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Soft tissue thin-plate spline analysis of pre-pubertal Korean and European-Americans with untreated Angle's Class III malocclusions

G.D. Singh[1], **J.A. McNamara Jr.**[2] **and S. Lozanoff**[3]

[1]Dundee Dental Hospital and School, University of Dundee, Scotland, UK; [2]Department of Orthodontics and Pediatric Dentistry, University of Michigan, Ann Arbor; [3]Departments of Anatomy and Reproductive Biology and of Surgery, University of Hawaii, Manoa

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Abstract: The purpose of this study was to assess soft tissue facial matrices in subjects of diverse ethnic origins with underlying dentoskeletal malocclusions. Pre-treatment lateral cephalographs of 71 Korean and 70 European-American children aged between 5 and 11 years with Angle's Class III malocclusions were traced, and 12 homologous, soft tissue landmarks digitized. Comparing mean Korean and European-American Class III soft tissue profiles, Procrustes analysis established statistical difference ($P < 0.001$) between the configurations, and this difference was also true at all seven age groups tested ($P < 0.001$). Comparing the overall European-American and Korean transformation, thin-plate spline analysis indicated that both affine and non-affine transformations contribute towards the total spline (deformation) of the averaged Class III soft tissue configurations. For non-affine transformations, partial warp (PW) 8 had the highest magnitude, indicating large-scale deformations visualized as labio-mental protrusion, predominantly. In addition, PW9, PW4, and PW5 also had high magnitudes, demonstrating labio-mental vertical compression and antero-posterior compression of the lower labio-mental soft tissues. Thus, Korean children with Class III malocclusions demonstrate antero-posterior and vertical deformations of the labio-mental soft tissue complex with respect to their European-American counterparts. Morphological heterogeneity of the soft tissue integument in subjects of diverse ethnic origin may obscure the underlying skeletal morphology, but the soft tissue integument appears to have minimal ontogenetic association with Class III malocclusions.

Key words: anterior crossbite – pre-normal occlusion – mandibular prognathism

Address reprint requests to Dr. G.D. Singh, Dundee Dental Hospital and School, University of Dundee, Park Place, Dundee DD1 4HR, Scotland, UK. E-mail: g.d.singh@dundee.ac.uk

Introduction

The developmental and functional relations of the dentoskeletal and facial soft tissues require further evaluation. Some studies suggest that the soft tissues act as a passive drape that reflects changes in the underlying skeletal and dental tissues [e.g. Schatz and Tsimas, 1995; Battagel and Orton, 1995; Ferrario and Sforza, 1997; Foley and Duncan, 1997; Miyajima et al., 1997; Lin and Kerr, 1998]. Other studies have produced experimental [Ritsila et al., 1973; Duker and Harle, 1974; Bardach et al., 1994] and post-treatment [Park and Burstone, 1986; Markus et al., 1992; Kapucu et al., 1996; Lee et al., 1996; Yamaguchi et al., 1997] evidence to the contrary. Lowe et al. [1983] suggested an active role for the circumoral musculature in the determination of facial form. By comparing the soft tissue matrices of different ethnic groups with known underlying hard tissue morphologies, dichotomy in the soft tissue matrices associated with the development of the Class III condition would, presumably, be highlighted and the putative contribution of the circumoral soft tissues to the development of Class III malocclusions demonstrated.

The increased prevalence of Class III malocclusions in South-East (S.E.) Asian populations [e.g., Yang, 1990; Kameda, 1982 inter alia] is likely to be genetically determined. Nevertheless, the great diversity of anatomical forms of Class III malocclusion must be taken into account [Delaire, 1997]. The developmental craniofacial components of S.E. Asian children with Class III malocclusions, however, have not been considered extensively. Specifically, there is limited information in the English language orthodontic literature concerning the morphology of Korean individuals with Class III malocclusions [Shin et al., 1989; Baik et al., 1991; Sung et al., 1992; Park and Sung, 1995; Sung, 1996]. In a previous study [Singh et al., 1998a], the skeletal components of pre-pubertal Korean and European-American children with Class III malocclusions were contrasted. Therefore, the aim of the current study is to investigate whether the soft tissue morphologies reflect the underlying skeletal morphologies. Rejection of the null hypothesis, that there is no difference in soft tissue morphology in children of diverse ethnic origin with dissimilar hard tissue morphologies, might provide support for the view of an active role of the soft tissue complex in the development of final facial form associated with Class III malocclusions.

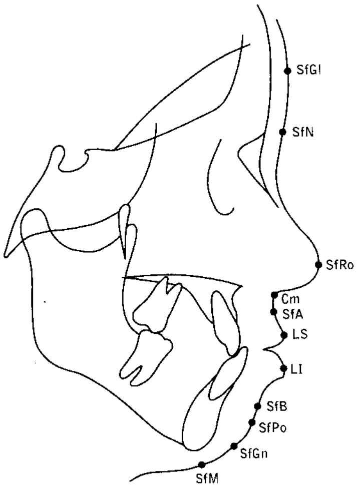

Fig. 1. Definitions of soft tissue landmarks employed in this study on a tracing of a lateral cephalograph of a child with a Class III malocclusion. SfGl, soft glabella (most prominent mid-sagittal point on the forehead); SfN, soft nasion (maximum concavity overlying the frontonasal suture); SfRo, soft rhinion (most prominent point on anterior tip of the nose); Cm, columella (point of intersection of nose with the philtrum of the upper lip); SfA, soft sub-spinale (maximum concavity of the upper lip below the anterior nasal spine corresponding to Point A); LS, labial superioris (maximum mid-sagittal convexity on the upper lip); LI, labial inferioris (maximum mid-sagittal convexity on the lower lip); SfB, soft supramentale (maximum concavity of the lower lip above menton corresponding to Point B); SfPo, soft pogonion (most anterior point directly opposite pogonion); SfGn, soft gnathion (most anterior-inferior point directly opposite gnathion); SfM, soft menton (inferior-most point directly opposite menton).

Materials and methods

After obtaining appropriate consent, pre-treatment lateral cephalographs of 70 consecutive, randomly-selected European-American subjects aged between 5 and 11 years with Angle's Class III molar malocclusion were retrieved [Guyer et al., 1986]. A similar 71 cephalographs of untreated Korean subjects with a Class III molar relationship were also obtained from a Korean orthodontic practice. The total sample included an approximately equal number of age-matched males and females. Initial statistical analysis showed that the two groups did not differ for this parameter. All subjects had a negative history of airway problems and no obvious vertical skeletal problems. The total sample was also discretizable into seven age groups (5–11 years) to facilitate developmental interpretation. It was presumed that all radiographs were taken from subjects exhibiting left–right symmetry and that the central X-ray passed along the transmeatal axis while the teeth were in occlusion. The chronological age was assumed to match developmental age in this study, as carpal ages were unavailable.

The magnification of each film was standardized to 8%. Each cephalograph was traced on frosted acetate film (0.03″ thick) by one investigator (GDS). Digitization of landmark co-ordinates from cephalographs taped to a light box of uniform brightness was achieved using appropriate software and a digitizing tablet. Twelve homologous soft tissue landmarks were digitized (Fig. 1) but neither automated landmark detection nor on-line digitization was employed in this current study. Any landmarks that demonstrated a discrepancy of $> 1\%$ for each x, y co-ordinate on duplicate digitization, however, were deemed to be identified unreliably and were excluded from the final analyses.

For the analysis of geometric transformation from an European-American to a Korean Class III soft tissue configuration, scaled mean morphologies of the European-American and Korean forms were employed. The configurations were tested under the assumption of equivalence of variance [Procrustes analysis; Goodall, 1991] to indicate whether statistically significant differences were demonstrable for the samples independently of the clinical presentation. Hence, further geometric-graphical analysis using thin-plate spline (TPS) analysis would be warranted. Soft tissue configurations of the mean forms were subjected to TPS using appropriate software [Rohlf, 1996], and the total deformation decomposed into a series of partial warps (PWs). The mode of each PW

TABLE 1. Procrustes analysis of mean soft tissue configurations of Korean and European-American Class III subjects[a]

Age (yrs)	5	6	7	8	9	10	11	TS
Residual	0.0035	0.0032	0.0041	0.0033	0.0039	0.0037	0.0033	0.0031
F value	2.4509	4.0427	6.0126	6.4712	5.3563	4.0018	2.2781	25.7667
P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[a] TS represents the total combined soft tissue comparison that is significantly different at the $P<0.001$ level. When the total sample is decomposed into age groups, all age groups maintain statistical difference at the $P<0.001$ level.

is determined by the configuration of landmarks in the starting form and represents the mode of relative landmark displacements for shape changes at that scale of localization. These modal forms are called the principal warps [eigenvectors of the bending energy matrix; Bookstein, 1989, 1991]. The multipliers of the eigenvectors (the TPS weighted sums of the principal warps) are the PWs.

Eigenvectors are interpreted at an inverse index to the scale of the corresponding principal warp. High eigenvalues are associated with highly localized features and high bending energy. As magnitude is a measure of how important a principal warp is for fitting the second form, PWs with large magnitudes are interpreted as making the most difference [Zelditch et al., 1992, 1993]. For these PWs, the bending energy is the product of the magnitude of the warp and its eigenvalue [Bookstein 1989, 1991]. The number of these PWs is three fewer than the number of landmarks [Bookstein, 1989, 1991; Swiderski, 1993]. Deformations of the soft tissue configurations were interpreted on this basis. The terms used in this paper are in accord with the NATO ASI Series [Slice et al., 1996].

Results

Residuals from the overall Procrustes analysis and those at each age are shown in Table 1. Statistically significant differences between the mean Korean and European-American Class III soft tissue configurations occurred at $P < 0.001$ for the total sample. When the total sample was decomposed over seven age intervals, the comparisons maintained statistical significance at $P < 0.001$ for all age groups tested. Therefore, further graphical analysis was undertaken employing TPS.

The pattern of deformations of the transformation grid to attain a Korean Class III soft tissue configuration starting from the European-American mean (the total spline; Fig. 2) showed some evidence of antero-posterior compression of the mid-facial region, affecting soft tissue landmarks at the columella and upper lip. Antero-posterior protrusion of the upper and lower lips was also noted, so that the labio-mental region appeared to be protrusive. In contrast, soft tissue landmarks of the mental region such as soft pogonion (SfPo) appeared to be displaced antero-superiorly.

The total spline for the overall deformation (Fig. 2) was decomposed into PWs to visualize components of the soft tissue deformations. PW8 had the highest magnitude (Table 2; Fig. 3a), indicating large-scale deformations stretching the soft tissue transformation grid antero-posteriorly in the upper and lower lip region accompanied by anterior displacement of the soft tissues of the mental complex. In contrast, PW9 (Table 2; Fig. 3b) showed remarkably little deformation, even though its magnitude was high. PW4 indicated vertical labio-mental deformations with antero-superior displacement of the landmarks of the lower labial-mental region (Table 2; Fig. 3c). Similarly, PW5 exhibited lower labio-mental retrusion (Table 2; Fig. 3d).

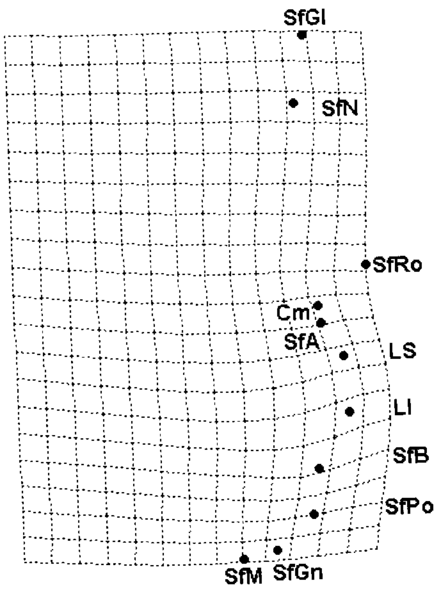

Fig. 2. The total spline. The transformation grid to attain a Korean Class III soft tissue configuration starting from the European-American Class III mean shows antero-posterior compression of the mid-facial region, antero-posterior protrusion of the upper and lower lips, protrusion of the labio-mental region and antero-superior displacement of landmarks of the mental region.

TABLE 2. Contribution of each partial warp (PW) towards the total spline[a]

Age	PW	Eigenvalue	Energy ($\times 10^{-3}$)	Magnitude ($\times 10^{-5}$)
5	1	593.65	32.68	5.51
	2	119.34	5.24	4.39
	3	97.16	2.70	2.78
	4	**42.50**	**15.31**	**36.02**
	5	**25.90**	**12.12**	**46.80**
	6	18.37	0.57	3.11
	7	13.90	1.02	7.34
	8	**5.52**	**2.01**	**36.38**
	9	**1.35**	**1.17**	**86.69**
6	1	515.30	19.39	3.76
	2	128.93	1.41	1.09
	3	108.88	2.09	1.92
	4	**48.53**	**15.56**	**32.06**
	5	**26.37**	**6.08**	**23.07**
	6	18.60	0.21	1.15
	7	13.50	1.21	8.99
	8	**5.72**	**1.36**	**23.77**
	9	**1.36**	**0.33**	**24.18**
7	1	432.58	8.81	2.04
	2	130.33	9.87	7.57
	3	100.23	6.37	6.35
	4	**48.42**	**11.72**	**24.19**
	5	27.71	4.21	15 18
	6	20.91	0.43	2.06
	7	12.68	0.50	3.92
	8	**5.77**	**3.15**	**54.54**
	9	**1.35**	**0.97**	**72.06**
8	1	392.21	5.51	1.41
	2	131.61	9.11	6.92
	3	96.50	0.31	0.32
	4	**47.29**	**15.05**	**31.82**
	5	**27.95**	**8.93**	**31.94**
	6	19.58	0.13	0.66
	7	14.16	3.73	26.36
	8	**5.37**	**1.86**	**34.62**
	9	**1.34**	**0.38**	**28.22**
9	1	447.20	8.36	1.87
	2	131.21	15.16	11.56
	3	102.03	11.90	11.67
	4	**45.71**	**15.33**	**33.53**
	5	**28.03**	**6.89**	**24.57**
	6	20.87	1.14	5.46
	7	13.86	1.24	8.93
	8	**5.71**	**1.85**	**32.44**
	9	**1.32**	**1.29**	**97.01**
10	1	441.09	11.47	2.60
	2	131.39	6.03	4.59
	3	99.72	3.70	3.71
	4	**49.61**	**30.11**	**60.68**
	5	27.99	6.75	24.11
	6	**23.19**	**6.25**	**26.94**
	7	12.38	2.45	19.78
	8	**5.58**	**1.59**	**28.45**
	9	1.31	0.25	18.90
11	1	311.24	9.08	2.92
	2	140.12	2.64	1.89
	3	107.39	1.10	1.03
	4	51.70	11.50	22.25
	5	**29.35**	**10.44**	**35.59**

TABLE 2. (Continued)

Age	PW	Eigenvalue	Energy ($\times 10^{-3}$)	Magnitude ($\times 10^{-5}$)
	6	20.15	2.03	10.06
	7	12.44	2.52	20.23
	8	**5.64**	**6.52**	**115.57**
	9	1.32	0.27	20.12
TS	1	428.61	10.60	2.47
	2	127.79	8.35	6.54
	3	102.80	1.00	0.97
	4	**47.35**	**15.16**	**32.01**
	5	**27.48**	**6.32**	**22.98**
	6	20.50	0.91	4.44
	7	13.25	1.25	9.42
	8	**5.63**	**2.34**	**41.55**
	9	**1.33**	**0.47**	**35.14**

[a] TS = total sample. PWs with high magnitudes are highlighted.

When the total sample was decomposed into seven age groups (5–11 years), each age-wise comparison for the mean Class I and Class III configurations maintained statistical significance ($P < 0.01$). Moreover, a similar pattern of deformation was identifiable at all age groups studied between 5 and 11 years. PW8, indicating large-scale deformations associated with a combination of columellar retrusion and labial protrusion, invariably had a high or the highest magnitude for the total sample and all age sub-groups (Table 2). Therefore, graphical analysis of the soft tissue complex using TPS demonstrated a pattern of large spatial-scale deformations affecting the soft tissue configuration with antero-posterior stretching of the upper and lower lips, compression of the columellar region, and antero-superior compression of the mental complex, in order to attain a Korean Class III soft tissue morphology.

Discussion

Analysis of the soft tissues is a crucial step in orthodontic treatment planning as the soft tissue facial matrix may limit therapeutic interventions [Ackerman and Proffit, 1997]. Facial soft tissue size and shape is influenced by parameters such as age [Foley and Duncan, 1997; Yamaguchi et al., 1997], sex [Blanchette et al., 1996], and to a lesser extent skeletal classification [Ferrario and Sforza, 1997; Singh et al., 1998b]. In addition, soft and hard tissue response to therapeutic procedures may vary according to ethnicity [Lew and Loh, 1991]. Yet, it is still not certain whether the facial soft tissues are a "passive drape". For example, Park and Burstone [1986] noted large variations in facial profiles in cases treated to a defined cephalometric dentoskeletal standard. Dissimilarities of morphologies may suggest developmental independence of hard and soft tissue matrices.

In this cross-sectional study, sexes were combined due to the relatively small sample size. Combining sexes in the 5–11 year age range generally is satisfactory because of only the modest sexual dimorphism of craniofacial structures present at these pre-pubertal ages (Riolo et al., 1974). Cognisant of the consensus that traditional cephalometry yields data of dubious scientific value [Lavelle and Carvalho, 1989], morphological differences were detected using TPS, as this technique permits rigorous analysis of shape and size change [e.g. Singh et al., 1998b inter alia). Indeed, Ferrario et al. [1995] noted that shape similarities largely can be overwhelmed by size differences, and Lele [1993] has highlighted the problems of using Procrustes analysis as a statistical tool. Employing TPS, however, the soft tissue matrices were found to differ for Class III Korean children and their European-American counterparts. Therefore, the use of combined samples consisting of pre-pubertal boys and girls appears to depict ethnic, presumably genetic, craniofacial soft tissue heterogeneity in children with Class III malocclusions.

The pattern of deformation of the European-American/Korean transformation grid showed antero-posterior protrusion of the upper and lower lips. In Chinese patients, upper lip protrusion correlates with maxillary incisor protrusion [Lew, 1990]. Similarly, upper and lower lip retraction correlates with maxillary incisor retraction [Talass et al., 1987; Yogosawa, 1990]. It is likely, therefore, that the Korean children exhibit bimaxillary proclination compared to their European-American counterparts to account for the soft tissue differences noted in the present study. In-

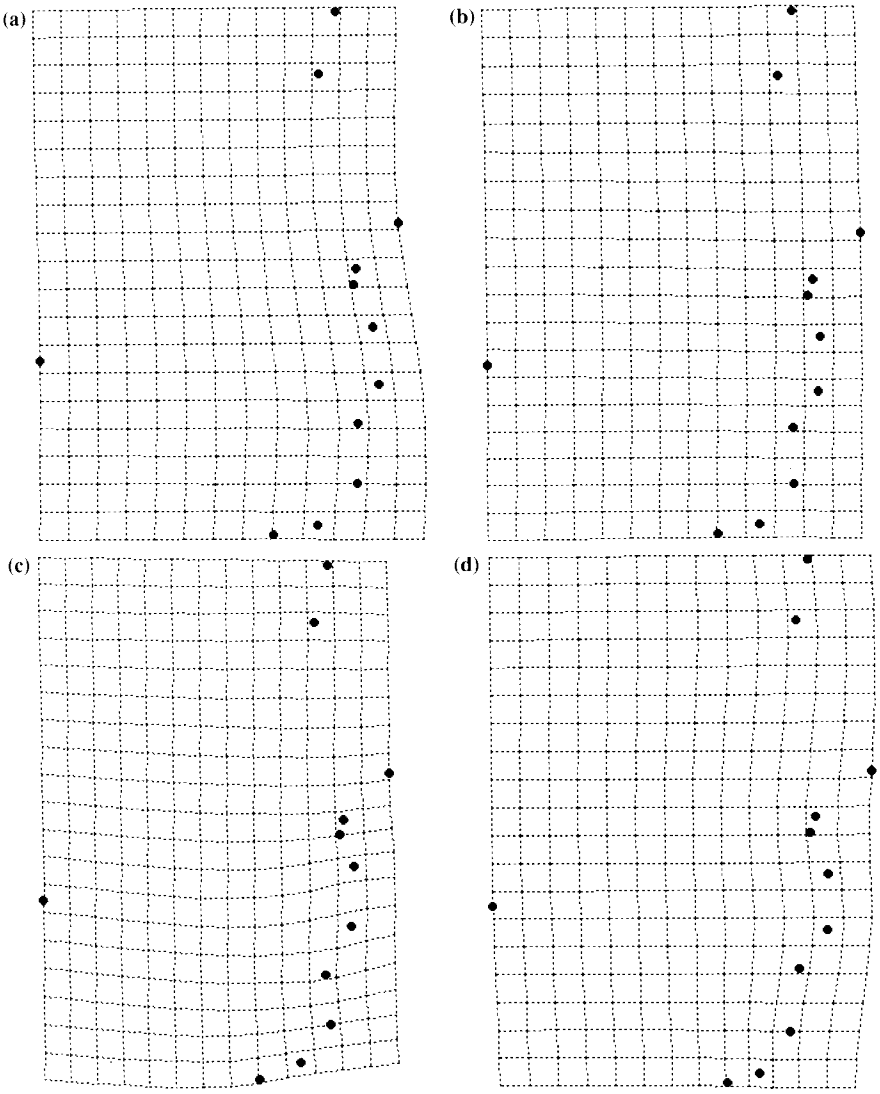

Fig. 3. (a) Partial warp (PW) 8. Large spatial-scale deformations stretch the transformation grid antero-posteriorly in the upper and lower lip region. Anterior displacement of the soft tissues of the mental complex is also visible. (b) PW9. There is remarkably little deformation despite the relatively high magnitude of this particular PW. (c) PW4. Vertical labio-mental deformations with antero-superior displacement of the landmarks of the lower labial-mental region are demonstrable. (d) PW5. Lower labio-mental retrusion of the soft tissue complex is evident.

deed, Yang [1997] treated Korean children with Class III malocclusions and noted both labioversion of the maxillary incisors and linguoversion of the mandibular incisors, improving the facial profile. Therefore, the position of the lips and the soft tissues overlying points A and B appear to be substantially related to the positions of the incisors [Saxby and Freer, 1985; Tan, 1996]. The current study, however, does not establish this fact, as assessment of incisor inclinations was not undertaken. Indeed, Richardson [1997] found only a tenuous relationship between changes in upper lip position and incisor angulation. Moreover, if tongue pressure exerted on the central incisors of both jaws in Class III children is higher than lip pressure [Bookhold and Hensel, 1989], then incisor position may be determined by tongue pressure [Lowe et al., 1985] rather than lip posture.

In contrast, it was also noted that soft tissue landmarks of the mental region, such as SfPo, appeared to be displaced antero-superiorly. This finding contrasts with those of Haskell [1979], who suggested that chin size increases as the mandibular type varies from a vertical to an horizontal growth pattern. Not surprisingly, Haskell [1979] was of the opinion that the extreme variability of chin form may be due to the contiguous soft and hard tissue environment, the intrinsic genotype of the mandible and the implied polygenic influence on symphyseal morphology. Earlier, Singh [1990] indicated that age, sex, and facial type influenced the soft tissue chin thickness. More recently, Kasai [1998] notes that chin form is influenced by hard tissue structures rather than by incisor position in accord with the therapeutic findings of Thuer et al. [1994], but contrasting with the surgical findings of

Lee et al. [1996] on Korean patients. Superficial soft tissue variations, therefore, may reflect differences in climatic conditions and other environmental factors [Jefferson, 1996].

Our findings suggest that morphological heterogeneity of the soft tissue integument in subjects of diverse ethnic origin may obscure the underlying skeletal morphology. This finding is in agreement with those of Fields et al. [1982] who suggested that soft tissue outlines do not provide sufficient information to assess the underlying skeletal pattern in children, particularly prognathic patterns. That the pattern of deformation varies little during the age range studied, suggests that soft tissue matrices are established at an early post-natal age. These findings are in bon accord with those of Tollaro et al. [1995], 1996]; the developmental pattern does not appear to change significantly up to the pre-pubertal stage. The skeletal pattern and soft tissue matrices may be inherited independently, but their functional relationship does not permit the decomposition of the contributing components, although Cobo et al. [1992] suggested that increased muscular tension in the lower lip and chin can be detected by densitometric scanning after active treatment. Therefore, soft tissues may exert pressures that actively mould the underlying hard tissues [Ackerman and Proffit, 1997], but complex dynamic anatomy cannot be elucidated from morphometrics alone [Talass et al., 1987], as gene–environmental interactions are likely. The findings of this study may have clinical implications for orthodontic interventions in subjects of diverse ethnicity.

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