identification, all subject DICOM files were uploaded into Stratovan Checkpoint's land-marking software.

A template of 146 landmarks was created to adequately represent the maxillary dentition, palate, nasal cavity, sinus, and maxillary arch. In selecting landmarks to plot, this study aimed to identify landmarks that would depict adjacent structures and the housing within which the maxillary permanent canine travels during its eruption pathway. Table I represents the various landmarks and their definitions.

Table 1. *Landmark Definitions*

Table I. Landmark Definitions

Quantitative Variables	*Values and definition*
Dental Measurements	
MD (tooth mesiodistal width)	Maximum mesiodistal crown diameter of maxillary anterior teeth (U1, U2, U3,U4,U5,U6)
BL (tooth buccolingual width)	Maximum buccolingual crown diameter of maxillary anterior teeth (U1, U2, U3,U4,U5,U6)
TA (Tip-Apex)	Maxium tooth legnth measured from root apex to crown cusp tip (U1,U2,U3,U4,U5,U6)
Alveolar Ridge Landmarks	
#Crest_(B/P)	Buccal Lingual width of U1,2,4,5,6 measured from height of alveolar ridge buccal and lingual
Arch Widths	
IP1 (anterior dental arch width)	Intermaxillary arch width between the deepest points of the Distal fossae of the maxillary first premolars (IP1)
IM1 (posterior dental arch width)	Intermaxillary arch width between mesial lingual cusp tips first molars (IM1)
Nasal Cavity Landmarks	
Anterior Limit (ANC)	Defined by the most anterior portion of the piriform aperture with a continuous cortex
ANC_Inf	Most inferior middle point
ANC_Lat_(R/L)	Most lateral limits of nasal cavity on both left and right
Posterior Limit (PNC)	Defined by the posterior nasal spine
PNS	Most inferior posterior point of palate
PNC_Lat_(R/L)	Most lateral limits of nasal cavity on both left and right
Maxillary Transverse Width	
M1_Basal_(R/L)	First molar basal width (at level of floor of nasal cavity)
M1_Alveolar_(R/L)	First molar alveolar width (at level of heigh of alveolar ridge)
P1_Basal_(R/L)	First premolar basal width (at level of palate)
P1_Alveolar_(R/L)	First premolar alveolar width (at level of heigh of alveolar ridge)
Pataltal Landmarks	
Palate Boundaries	a. 9 points on Mid-sagital suture (Defined as "MS_#") c. Distal boarder: 9 points distal to first molars perpendicular to Mid-sagittal suture (Defined as "Distal Border Palate (DBP_#)")
Maxillary sinus Landmarks	
Sinus Floor # (R/L)	9 points on the floor of the maxillary sinus from the distal of the first molar to most anterior portion of sinus in A-P (Sinus_#)

For each of the landmarks, a standardized protocol and orientation was established in order to be able to reliably replicate and place landmarks. A total of five examiners landmarked the CBCT data in Stratovan Checkpoint using the aforementioned template consisting of 146 landmarks. Prior to landmarking the 106 cases, each examiner landmarked 5 of the same cases to evaluate inter-rater reliability and agreement using within subject standard deviations and agreement analysis. There was a total of 9 errors where one examiner disagreed with the others by greater than 0.5mm and therefore required correction (out of 6570) measurements. It was determined that there was a high level of agreement amongst the examiners. Tables 2 and 3 depict the various numerical landmarks and the error (in mm) between the three examiners.

Table 2. *Numerical Values*

Table II. Numerical Landmarks															
1	UR1_M	21	UR3_A	41	UR6_B	61	UL2Crest_B	81	UL5_A	101	PNC_Lat_R	121	DBP_2	141	Sinus_L4
2	UR1_D	22	UR3_T	42	UR6_P	62	UL2Crest_P	82	UL5_T	102	PNC_Lat_L	122	DBP_3	142	Sinus_L5
3	UR1_P	23	UR4_M	43	UR6_A	63	UL3_M	83	UL5Crest_B	103	M1_Basal_R	123	DBP_4	143	Sinus_L6
4	UR1_B	24	UR4_D	44	UR6_T	64	UL3_D	84	UL5Crest_P	104	M1_Basal_L	124	DBP_5	144	Sinus_L7
5	UR1_A	25	UR4_P	45	UR6Crest_B	65	UL3_B	85	UL6_M	105	M1_Alveolar_R	125	DBP_6	145	Sinus_L8
6	UR1_T	26	UR4_B	46	UR6Crest_P	66	UL3_P	86	UL6_D	106	M1_Alveolar_L	126	DBP_7	146	Sinus_L9
7	UR1Crest_B	27	UR4_A	47	UL1_M	67	UL3_A	87	UL6_B	107	P1_Basal_R	127	DBP_8		
8	UR1Crest_P	28	UR4_T	48	UL1_D	68	UL3_T	88	UL6_P	108	P1_Basal_L	128	DBP_9		
9	UR2_M	29	UR4Crest_B	49	UL1_B	69	UL4_M	89	UL6_A	109	P1_Alveolar_R	129	Sinus_R1		
10	UR2_D	30	UR4Crest_P	50	UL1_P	70	UL4_D	90	UL6_T	110	P1_Alveolar_L	130	Sinus_R2		
11	UR2_B	31	UR5_M	51	UL1_A	71	UL4_B	91	UL6Crest_B	111	MS_1	131	Sinus_R3		
12	UR2_P	32	UR5_D	52	UL1_T	72	UL4_P	92	UL6Crest_P	112	MS_2	132	Sinus_R4		
13	UR2_A	33	UR5_P	53	UL1Crest_P	73	UL4_A	93	IP1_R	113	MS_3	133	Sinus_R5		
14	UR2_T	34	UR5_B	54	UL1Crest_B	74	UL4_T	94	IP1_L	114	MS_4	134	Sinus_R6		
15	UR2Crest_P	35	UR5_A	55	UL2_M	75	UL4Crest_B	95	IM1_R	115	MS_5	135	Sinus_R7		
16	UR2Crest_B	36	UR5_T	56	UL2_D	76	UL4Crest_P	96	IM1_L	116	MS_6	136	Sinus_R8		
17	UR3_M	37	UR5Crest_B	57	UL2_B	77	UL5_M	97	ANC_Inf	117	MS_7	137	Sinus_R9		
18	UR3_D	38	UR5Crest_P	58	UL2_P	78	UL5_D	98	ANC_Lat_R	118	MS_8	138	Sinus_L1		
19	UR3_P	39	UR6_M	59	UL2_A	79	UL5_B	99	ANC_Lat_L	119	MS_9	139	Sinus_L2		
20	UR3_B	40	UR6_D	60	UL2_T	80	UL5_P	100	PNS	120	DBP_1	140	Sinus_L3		

Table 3. *Inter-rater Analysis (error in mm)*

Table III. Inter-rater analysis								
Landmark	Error	Landmark	Error	Landmark	Error	Landmark	Error	Landmark
MS_5	0.36788848	UL2_P	0.18777025	DBP_2	0.13035362	UR4Crest_P	0.09911811	UL6_A
UL3_M	0.35722038	UL2_M	0.18765927	UL4_M	0.12979985	UR5_D	0.09870934	UL5_M
UR3_P	0.33199367	Sinus_R8	0.18612397	Sinus_L7	0.12765474	UR4Crest_B	0.09811898	UR6_P
MS_7	0.31991905	Sinus_L3	0.18138118	UR3_A	0.12526026	M1_Alveolar_R	0.09770295	UL6_P
UR3_B	0.31224125	UL2_D	0.17987106	UR4_D	0.12338152	MS_8	0.09769476	UL5_P
UR3_D	0.30842384	UL2_B	0.17652441	UL6_D	0.12211879	UL4_D	0.09766234	Sinus_R2
ANC_Lat_L	0.30272826	PNC_Lat_R	0.1733309	IP1_L	0.11724106	Sinus_L9	0.09742043	UL2_T
UL3_D	0.29517362	Sinus_L4	0.17072161	DBP_4	0.11666819	UL1_M	0.09734132	UR2Crest_P
MS_4	0.29508903	UL2_A	0.16994019	UL4_B	0.11403859	DBP_8	0.09707386	UR4_M
MS_3	0.2897087	Sinus_R7	0.16589475	UR2Crest_B	0.11337783	PNS	0.09704707	UR1_A
UL1Crest_B	0.27906893	UL6_T	0.16589173	UR5_A	0.11241323	Sinus_R1	0.09637427	UL1_T
UR3_M	0.27240117	IM1_L	0.16457967	UR6_B	0.11057155	UR5_M	0.0954966	UL5_T
M1_Basal_L	0.2682843	Sinus_L2	0.16336034	UL4_A	0.10834359	UR1_D	0.09508943	UL1_P
UR1Crest_P	0.26388571	MS_9	0.16300307	UR6Crest_B	0.10830789	UL6Crest_P	0.09480331	UR5_B
MS_6	0.26272673	UL4Crest_B	0.16113266	P1_Alveolar_R	0.10641554	UL6_B	0.09370984	UL1_B
ANC_Lat_R	0.26229652	Sinus_R6	0.16015763	DBP_3	0.10538849	UL5_D	0.09174239	IP1_R
UR1Crest_B	0.2572949	UR2_M	0.15667738	DBP_1	0.10537615	DBP_5	0.09103845	UR5_T
UL1Crest_P	0.25143442	IM1_R	0.15172914	UL4Crest_P	0.10335247	UR4_P	0.08941775	UR4_B
UL3_P	0.22260638	UL1_D	0.1478754	UR6Crest_P	0.10315038	UL5Crest_P	0.08909807	UL4_T
UL3_B	0.21182823	Sinus_L5	0.14756219	UR6_M	0.10306341	UR1_M	0.0875694	UR5_P
P1_Basal_L	0.20562685	DBP_7	0.14623725	DBP_9	0.1029686	UR2_P	0.08748143	UR5Crest_B
UR1_B	0.20294367	UL6Crest_B	0.14292865	Sinus_R3	0.10285815	UR6_T	0.08716957	UR2_T
UR1_P	0.20200363	Sinus_R9	0.14274826	UR6_A	0.10275213	UR2_B	0.0869977	UL3_T
UR6_D	0.20185027	Sinus_R4	0.14143173	MS_2	0.10240866	UR2_A	0.08362376	UR3_T
UL3_A	0.20180172	Sinus_L1	0.14087701	P1_Basal_R	0.10066148	UR4_A	0.08338385	UR1_T
M1_Basal_R	0.20026266	P1_Alveolar_L	0.13815764	Sinus_L8	0.10053623	UL4_P	0.0830538	UR4_T
UL2Crest_P	0.19412092	ANC_Inf	0.13736957	UR2_D	0.10006798	MS_1	0.08302329	
PNC_Lat_L	0.19224099	Sinus_L6	0.13735768	UL1_A	0.09933345	UL5_B	0.0826422	
UL2Crest_B	0.19005701	M1_Alveolar_L	0.13506073	UL5Crest_B	0.09918736	DBP_6	0.08213607	
UL5_A	0.18924887	Sinus_R5	0.13044846	UL6_M	0.09918266	UR5Crest_P	0.07999292	

The following figures 1-6 depict the orientations and used to plot dental landmarks, nasal cavity landmarks, palate landmarks, alveolar landmarks, and sinus landmarks.

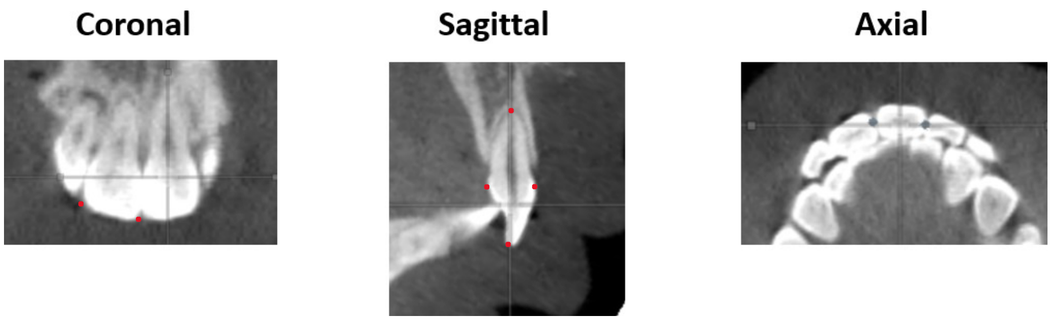

Figure 1. *Dental Orientation and 6 landmarks of dentition marked in red*

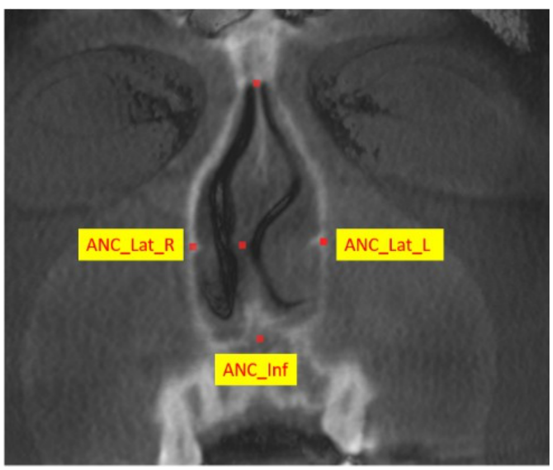

Figure 2. *Nasal Cavity Orientation with anterior nasal cavity limits defined*

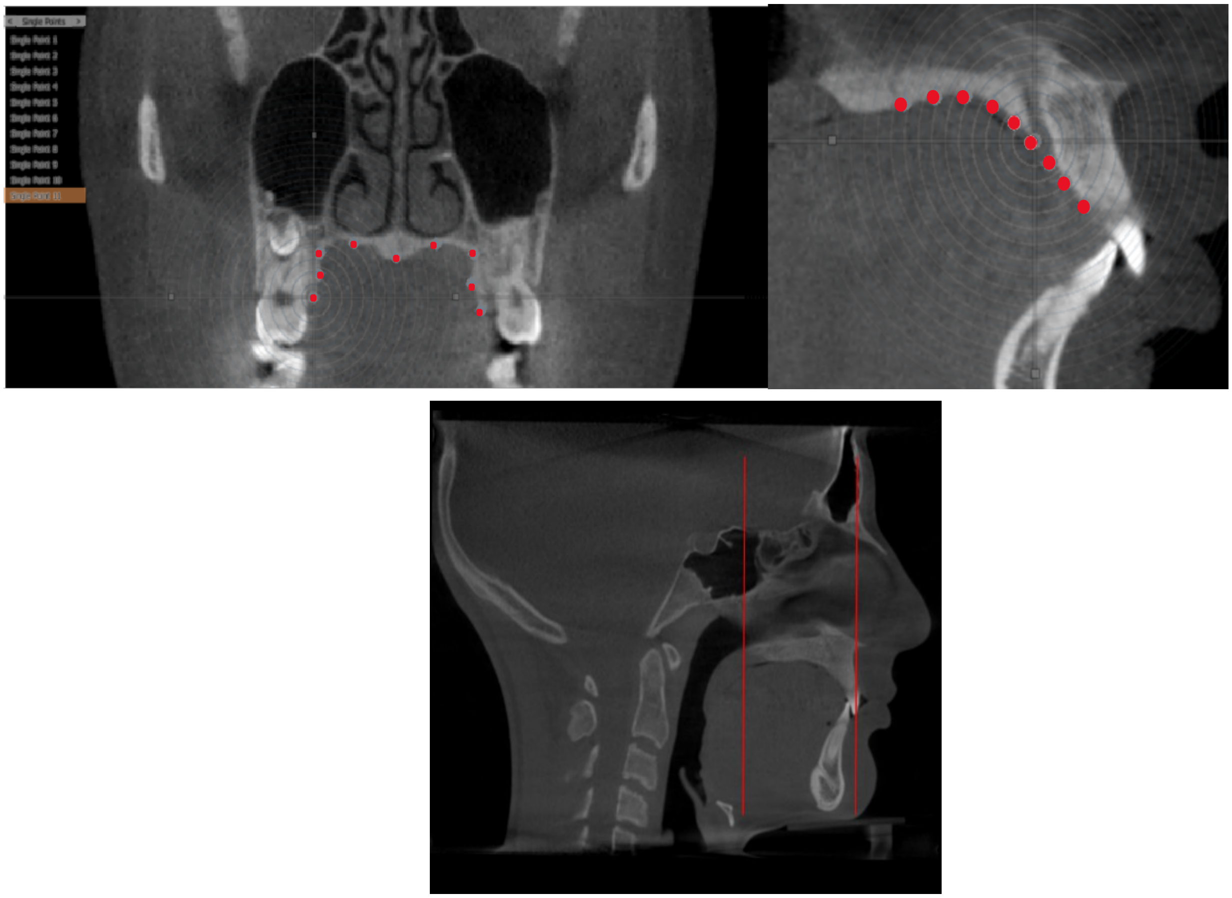

Figure 3. *Palate Orientation and landmarking*

Figure 4. *Alveolar Orientation*

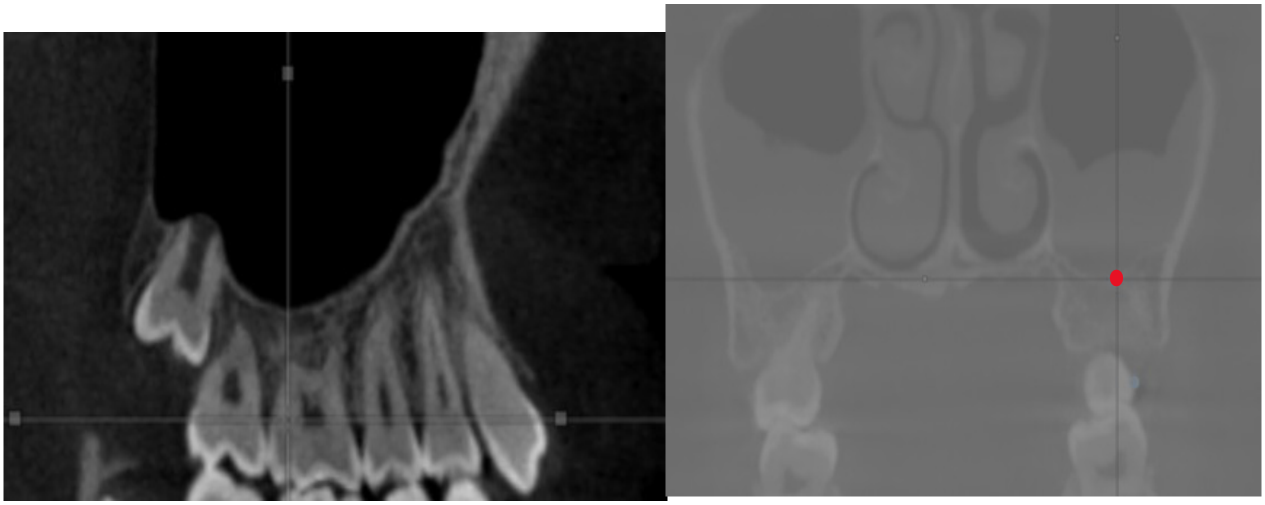

Figure 5. *Sinus Orientation*

106 cases were landmarked in Stratovan Checkpoint, landmarked 3D data points were then transferred to MorphoJ Geometric Morphometric software (Klingenberg lab, Manchester, UK) to standardize the superimpositions across all subjects in this study, generating a list of procrustes coordinates that control for scalar differences between images.

Principal component analysis (PCA) as well calculation of centroid size of dentition, overall maxillary landmarks without dentition, palate, and dental arch width was then completed using MorphoJ software. A separate PCA on the asymmetric component was run for all landmarks excluding dentition to understand the effect of impacted maxillary canines on overall maxillary structure shape.

After data was obtained from the PCA and centroid size calculation, a linear regression was completed to better understand the relationship between the centroid size of the impacted canine and overall maxillary structures with other classifiers including age and gender. Additionally, a multivariate analysis was run between the groups for to determine if there is statistical significance difference between sample populations.

RESULTS

Shape Results

Shape of the overall landmarks was first analyzed. Landmarks were converted into Procrustes coordinates using MorphoJ software to control for scalar, translational, and rotational differences. Procrustes coordinates were graphed in MorphoJ and represented in 2D across 3 axes (see figure 6). A principal component analysis was then performed on the newly adjusted Procrustes coordinates while selecting for impaction v control groups.

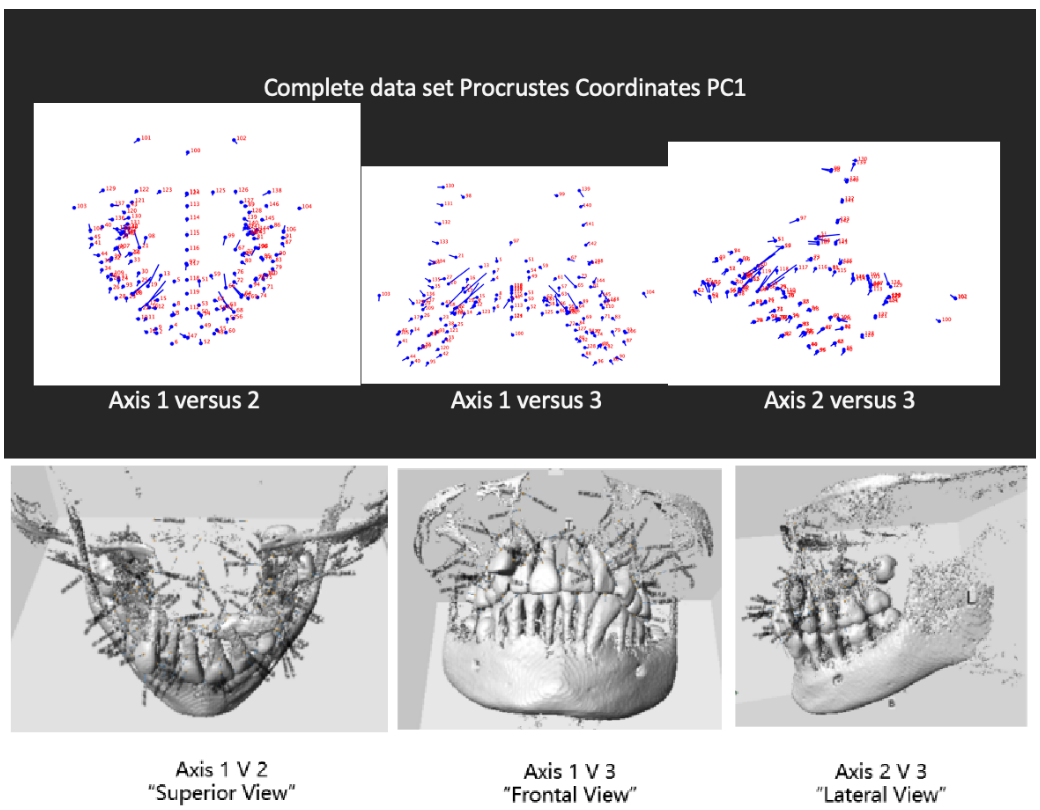

Figure 6. *PC 1 of Complete Data Set and respective model views*

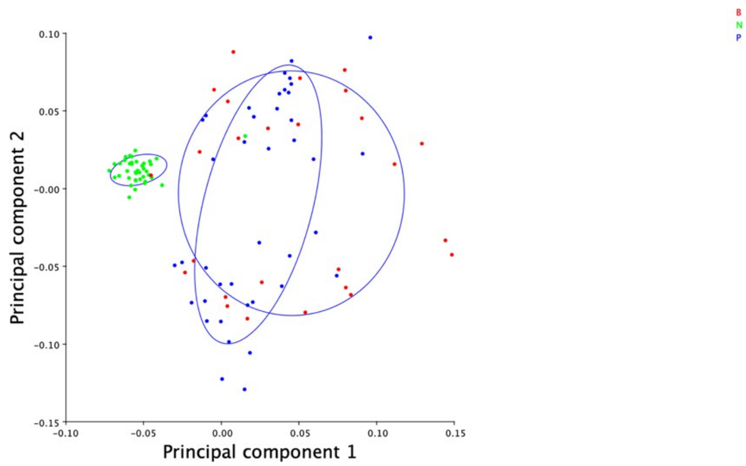

Figure 7. *PC1 versus PC2 of Entire Data Set*

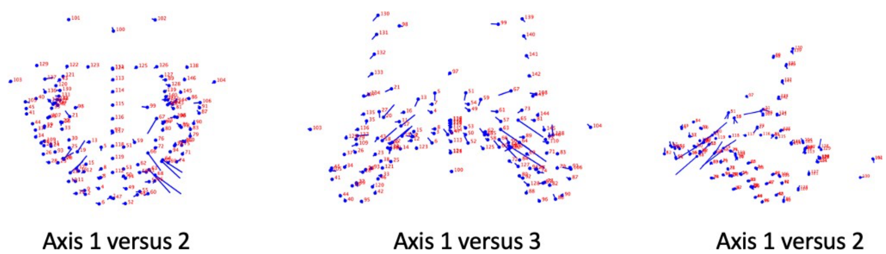

Figure 8. *PC2 of Complete Data Set*

The first principal component graphed against the second principal component revealed a tight clustering of the impaction v control group less dense clustering between the palatal versus buccal impaction group. (figure 7) The first two principal components of the shape variation which contribute to 11.7% and 10.3% respectively of the variation. Based on the diagrams, the palatal versus buccal location as see in figure 6 versus 8 depict the varying canine locations as the major contributor of shape difference between the principal components and is reflected in the Eigenvalues of the PCA. (figure 9)

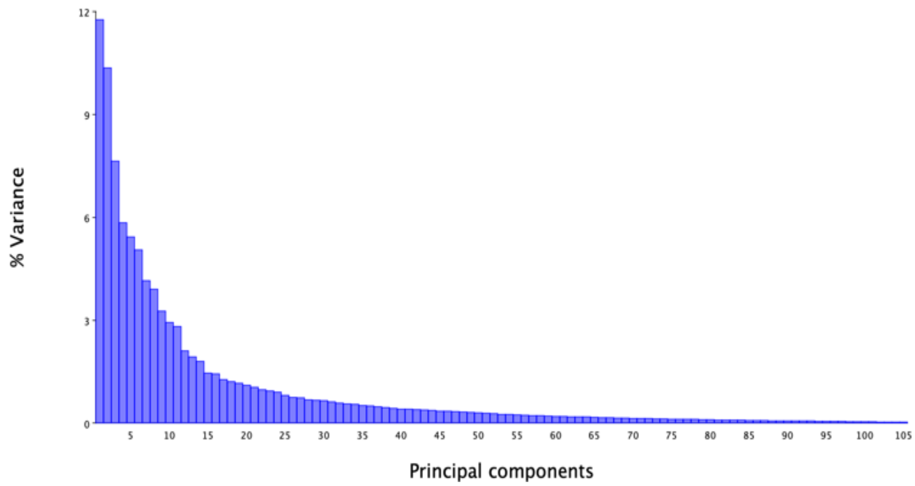

Figure 9. *Eigenvalues of PCA of overall data set*

To remove the significant difference in shape due to location of canine impactions, a PCA was then performed for only the skeletal landmarks (landmark numbers 93-146) of the asymmetric component to further evaluate skeletal effects from impacted maxillary canines. The skeletal landmarks involved in the PCA analysis include arch width, nasal cavity, palate, and floor of sinus landmarks.

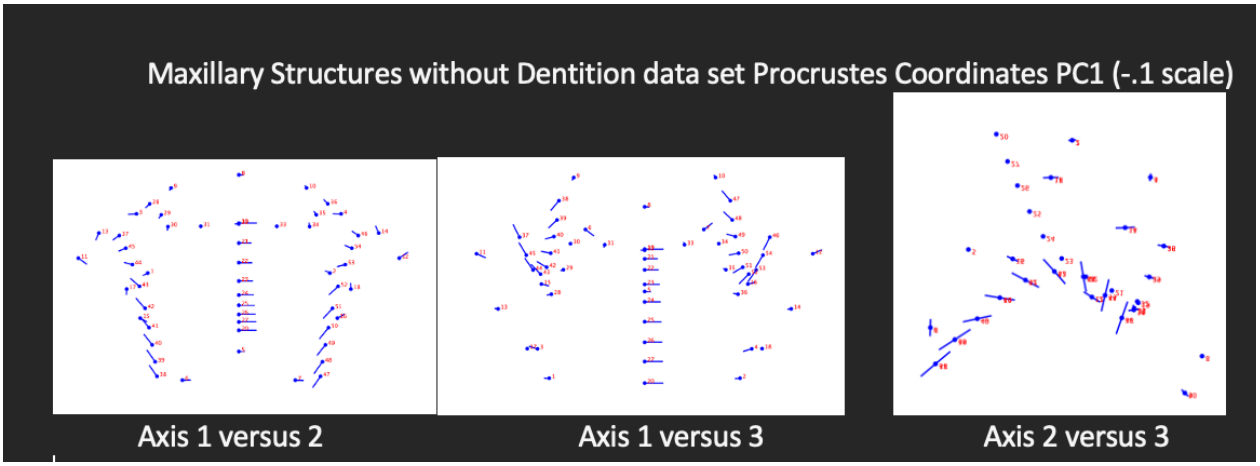

Figure 10. *PC1 of the Maxillary Structures without Dentition*

The first and second principal component analysis accounted for 31.5% of the total shape variation, with PC1 comprising 16.5% and PC2 comprising 14.0% of the total variation. Looking at the first principal component, we can see a shift towards the side of the impaction on axis 1 versus 2, as well as a shift of the sinus floor towards the occlusal plane on axis 1 versus 3. (Figure 10)

When analyzing the principal component 1 for statistical difference between groups when analyzing the landmarks without dentition, it was found through an ANOVA that the mean for the buccal maxillary impacted was -0.04, palatal maxillary impacted -0.09, and control was 0.13. There was not found to be any statistically significant difference between the groups for principal component 1 with a p-value of 0.22. Further analysis was completed to evaluate for shape differences without dentition included between gender and none was found after conducting a unpaired two-tailed t-test on PC1 between male and females with a final p-value of .745.

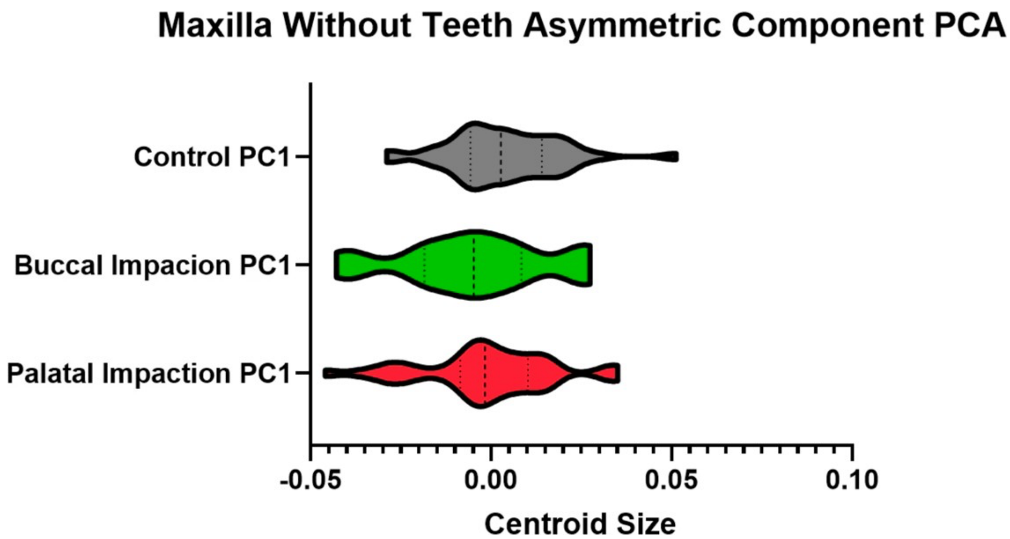

Figure 11. *Violin Plot of PC1 Values of Asymmetric Component of Maxilla without Teeth*

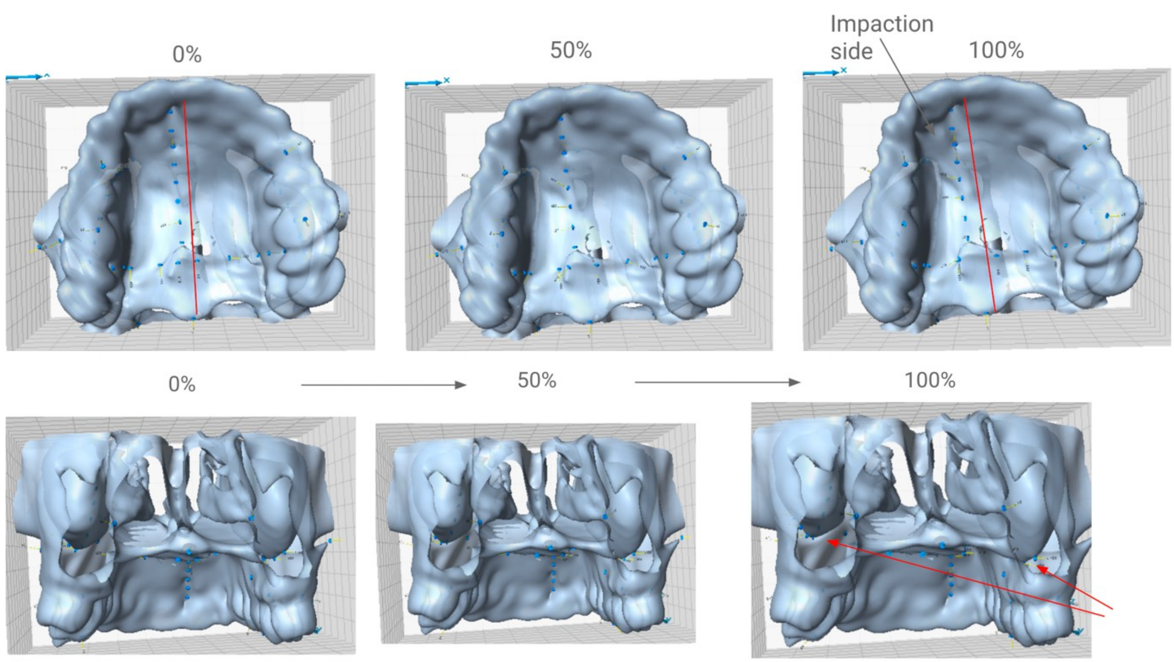

Figure 12. *Warps of maxilla from PC1 towards the scale of .02*

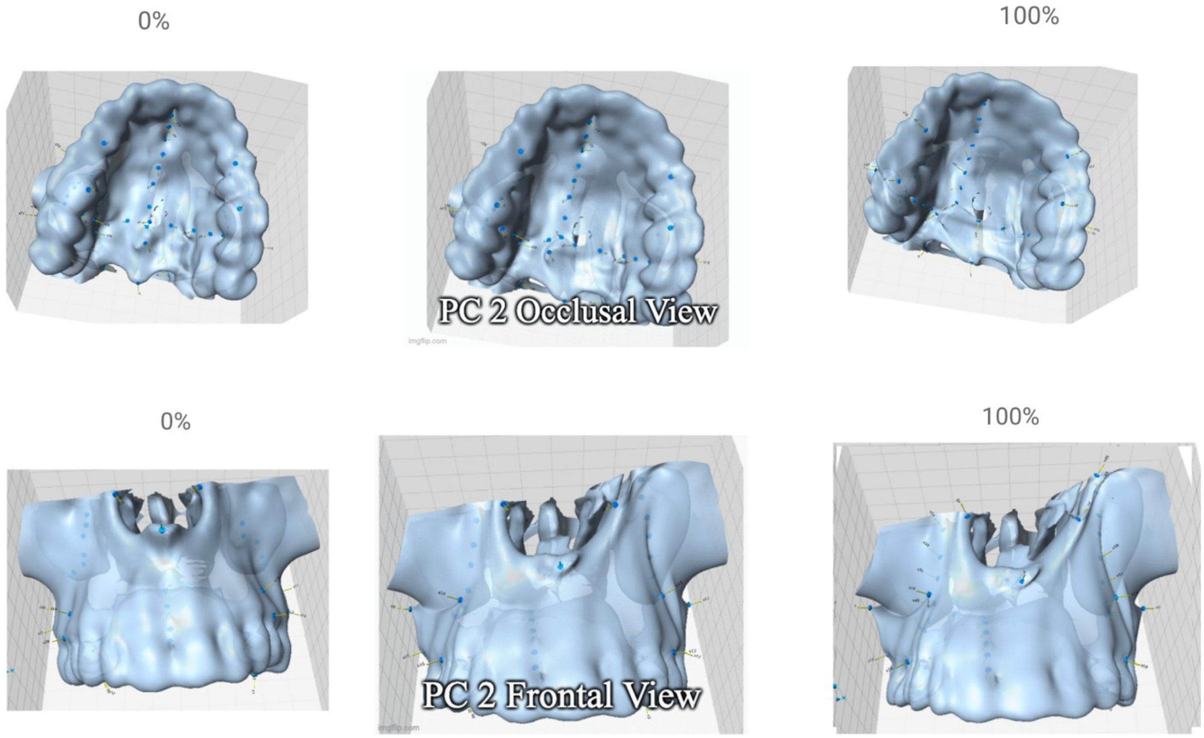

Figure 13. *Warps of maxilla from PC2 towards the scale of .02*

To visualize these asymmetries, the shape changes were applied to a generic maxilla and morphed in *Landmark* software to show the changes in skeletal features with patients with impacted maxillary canines versus control. PC1 and PC2 was utilized to warp a generic maxilla to visualize the shape differences in these PCA graphs. (Figure 13) It can be noted that there is a miniaturization and shift of the midline towards the side of the impaction as well as a lowering of the sinus floor with the impacted side generally lower and the unimpacted expanding on the distal aspect.

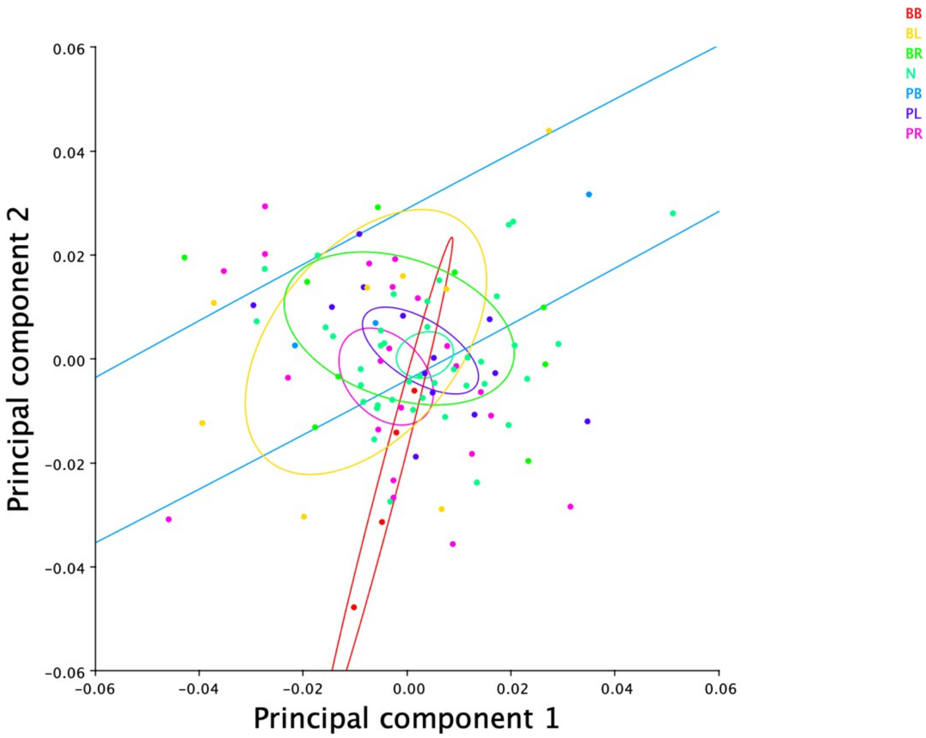

Figure 14. *PC1 versus PC2 distribution PCA Asymmetric Component*

Looking at the overall skeletal shape without dentition it can be noted that the buccal maxillary impaction group is much more tightly impacted by PC 2 compared to the other groups. Additionally, it can be noted that the palatal bilateral group had the greatest variance in shape.

Size Results

Evaluating the size of the objects we utilized the measurement of the centroid for skeletal and dental landmarks to determine differences between the study groups. First to account of variability in variable maxillary size in patients we conducted a linear regression of all the teeth to the overall maxilla size without dentition. (Figure 15) We found that that the impacted canine had a R of .0304 and the slope was not was significantly nonzero.

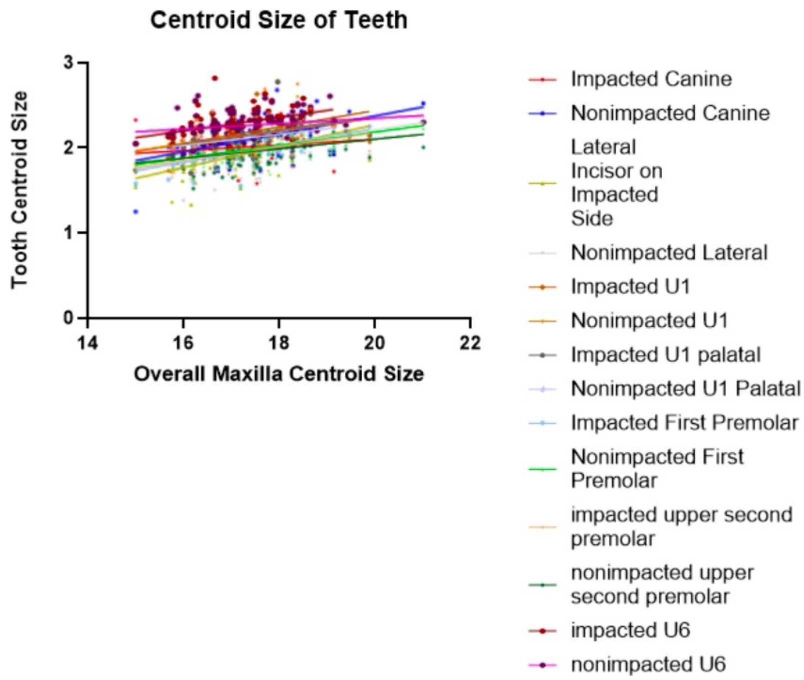

Figure 15. *Linear regression of tooth size to overall maxilla size*

Looking at the centroid size of the teeth we started utilized a linear regression with the overall maxillary landmarked size with each individual centroid tooth size. In this regression we found that all teeth except for the impacted canine had a statistically significant relationship to the overall maxillary skeletal features except for the impacted canine with an F-value of 1.993. This reflects the variable nature of the size of the impacted canine versus the control.

To account for differences in maxillary size, a ratio was created between the tooth size and overall maxilla size for the remaining dentition to study the relationship of canine impaction on neighboring teeth size. We found the central incisor and first molar were statistically different between the impacted and nonimpacted groups and reduction in centroid size of all dentition size when compared to the nonimpacted groups. (Table 6) In a separate regression (Table 4) the canine was found to statistically smaller ($p<.0001$) when comparing the impacted versus impacted groups however the size differences were not reflected between palatal versus buccal impaction groups. ($p=.16$). The distribution of canine sizes was normally distributed in size as seen in figure 16 in both impacted and nonimpacted groups with minimal outliers.

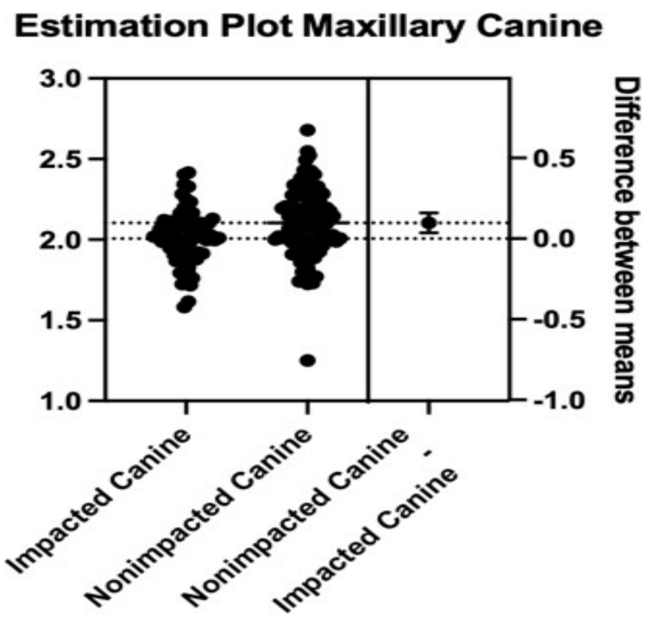

Figure 16. Distribution of canine centroid sizes

Table 4. *ANOVA of Canine Size*

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Palatal Canine	40	80.6559047	2.01639762	0.02739554		
Control Canine	40	87.9125205	2.19781301	0.03539006		
Buccal Canine	26	51.2390389	1.97073227	0.03954401		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.02316512	2	0.51158256	15.3300401	1.486E-06	3.08457678
Within Groups	3.43723849	103	0.03337125			
Total	4.46040362	105				

Table 5. *T-test Between Impacted Canine Sizes*

t-Test: Two-Sample Assuming Unequal Variances		
	Palatal	*Buccal*
Mean	2.01639762	1.97073227
Variance	0.02739554	0.03954401
Observations	40	26
Hypothesized	0	
df	47	
t Stat	0.97230515	
P(T<=t) one-	0.16793819	
t Critical one	1.67792672	
P(T<=t) two-	0.33587638	
t Critical two	2.01174051	

There were no statistically significant size differences between the impacted maxillary canine groups however there was a slight reduction in size in the buccal size versus the palatal side. (Table 5) The centroid sizes of the maxilla, arch width, and palate size in the impacted versus the nonimpacted group were all statistically different from the control group with the impacted group being smaller while there was no difference between the palatal versus buccal groups. (Table 7)

Table 6. *Tooth Size to Maxillary Centroid Size*

Differences in Centroid Size of Maxillary Tooth to Skeletal Landmark Ratios			
Maxillary Tooth	Nonimpacted- Impacted Difference	P Value*	Statistically Significant
Central Incisor	0.0212	<.0001	Yes
Lateral Incisor	0.0013	0.7461	No
First Premolar	0.0059	0.4342	No
Second Premolar	0.0068	0.0737	No
First Molar	0.0256	<.0001	Yes
	*Unpaired T-test		

Table 7. *Maxillary Structures Centroid Size*

Statistical Significance Between Impacted Versus Non-Impacted Maxila Skeletal Features				
Landmark	Average Size (Control, Buccal, Palat	P Value*	Statistically Significant	Significant between Impaction Groups
Overall Maxilla	4.33, 4.16, 4.18	<.0001	Yes	No
Palate	17.73, 17.18, 17.16	0.0151	Yes	No
Arch Width	4.33, 4.16, 4.18	0.0569	Yes	No
Test conducted			*test through ANOVA	*unpaired t-test

When looking at the relationship between the maxillary overall centroid size and tooth size through a linear regression, the impacted canine was the only tooth with no correlation to the skeletal maxillary centroid size as the slope was not significantly non-zero. Additionally in a multivariate regression for the relationship of the canine size and gender, canine impaction, age, and overall maxillary centroid size, the nonimpacted group and overall centroid size had a statistically significant relationship to canine centroid size. The centroid size of the overall maxilla without dentition with impaction was compared taking into consideration gender and found males to be statistically significantly larger.

Table 8. *Maxillary Structures Centroid Size*

t-Test: Two-Sample Assuming Unequal Variances		
MAXILLA WITHOUT DENTITION CENTROID SIZE		
	IMPACTED MALES	*IMPACTED FEMALES*
Mean	17.40659145	16.92576281
Variance	0.69556316	0.67958001
Observations	29	34
Hypothesized	0	
df	59	
t Stat	2.292975095	
P(T<=t) one-	0.012715334	
t Critical one	1.671093032	
P(T<=t) two-	0.025430667	
t Critical two	2.000995378	

Discussion

This study provides valuable information about the relationship of maxillary shape and size with palatally and buccal impacted maxillary canines to patients with fully erupted maxillary canines. Prior to this study there was limited information on the association of skeletal and dental shape and size studied with GMM with the impaction of maxillary canines. The use of CBCT imaging and GMM analysis provides valuable insight to the overall skeletal housing and contributing factors associated with palatally and buccal impacted maxillary canines. Previous studies that have examined the relationship between impacted canines and maxillary structures have either only utilized two-dimensional analysis to obtain canine angulations and sectors prone to impaction or three-dimensional analysis limited to either tooth size in a linear dimension or limited to just maxillary segments rather than the overall housing in which the canine erupts through.

The age of included subjects in this study was at least 12 years to allow the normal time needed for the maxillary canine to fully erupt into its final position. Better control of the sample population could have matched between the impaction groups bilateral versus unilateral canine impactions allowing for better quality data through split mouth studies.

Principal component analysis of the entire data set revealed a tight clustering of the control versus impaction groups, indicative of significant shape differences between the two groups based on the location of the canines. To remove the greatest shape difference of the location of the canine, dentition was removed to conduct a PCA of the asymmetric components of the maxilla to better understand the influence of the maxillary canine impaction on the overall maxilla shape, arch shape, palate, and sinus floor. By studying the asymmetric component, the principal components analysis maximizes asymmetries in the sample population. Due to possible landmarking errors and out outliers, 5 samples were removed from the analysis.

Principal components 1 and 2 in this analysis contributed to 31.5% of the variance of the shape. The shape reflected a constriction in size of the arch on the side of the impaction, a shift in midline towards the side of the impaction and a lowering of the sinus floor on the side of the impaction. Principal component 2 reflected more of the effects of the bilateral impaction as both sinus floors exhibited lowering however one side showed more changes in the vertical dimension and reflected in figure 13. On the side of non-impaction there was an increase in the overall shape of the maxilla as well as a rising of the sinus floor. The palate and arch width also expanded.

Size analysis continued to reflect a continued reduction in size for certain dentition and all skeletal landmarks when comparing impacted maxillary canine cases versus the control group. When accounting for maxilla size the first maxillary incisor and first molar were found to be statistically smaller in patients with maxillary impacted canines compared to patients with no maxillary canine impactions. This reduction in size on the side of the canine impaction of both the teeth and maxillary structures may contribute to the lack of space for the maxillary canine to erupt. It also may attribute the lack of skeletal size and shape from the lack of eruption of permanent teeth.

Conclusion

In conclusion, we have found that there is a difference in shape and size between the impacted group versus nonimpacted group however not always a statistically significant one. Between the buccal impaction group and palatal impaction group there were minimal differences in significance. We found that consistently between impaction and non-impaction groups there was no statistically difference in size or shape.

This study does not support the guidance theory in that a lateral incisor needs to be sufficiently sized to guide the maxillary canine into its proper occlusion as we found no statistically significant difference in size between the control group versus the impaction groups. Diminished canine size, central incisor size, and first molar size and a relatively broader mesial-distal and buccal-lingually (in relation to length) canine is associated with a maxillary impaction. The permanent first molar erupts at 6-7 years of age and first incisor erupts at age 7-8 years of age. These two teeth could be related to establishing dental arch length and width and the reduction in both of these can lead to the inability for the permanent canines to erupt. The arch width, palate size and overall maxilla size were all found to be statistically significantly smaller in the impacted groups versus the nonimpacted group.

A constriction and narrowing of the dental arch and lowering of the sinus floor can be seen as asymmetries correlated with maxillary canine impaction. This loss of space in the maxilla in both the horizontal and vertical dimension may be a contributing factor to the canine impaction on either buccal or lingual. Since the canine erupts from the palatal to the buccal, the pathway of least resistance would lead to palatal impaction more commonly.

The continued research on the maxillary structure associations can be utilized as a predictor for maxillary canine impaction and treatment to increase the size of maxillary structures while the patient is still growing, and the maxillary canine still has eruptive potential. Future studies can be conducted on unilateral canine impactions only versus including bilateral impactions so that the dataset can better understand the effects on one side of the maxilla versus the other.

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